

Towards a Constrained-Efficiency Framework for the Digital Transformation in Agri-food  
Supply Chains: A Case of the Tomato Supply Chain in Nigeria.

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## Thesis Abstract

This thesis interrogates the paradoxes of digital transformation in Nigeria's agri-food supply chains, with particular focus on tomato production. While digital technologies are widely promoted for their potential to increase efficiency, reduce food loss and waste, and enable market access, their real-world performance in resource-constrained contexts often falls short of these promises. Against staggering post-harvest losses, with up to 50% of fresh tomato production wasted before consumption, this study asks a fundamental question: Why do digital interventions in agriculture often fail to deliver their intended outcomes, and under what governance conditions can their performance be enhanced? The inquiry is situated at the intersection of development economics, institutional theory, and digital transformation studies. Drawing on a critical realist philosophy and an abductive research design, the study synthesises insights from two systematic literature reviews and 79 in-depth interviews across two contractually distinct cases of tomato production: government-led and donor-driven production hubs, and private-led venture-backed commercial innovation platforms. Using the Gioia method for thematic coding, the research surfaces five paradoxical constraint mechanisms characterising digital transformation in agri-food systems: Constrained Efficiency, Fragmented Formalisation, Disrupted Informality, Residual Governance, and Algorithmic Mistrust. These paradoxes reveal a counterintuitive insight: digital inefficiencies are not simply products of infrastructural deficits or behavioural inertia but are often embedded within incomplete contractual architectures, fragmented institutional environments, and asymmetrical governance logics. This insight culminates in developing the Digital Constraint Paradox (DCP) Framework, a novel conceptual typology mapping the interaction between institutional support and resource capabilities in shaping digital outcomes. Theoretically, this dissertation advances an extended governance-based theory of digital transformation by integrating paradox theory, institutional logics, and incomplete contract theory. This study repositions digital transformation as a terrain of contestation, where efficiency is neither automatic nor apolitical, but a negotiated outcome shaped by governance, trust, and the invisible architectures of constraint.

**Keywords:** Digital transformation; Agri-food supply chains; Food loss and waste; Nigeria; Tomato supply chain; Incomplete contract theory; Institutional theory; Paradox theory; Platform governance; Digital Constraint Paradox Framework

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## Table of Contents

|                                                                                                                       |            |
|-----------------------------------------------------------------------------------------------------------------------|------------|
| <b>Thesis Abstract .....</b>                                                                                          | <b>ii</b>  |
| <b>Acknowledgements .....</b>                                                                                         | <b>iii</b> |
| <b>List of Abbreviations .....</b>                                                                                    | <b>x</b>   |
| <b>List of Tables .....</b>                                                                                           | <b>xv</b>  |
| <b>List of Figures .....</b>                                                                                          | <b>xvi</b> |
| <b>1 Chapter One: Introduction .....</b>                                                                              | <b>1</b>   |
| 1.1 Chapter introduction .....                                                                                        | 1          |
| 1.2 Overview .....                                                                                                    | 1          |
| 1.3 Background of the study .....                                                                                     | 1          |
| 1.4 Problem statement: The Digital Constraint Paradox in food supply chains .....                                     | 2          |
| 1.5 Digital interventions in Sub-Saharan African agri-food supply chains.....                                         | 3          |
| 1.6 Food loss and waste measurement and the role of technology.....                                                   | 4          |
| 1.7 Framing the research problem, aim, and research questions.....                                                    | 4          |
| 1.8 Research justification and significance .....                                                                     | 5          |
| 1.9 Scope of the study .....                                                                                          | 5          |
| 1.10 Structure of the dissertation .....                                                                              | 6          |
| 1.11 Chapter conclusion .....                                                                                         | 6          |
| <b>2 Chapter Two: Literature Review .....</b>                                                                         | <b>7</b>   |
| 2.1 Introduction .....                                                                                                | 7          |
| 2.2 Description of the agri-food supply chain .....                                                                   | 8          |
| 2.3 Addressing Data Gaps in Upstream Agrifood Supply Chains: A Systematic Review<br>of Food Loss Quantification ..... | 11         |
| 2.3.1 Abstract .....                                                                                                  | 11         |
| 2.3.2 Introduction.....                                                                                               | 12         |
| 2.3.3 Methodology.....                                                                                                | 14         |
| 2.3.4 Descriptive analysis.....                                                                                       | 21         |
| 2.3.5 Thematic analysis.....                                                                                          | 26         |

|       |                                                                                                                                                                                           |     |
|-------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 2.3.6 | Framework for Food Loss Quantification .....                                                                                                                                              | 35  |
| 2.3.7 | Future Research Directions.....                                                                                                                                                           | 41  |
| 2.3.8 | Conclusion and Contributions .....                                                                                                                                                        | 43  |
| 2.4   | <i>The Digital Transformation of Agri-food Supply Chains</i> .....                                                                                                                        | 44  |
| 2.4.1 | Overview .....                                                                                                                                                                            | 44  |
| 2.4.2 | Digital Transparency and Power Asymmetries in Agri-food Systems: An Example of Blockchain Technology .....                                                                                | 47  |
| 2.4.3 | Efficiency as Conditional and Contextual .....                                                                                                                                            | 48  |
| 2.4.4 | The Environmental Costs of Digital Solutions .....                                                                                                                                        | 48  |
| 2.4.5 | Toward Critical Digital Transformation .....                                                                                                                                              | 48  |
| 2.4.6 | Summary .....                                                                                                                                                                             | 52  |
| 2.5   | <i>Multisided Platforms in Agri-food Supply Chains</i> .....                                                                                                                              | 52  |
| 2.5.1 | Overview .....                                                                                                                                                                            | 52  |
| 2.5.2 | Current State and Challenges .....                                                                                                                                                        | 53  |
| 2.5.3 | Theoretical Framework for Agrifood MSPs .....                                                                                                                                             | 55  |
| 2.5.4 | Critical Synthesis of Digital Agrifood MSPs.....                                                                                                                                          | 59  |
| 2.5.5 | Implementation Challenges in Agrifood Supply Chains .....                                                                                                                                 | 60  |
| 2.6   | <i>Strategic Interventions for Minimising Food Loss in Agri-food Supply Chains: A Systematic Literature Review and Conceptual Framework Development (Published journal article)</i> ..... | 62  |
| 2.6.1 | Abstract .....                                                                                                                                                                            | 62  |
| 2.6.2 | Introduction.....                                                                                                                                                                         | 63  |
| 2.6.3 | Methods.....                                                                                                                                                                              | 65  |
| 2.6.4 | Results and findings .....                                                                                                                                                                | 69  |
| 2.6.5 | Findings.....                                                                                                                                                                             | 72  |
| 2.6.6 | Synthesis.....                                                                                                                                                                            | 79  |
| 2.6.7 | Framework for the Implementation of Strategic Interventions.....                                                                                                                          | 82  |
| 2.6.8 | Discussion .....                                                                                                                                                                          | 85  |
| 2.7   | <i>The Nigerian Tomato Supply Chain</i> .....                                                                                                                                             | 87  |
| 2.7.1 | Overview of The Nigerian Tomato Supply Chain .....                                                                                                                                        | 87  |
| 2.7.2 | Actors in Nigeria's Tomato Supply Chain.....                                                                                                                                              | 92  |
| 2.7.3 | Innovations in Policies and Infrastructure .....                                                                                                                                          | 111 |
| 2.8   | <i>Conclusion of Literature Review</i> .....                                                                                                                                              | 111 |
| 2.8.1 | Integration with the theoretical framework and research design .....                                                                                                                      | 115 |

|          |                                                                                                |            |
|----------|------------------------------------------------------------------------------------------------|------------|
| <b>3</b> | <b>Chapter Three: Theoretical Framework .....</b>                                              | <b>117</b> |
| 3.1      | <i>Introduction .....</i>                                                                      | 117        |
| 3.2      | <i>Theoretical Foundations: From Contract Theory to Constrained Efficiency.....</i>            | 119        |
| 3.2.1    | Classical Contract Theory and Its Limitations .....                                            | 120        |
| 3.2.2    | The Turn to Institutional and Incomplete Contract Theory .....                                 | 120        |
| 3.2.3    | Integrating Resource-Based Perspectives .....                                                  | 121        |
| 3.2.4    | Paradox Theory and the Co-presence of Efficiency and Constraint .....                          | 121        |
| 3.3      | <i>Incomplete Contract Theory and Digital Platform Governance .....</i>                        | 122        |
| 3.3.1    | Foundations of Incomplete Contract Theory .....                                                | 122        |
| 3.3.2    | Power Asymmetries and Hold-Up in Agri-Food Contracts .....                                     | 123        |
| 3.3.3    | Digital Platforms, Contracts and Surveillance .....                                            | 124        |
| 3.3.4    | Algorithmic Governance, Platform Power, and the Reconfiguration of Market<br>Coordination..... | 125        |
| 3.3.5    | ICT Under Resource Scarcity and Institutional Weakness .....                                   | 126        |
| 3.3.6    | Link to Gap 3: Contracts, Platforms and Digital Transformation .....                           | 127        |
| 3.4      | <i>Institutional and Resource Perspectives .....</i>                                           | 127        |
| 3.4.1    | New Institutional Economics: Institutional Voids and Path Dependence .....                     | 127        |
| 3.4.2    | Institutions, Digital Transformation and Food Loss .....                                       | 128        |
| 3.4.3    | Resource-Based View: Capabilities, Complementarities and Thin Digitalisation<br>129            |            |
| 3.4.4    | Institutional and Resource Mechanisms for the Thesis Gaps .....                                | 129        |
| 3.5      | <i>Integrating Theories: The Constrained Efficiency and DCP Framework.....</i>                 | 130        |
| 3.5.1    | The Limits of Contract and Resource Logics in Isolation .....                                  | 130        |
| 3.5.2    | Constrained Efficiency as an Integrative Concept .....                                         | 131        |
| 3.5.3    | The Digital Constraint Paradox (DCP) Framework .....                                           | 132        |
| 3.5.4    | DCP and the Thesis Research Gaps .....                                                         | 134        |
| 3.5.5    | Operationalisation and Implications for Case Design .....                                      | 135        |
| 3.6      | <i>Conclusion .....</i>                                                                        | 138        |
| <b>4</b> | <b>Chapter Four: Methodology .....</b>                                                         | <b>140</b> |
| 4.1      | <i>Introduction .....</i>                                                                      | 140        |
| 4.2      | <i>Research Phases and Linkage to the Research Questions.....</i>                              | 142        |
| 4.3      | <i>The Evolution of Research Inquiry.....</i>                                                  | 143        |
| 4.4      | <i>Critical Realism as an Ontological and Epistemological Foundation .....</i>                 | 144        |

|          |                                                                                      |            |
|----------|--------------------------------------------------------------------------------------|------------|
| 4.4.1    | Ontological Positioning.....                                                         | 144        |
| 4.4.2    | Epistemological Positioning .....                                                    | 144        |
| 4.5      | <i>Theorizing Digital Constraints Through a Contractual Lens.....</i>                | 145        |
| 4.6      | <i>Research Design and the Structuring of the Multiple-Case Study.....</i>           | 146        |
| 4.6.1    | Justifying the Multiple-Case Study Approach.....                                     | 146        |
| 4.6.2    | Mapping the Cases: Contractual Configurations and Selection Criteria .....           | 147        |
| 4.7      | <i>Actor Selection and the Logic of Snowball Sampling.....</i>                       | 149        |
| 4.8      | <i>Instrumentation and Data Collection .....</i>                                     | 150        |
| 4.8.1    | Pilot Study .....                                                                    | 153        |
| 4.8.2    | Phase One .....                                                                      | 154        |
| 4.8.3    | Phase Two .....                                                                      | 155        |
| 4.8.4    | Focus Group Discussions .....                                                        | 156        |
| 4.9      | <i>Archival Data Collection .....</i>                                                | 157        |
| 4.10     | <i>Ethical Considerations .....</i>                                                  | 158        |
| 4.11     | <i>Development of First- and Second-Order Themes .....</i>                           | 159        |
| 4.11.1   | Addressing Trustworthiness in this Study .....                                       | 159        |
| 4.12     | <i>Summary.....</i>                                                                  | 163        |
| <b>5</b> | <b>Chapter Five: Results .....</b>                                                   | <b>164</b> |
| 5.1      | <i>Overview .....</i>                                                                | 164        |
| 5.2      | <i>Case One: Primary and Emerging Tomato Production Hubs .....</i>                   | 164        |
| 5.2.1    | Technological Absorption and Infrastructure Constraints .....                        | 165        |
| 5.2.2    | Digital Access and Knowledge Fragmentation.....                                      | 169        |
| 5.2.3    | Regulatory Control and Market Coordination Failures .....                            | 172        |
| 5.2.4    | Algorithmic Supply Chain Control and Power Asymmetries .....                         | 174        |
| 5.2.5    | Institutional Adaptation and Digital Governance Challenges .....                     | 177        |
| 5.2.6    | Case One: synthesis and linkage to research objectives and research questions<br>179 |            |
| 5.3      | <i>Case Two: Commercial and Innovation-Driven Tomato Hubs.....</i>                   | 181        |
| 5.3.1    | Algorithmic Market Governance and Adaptive Infrastructure.....                       | 181        |
| 5.3.2    | Hybrid NGO-Private Sector Models .....                                               | 182        |
| 5.3.3    | Decentralised Digital Finance and Market Fluidity .....                              | 183        |
| 5.3.4    | Data Monetisation and Market Intelligence Concentration.....                         | 185        |
| 5.3.5    | Strategic Partnerships and Network Synergies.....                                    | 187        |

|          |                                                                                           |            |
|----------|-------------------------------------------------------------------------------------------|------------|
| 5.3.6    | Digital Platform Dependence and Algorithmic Lock-ins .....                                | 188        |
| 5.3.7    | Market-Driven Innovation and Commercial Knowledge Hybridisation .....                     | 190        |
| 5.3.8    | Case Two synthesis and linkage to research objectives and research questions<br>192       |            |
| <b>6</b> | <b>Chapter Six: Discussion.....</b>                                                       | <b>197</b> |
| 6.1      | <i>Introduction .....</i>                                                                 | <i>197</i> |
| 6.2      | <i>Digital Transformation as a Structurally Constrained Process.....</i>                  | <i>198</i> |
| 6.3      | <i>Digital Intermediation as a Structural Necessity.....</i>                              | <i>201</i> |
| 6.3.1    | The Reconfiguration of Market Intermediation .....                                        | 201        |
| 6.3.2    | Data Intermediation and Informational Gatekeeping.....                                    | 202        |
| 6.3.3    | Contractual Intermediation .....                                                          | 203        |
| 6.4      | <i>Contractual Voids and the Institutional Fragility of Digital Market Governance ...</i> | <i>204</i> |
| 6.4.1    | The Structural Persistence of Contractual Incompleteness .....                            | 205        |
| 6.4.2    | Algorithmic Enforcement and the Technocratic Shift in Contract Governance                 | 206        |
| 6.4.3    | Residual Benefits and Digital Market Enclosure .....                                      | 206        |
| 6.5      | <i>Algorithmic Power and the Reconfiguration of Market Coordination.....</i>              | <i>207</i> |
| 6.5.1    | Algorithmic Price-Setting and the Erosion of Bargaining Autonomy .....                    | 208        |
| 6.5.2    | Predictive Optimisation and the Foreclosure of Market Access .....                        | 209        |
| 6.5.3    | Data-Driven Scoring and the Algorithmic Stratification of Opportunity.....                | 209        |
| 6.6      | <i>Institutional Rigidities and the Limits of Digital Transformation.....</i>             | <i>210</i> |
| 6.6.1    | Regulatory Fragmentation and the Limits of Policy Coherence .....                         | 211        |
| 6.6.2    | Bureaucratic Inertia and the Resistance to Digital Adaptation .....                       | 212        |
| 6.6.3    | The Systematic Marginalisation of Food Waste as a Policy Priority .....                   | 213        |
| 6.7      | <i>The Digital Constraint Paradox Framework .....</i>                                     | <i>215</i> |
| 6.7.1    | The Two Axes of the Digital Constraint Paradox .....                                      | 216        |
| 6.7.2    | Quadrant I: The Stagnation Trap .....                                                     | 219        |
| 6.7.3    | Quadrant II: The Illusion of Efficiency .....                                             | 220        |
| 6.7.4    | Quadrant III: Institutionalised Rigidity.....                                             | 222        |
| 6.7.5    | Quadrant IV: The Zone of Digital Synergy .....                                            | 223        |
| 6.8      | <i>Conclusion .....</i>                                                                   | <i>225</i> |
| <b>7</b> | <b>Chapter Seven: Conclusion .....</b>                                                    | <b>227</b> |
| 7.1      | <i>Introduction .....</i>                                                                 | <i>227</i> |



|          |                                                                                                      |            |
|----------|------------------------------------------------------------------------------------------------------|------------|
| 7.2      | <i>The Digital Constraint Paradox and the Institutional Embedding of Digital Transformation.....</i> | 227        |
| 7.3      | <i>From Empirical Puzzles to Theoretical Synthesis.....</i>                                          | 228        |
| 7.4      | <i>Synthesising the Core Propositions of the Study.....</i>                                          | 229        |
| 7.5      | <i>Positioning the Contribution within Corley and Gioia’s Framework.....</i>                         | 232        |
| 7.6      | <i>Final Reflections and Theoretical Roadmap for Future Research .....</i>                           | 232        |
| 7.6.1    | <i>Theoretical Contributions .....</i>                                                               | 233        |
| 7.6.2    | <i>From Incomplete Contracts to Digital Intermediation and Algorithmic Control.....</i>              | 234        |
| 7.6.3    | <i>A Structuralist Perspective on Digital Failure .....</i>                                          | 234        |
| 7.6.4    | <i>Institutional Rigidity and the Marginalisation of Digital Waste Reduction.....</i>                | 235        |
| 7.7      | <i>Final Reflections on the Theoretical Legacy of the Digital Constraint Paradox ...</i>             | 235        |
| 7.8      | <i>Practical Contributions of the Study.....</i>                                                     | 235        |
| 7.8.1    | <i>Rethinking Digital Interventions.....</i>                                                         | 238        |
| 7.8.2    | <i>Addressing Food Loss and Waste .....</i>                                                          | 238        |
| 7.8.3    | <i>Digital Inclusion Strategies to Counteract Power Asymmetries .....</i>                            | 238        |
| 7.8.4    | <i>Designing for Residual Benefits, Not Just Residual Risks .....</i>                                | 238        |
| 7.9      | <i>Limitations.....</i>                                                                              | 239        |
| <b>8</b> | <b>List of References .....</b>                                                                      | <b>240</b> |
| <b>9</b> | <b>Appendices.....</b>                                                                               | <b>286</b> |
| 9.1      | <i>Appendix 1: Details of Quality Assessment Criteria.....</i>                                       | 286        |
| 9.2      | <i>Appendix 2: Included Papers in Systematic Review 1 .....</i>                                      | 287        |
| 9.3      | <i>Appendix 3: 1<sup>st</sup> Conceptual Framework for Food Loss Interventions.....</i>              | 352        |
| 9.4      | <i>Appendix 4: Stacking and Multiplier Losses.....</i>                                               | 353        |
| 9.5      | <i>Appendix 5: Archival Data Sources and Policy Documents.....</i>                                   | 354        |
| 9.6      | <i>Appendix 6: Research protocol and data collection instruments .....</i>                           | 358        |
| 9.6.1    | <i>Appendix 6.1: Full research protocol and data collection instruments .....</i>                    | 358        |
| 9.6.2    | <i>Appendix 6.2 : Coding modes, coding manual, and reliability procedure .....</i>                   | 365        |
| 9.7      | <i>Appendix 7: Semi-Structured Interview and Focus Group Discussion Questions.....</i>               | 374        |
| 9.7.1    | <i>Semi- Structured Interview Questions.....</i>                                                     | 374        |
| 9.8      | <i>Appendix 8: Rationale for Actor Group Categorisation .....</i>                                    | 380        |

|      |                                                                                    |            |
|------|------------------------------------------------------------------------------------|------------|
| 9.9  | <i>Appendix 9: Codes and Quotes from First-Order to Conceptual Categories.....</i> | <i>384</i> |
| 9.10 | <i>Appendix 10: Parent-child Mapping of Data.....</i>                              | <i>404</i> |

## **List of Abbreviations**

3R: Reduce, Reuse, Recycle (in a circular economy)

ABP: Anchor Borrowers' Programme

AfDB: African Development Bank

AFSCs: Agri-food Supply Chains

AGR: Agronomists and Sustainability Experts (in participant coding)

AI: Artificial Intelligence

API: Application Programming Interface

APP: Agricultural Promotion Policy

APQCA: Agricultural Produce Quality Control Act

ATASP-I: Agricultural Transformation Agenda Support Program

BaaS: Blockchain-as-a-Service

BoA: Bank of Agriculture

BCT: Behavioural Contract Theory

CA: Controlled Atmosphere

CAS: Complex Adaptive Systems

CASP: Critical Appraisal Skills Programme (referenced in research methodology)

CBN: Central Bank of Nigeria

CE: Circular Economy

CEF: Constraint Efficiency Framework

CSR: Corporate Social Responsibility

DADI: Digital Agriculture Development Initiative

DC: Dynamic Capabilities

DCP: Digital Constraint Paradox

DMAIC-DLL: Define, Measure, Analyze, Improve, Control - Double-Loop Learning

EBSCO: Elton B. Stephens Company (database mentioned in methodology)

ERP: Enterprise Resource Planning

EXT: Extension Services (in participant coding)

FAO: Food and Agriculture Organization (of the United Nations)

FCI: Food Chain Inefficiency

FEFO: First-Expiry-First-Out

FIN: Financial and Insurance Services (in participant coding)

FL: Food Loss

FLW: Food Loss and Waste

FMARD: Federal Ministry of Agriculture and Rural Development

FMCGs: Fast-Moving Consumer Goods

FMCIIDE: Federal Ministry of Communications, Innovation, and Digital Economy

FMEEnv: Federal Ministry of Environment

FMSTI: Federal Ministry of Science, Technology, and Innovation

FPO: Farmer Producer Organization

FPOs: Farmer Producer Organizations

FRM: Farmer Category (in participant coding)

FSC: Food Supply Chain

FW: Food Waste

GAP: Good Agricultural Practices

GDPR: General Data Protection Regulation

GM: Genetically Modified

GPS: Global Positioning System

GST: General Systems Theory

ICT: Information and Communication Technology

IoT: Internet of Things

LCA: Life Cycle Assessment

LOG: Logistics (in participant coding)

MAP: Modified Atmosphere Packaging

MFA: Material Flow Analysis

MMAT: Mixed Methodologies Appraisal Tool

MRI: Magnetic Resonance Imaging

MSPs: Multi-sided Platforms

NAFDAC: National Agency for Food and Drug Administration and Control

NAIC: Nigerian Agricultural Insurance Corporation

NAQS: Nigeria Agricultural Quarantine Service

NASC: National Agricultural Seeds Council

NATIP: National Agricultural Technology and Innovation Policy

NBP: National Broadband Plan

NBMA: National Biosafety Management Agency

NCC: Nigerian Communications Commission

NDAS: Nigeria Digital Agriculture Strategy

NDEPS: National Digital Economy Policy and Strategy

NEPC: Nigeria Export Promotion Council

NGO: Non-Governmental Organization

NiMet: Nigerian Meteorological Agency

NIHORT: National Horticultural Research Institute

NIE: New Institutional Economics

NIRP: National Industrial Revolution Plan

NIRSAL: Nigerian Incentive-based Risk-Sharing System for Agricultural Lending

NITDA: National Information Technology Development Agency

NPFSIS: National Policy on Food Safety and Its Implementation Strategy

NSPA: Niger State Policy On Agriculture

OECD: Organisation for Economic Co-operation and Development

ORG: Organizational Leadership and Advocacy (in participant coding)

PEO: Population, Exposure, and Outcome

PICS: Purdue Improved Crop Storage

PPA: Preferential Procurement Policies

PRC: Processing (in participant coding)

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analysis

PRJ: Project Management and Coordination (in participant coding)

RAAMP: Rural Access and Agricultural Marketing Project

RBV: Resource-Based View

REG: Regulatory Authorities (in participant coding)

RFID: Radio-Frequency Identification

RPCs: Reusable Plastic Crates

RSR: Researchers and Consultants (in participant coding)

RTL: Retail (in participant coding)

SACCOs: Savings and Credit Cooperative Organizations

SCM: Supply Chain Management (in participant coding)

SDG: Sustainable Development Goal

SFSCs: Short Food Supply Chains

SLR: Systematic Literature Review

SMEs: Small and Medium-sized Enterprises

SON: Standards Organisation of Nigeria

STS: Science and Technologies Studies

TAM: Technology Acceptance Model

TCE: Transaction Cost Economics

TEC: Technology Experts (in participant coding)

UN: United Nations

UNEP: United Nations Environment Programme

VC: Value Chain

WRI: World Resources Institute

ZECC: Zero Energy Cooling Chamber

## List of Tables

|                                                                                                                                |     |
|--------------------------------------------------------------------------------------------------------------------------------|-----|
| Table 1: Categorisation of the Definitions of Agri-food Supply Chain .....                                                     | 9   |
| Table 2: Keyword taxonomy for systematic literature search .....                                                               | 15  |
| Table 3: Journal Distribution of Selected Papers .....                                                                         | 24  |
| Table 4: Quantification Methods for Food Loss .....                                                                            | 29  |
| Table 5: Measurement approach and system features .....                                                                        | 31  |
| Table 6: Cross-scale measurement challenges in formal and informal contexts .....                                              | 33  |
| Table 7: Digitisation, Digitalisation, and Digital Transformation in Agrifood Supply Chains<br>(Food Loss Focus) .....         | 46  |
| Table 8: Digital Transformation Inefficiencies in Agri-Food Supply Chains .....                                                | 49  |
| Table 9: Approaches to Address MSP Challenges .....                                                                            | 61  |
| Table 10: Food Loss Interventions and Benchmarking Leverage (Source: Author's own work)<br>.....                               | 73  |
| Table 11: Systemic Benchmarking Device for Food Loss Interventions in AFSCs (Source:<br>Author's own work) .....               | 80  |
| Table 12: Food Regulatory Bodies in Nigeria and their Role Description .....                                                   | 108 |
| Table 13: Digital Regulatory Bodies and Their Roles .....                                                                      | 110 |
| Table 14: Certification Bodies and Their Roles .....                                                                           | 111 |
| Table 15: Mapping between thesis gaps derived foci and theoretical lenses .....                                                | 118 |
| Table 16: Operationalisation of DCP Framework Constructs .....                                                                 | 135 |
| Table 17: Mapping of study objectives and research questions to phases of research .....                                       | 141 |
| Table 18: Sample Interview Questions and Themes Covered .....                                                                  | 155 |
| Table 19: Governance Themes Captured in Interview Questions .....                                                              | 156 |
| Table 20: Criteria for trustworthiness of study and findings .....                                                             | 160 |
| Table 21: Case One summary: Primary and emerging production hubs (consolidated<br>findings and governance implications) .....  | 180 |
| Table 22: Case Two summary: Commercial and innovation-driven hubs (consolidated<br>findings and governance implications) ..... | 194 |
| Table 23: Constraint Mechanisms and Corresponding Paradoxes .....                                                              | 215 |
| Table 24: Consolidated Propositions of the Digital Constraint Paradox Framework .....                                          | 230 |
| Table 25: Policy and design levers aligned to the Digital Constraint Paradox (DCP)<br>framework. ....                          | 236 |

## List of Figures

|                                                                                                                                            |     |
|--------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Fig. 1: PRISMA flow diagram for Food Loss Quantification literature(Source: Haddaway et al., 2022) .....                                   | 17  |
| Fig. 2: Summary of Geographical distribution of Selected Papers by Region and Country ..                                                   | 22  |
| Fig. 3: Distribution of Research Methods of Selected Papers .....                                                                          | 23  |
| Fig. 4: Temporal Distribution of Reviewed Studies (n=95) .....                                                                             | 26  |
| Fig. 5: Relationship between Food Loss Challenges and Proposed Framework .....                                                             | 37  |
| Fig. 6: Integrated Food Loss Quantification Framework .....                                                                                | 39  |
| Fig. 7: A simplified Agri-food Supply Chain System (Source: Kamilaris et al., 2019) .....                                                  | 47  |
| Fig. 8: Network Effects in Typical MSPs (Øverby and Audestad, 2021).....                                                                   | 56  |
| Fig. 9: The MSP Dynamic Triangle .....                                                                                                     | 58  |
| Fig. 10: Systematic Literature Review Process (Source: Denyer and Tranfield, 2009).....                                                    | 66  |
| Fig. 11: PRISMA flow diagram for Strategic Interventions Literature (Source: Haddaway et al., 2022).....                                   | 69  |
| Fig. 12: Number of Research Articles Published Per Year (Source: Author's own work).....                                                   | 70  |
| Fig. 13: Methodologies Used in Papers Analysed (Source: Author's own work).....                                                            | 71  |
| Fig. 14: Conceptual Framework for Strategic Interventions to Reduce Food Loss (Source: Author's own work) .....                            | 82  |
| Fig. 15: Tomato Production and Sales in Nigeria (source research participants).....                                                        | 88  |
| Fig. 16: Map of Nigeria Depicting Tomato Producing States and Production in Megatons (Adapted from World Bank, 2020) .....                 | 89  |
| Fig. 17: Greenhouses for Sale by Local Input Supplier (source research participant) .....                                                  | 94  |
| Fig. 18: Greenhouse Primary Production of Tomatoes (source research participant).....                                                      | 96  |
| Fig. 19: Tomatoes Arriving in Mile 12 market in Lagos State (source research participants) .....                                           | 100 |
| Fig. 20: Modern Cooling Vans for Agri-fresh foods in Nigeria.....                                                                          | 100 |
| Fig. 21: Open Market Sales of Tomatoes(top) and Locally Pureed Tomatoes(bottom) Sold in Public Markets (source research participants)..... | 103 |
| Fig. 22: Plastic Crates(top) Innovation Versus Local Baskets (bottom) Used for Transporting Tomatoes (source research participants) .....  | 104 |
| Fig. 23: The Digital Constraint Paradox (DCP) Theoretical Framework .....                                                                  | 133 |
| Fig. 24: The Digital Constraint Paradox Framework .....                                                                                    | 218 |



## **1 Chapter One: Introduction**

### **1.1 Chapter introduction**

This chapter introduces the thesis by situating the research problem within the broader challenges of food loss and waste (FLW) in agri-food supply chains and the contested promise of digital transformation. It defines the core research problem, establishes the study's purpose and analytical focus, and specifies the research questions and objectives that structure the remainder of the dissertation. The chapter then clarifies the scope and empirical setting, and concludes with a chapter map that reflects the final thesis architecture and sequencing.

### **1.2 Overview**

The global food system faces escalating inefficiencies as rising food insecurity and persistent post-harvest losses threaten food security, social stability, and environmental sustainability (Mogale et al., 2022; Heydari, 2024; Even et al., 2024). Digital technologies are frequently positioned as transformative solutions; however, empirical evidence indicates that digital interventions often yield contradictory outcomes and fail to deliver the efficiency gains anticipated by dominant techno-optimistic narratives (Trevisan and Formentini, 2023; Wang et al., 2024). Nigeria's tomato supply chain is a salient case of this contradiction. Despite growing digital experimentation across production, aggregation, logistics, finance, and marketing, post-harvest losses remain high, and the sector continues to exhibit structural frictions that undermine both value creation and loss reduction outcomes (Ayoola et al., 2020; FAO, 2021).

This thesis argues that these outcomes cannot be explained adequately by technological access constraints alone. Rather, digital tools are embedded within governance configurations that shape who can participate, how coordination and enforcement operate, how data and value are controlled, and whether efficiencies translate into measurable reductions in loss. The study, therefore, focuses on governance as the decisive mediating layer between digital intervention and realised performance in a resource-constrained agri-food system.

### **1.3 Background of the study**

Emerging technologies are widely expected to enhance supply chain visibility, improve coordination, and reduce waste in agri-food systems (Rejeb et al., 2021). Across diverse contexts, tools such as Internet of Things (IoT) sensors, blockchain-enabled traceability, data analytics, and artificial intelligence (AI)- enabled decision support are promoted as

mechanisms to mitigate perishability, reduce coordination failures, and improve logistics (Béné, 2022; Stone and Rahimifard, 2018). These promises are especially salient for fresh produce supply chains, where biological perishability and time-critical logistics create persistent loss risks (Gustavsson, Cederberg and Sonesson, 2011; Giustiziero et al., 2023; Heaton et al., 2023).

Food loss and waste generate high economic, environmental, and social costs. Estimates indicate that approximately one-third of food produced globally is lost or wasted (FAO, 2019). The burden is often concentrated in the upstream and midstream stages in low- and middle-income countries, where post-harvest losses for perishable commodities can exceed 40 per cent due to infrastructure deficits, volatile markets, and limited capacity for storage, aggregation, and cold-chain integration (Parfitt et al., 2010). In Nigeria, where agriculture remains a central livelihood and economic sector, FLW undermines food security and accentuates vulnerability among smallholders and informal market actors (World Bank, 2022). Tomatoes exemplify these dynamics because they combine high perishability, strong seasonal price volatility, and a wide set of intermediated transactions.

#### **1.4 Problem statement: The Digital Constraint Paradox in food supply chains**

Despite repeated interventions to mitigate loss, evidence indicates that a large share of Nigeria's fresh tomato production is lost before consumption, with the burdens disproportionately borne by rural producers and informal market actors (Odeyemi et al., 2021; Korie et al., 2023). A range of digital interventions has been introduced to address these challenges, including IoT-enabled storage monitoring, mobile-based extension and advisory services, digital platforms aimed at improving market linkage and price coordination, and traceability architectures proposed to enhance transparency in exchanges (Plaisier et al., 2019; Bello et al., 2022; Kitinoja et al., 2019).

However, the persistence of loss and the uneven performance of digital interventions indicate a paradoxical pattern: digitalisation promises efficiency, yet operational frictions persist and, in some configurations, are intensified. Existing explanations frequently separate an efficiency-focused perspective, which expects digital tools to reduce information asymmetry and transaction costs (Williamson, 1985), from an institutional constraint perspective, which emphasises how regulatory structures and market norms shape adoption and implementation (Scott, 1995). Neither perspective, on its own, provides a sufficient account of the patterned contradictions observed in Nigeria's tomato supply chain (Giustiziero et al., 2023; Heaton et al., 2023).

This thesis conceptualises this puzzle as a Digital Constraint Paradox: the tendency for digital technologies to introduce new constraints and or reproduce existing constraints, thereby limiting or reversing expected efficiency gains and weakening food loss reduction outcomes. The study foregrounds governance mechanisms, including contractual terms, platform rules, data control, and enforcement practices, as central mediators of digital performance. Contractual governance is treated not simply as formal documentation but as the wider set of instruments through which digital participation is structured and contested within both formal and informal market arrangements (Hart and Moore, 1999; Rahman et al., 2024; Engert et al., 2025).

### **1.5 Digital interventions in Sub-Saharan African agri-food supply chains**

In this thesis, digital interventions refer to purposive socio-technical arrangements introduced to reconfigure upstream tomato supply chain activities through digital artefacts (for example, mobile applications, platform interfaces, digital payment and record systems, and data capture tools), and through the associated changes in roles, routines, and decision processes that these artefacts enable. This operationalisation aligns with digital transformation scholarship that treats digitisation as organisational change enabled by digital technologies rather than as a purely technical upgrade (Hanelt et al., 2021), and with work on digital innovation that emphasises the distinctive characteristics of digital technologies in shaping distributed agency and reprogrammable processes (Nambisan et al., 2017; Giustiziero et al., 2023; Engert et al., 2025).

Governance mechanisms is used operationally to denote the concrete arrangements through which decision rights, control, incentives, and enforcement are allocated and enacted across interdependent actors participating in, or affected by, a digital intervention. In practice, this includes contractual terms (e.g., obligations, penalties, and dispute resolution), platform rules (e.g., participation criteria, pricing policies, and transaction protocols), data access and ownership conditions, verification procedures, and sanctioning or escalation practices. This definition is consistent with platform research that conceptualises platform governance in terms of decision rights and control mechanisms that shape ecosystem behaviour and outcomes (Tiwana et al., 2010). Recent syntheses also emphasise that platform rule-setting and enforcement choices structure accountability and power relations in digitally mediated exchange (Rahman et al., 2024; Krämer and Shekhar, 2025; Heaton et al., 2023; Dehling and Sunyaev, 2024)

## 1.6 Food loss and waste measurement and the role of technology

Credible FLW reduction strategies depend on credible quantification, yet measurement remains heterogeneous and often weak in upstream stages. Standardised approaches such as the Food Loss and Waste Accounting and Reporting Standard provide a basis for comparability (WRI, 2016), but many low-resource contexts rely on estimation, limited surveys, or proxy indicators, producing high uncertainty and limited decision usefulness (Parfitt et al., 2010; Bellemare et al., 2017).

Digital technologies can improve temporal resolution and traceability of losses through sensing, tracking, and auditable reporting. Yet, in practice, these gains are constrained by data asymmetry, limited interoperability across platforms, and contractual opacity that shapes who can access, validate, and act on loss data (Rejeb et al., 2021). The thesis treats measurement as a socio-technical practice embedded in governance arrangements rather than as a purely technical exercise.

## 1.7 Framing the research problem, aim, and research questions

The study investigates how digital interventions in Nigeria's tomato supply chain generate paradoxical outcomes of efficiency and constraint, and how governance mechanisms shape these outcomes across contrasting configurations. The research is anchored in a critical realist philosophy and an abductive approach that iteratively links empirical evidence to mechanism-centred theory development.

The research questions guiding the thesis are:

**Research Question 1 (RQ1):** *How do digital interventions in Nigeria's tomato supply chain generate paradoxes of efficiency and constraint, and what governance mechanisms shape these outcomes?*

**Research Question 2 (RQ2):** *How can these paradoxes be systematically characterised, and what governance frameworks enable digital interventions to reduce constraints and improve food waste reduction outcomes?*

To address these questions, the thesis pursues four objectives:

- i. To identify and explain the mechanisms through which digital interventions in Nigeria's tomato supply chain generate paradoxical outcomes of efficiency and constraint.

- ii. To examine the governance mechanisms, including contractual terms, platform rules, data control and enforcement practices, that shape these outcomes across different actor groups.
- iii. To develop a systematic characterisation of efficiency–constraint paradoxes, operationalised through the Digital Constraint Paradox framework, and to specify how these patterns vary across contrasting governance configurations.
- iv. To identify and assess governance frameworks and practical intervention levers that can reduce constraints and improve food loss reduction outcomes, with explicit attention to distributional consequences.

## **1.8 Research justification and significance**

The thesis contributes to digital transformation scholarship by shifting emphasis from adoption-centric accounts to post-implementation operationalisation, explaining why digital tools can improve visibility while failing to stabilise coordination or reduce loss. It contributes to FLW research by treating loss reduction as conditioned by governance configurations that shape measurement, accountability, and the distribution of costs and benefits. It contributes to contract and supply chain governance scholarship by foregrounding how contractual incompleteness, enforcement capacity, and platform rule systems mediate digital performance and value capture. (Giustiziero et al., 2023; Heaton et al., 2023; Rahman et al., 2024)

Practically, the analysis provides a governance-sensitive basis for designing digital interventions that are resilient to infrastructural constraints, attentive to power asymmetries, and oriented towards durable loss reduction rather than short-lived pilot gains. The study is therefore relevant to policymakers, agri-tech firms, development actors, and supply chain organisations seeking to embed digital systems in ways that improve both efficiency and equity outcomes. (Krämer and Shekhar, 2025; Dehling and Sunyaev, 2024)

## **1.9 Scope of the study**

The empirical setting is Nigeria's tomato supply chain, selected due to its scale, strategic relevance to food security, and persistent post-harvest losses despite ongoing interventions. The study adopts a multiple-case design organised around two contractually distinct configurations that enable within-case and cross-case comparison of governance and capability conditions shaping digital performance.

Case One examines primary and emerging tomato production hubs in which digitalisation unfolds within mixed governance conditions, including informal coordination and state-led programmes. Case Two examines commercial and innovation-driven hubs in which

digitalisation is structured through private-sector platforms and hybrid NGO–private sector initiatives. Data are drawn primarily from semi-structured interviews across actor groups and triangulated with documentary sources where these illuminate design intent, implementation mechanisms, and governance arrangements.

### **1.10 Structure of the dissertation**

The thesis is organised into seven chapters. Chapter Two develops the literature base through a three-part review that synthesises upstream food loss quantification, digital transformation and platformisation in agri-food supply chains, and intervention typologies and their governance implications. Chapter Three develops the theoretical framework by integrating incomplete contract theory, new institutional economics, and resource-based perspectives, and formalises the Digital Constraint Paradox framework as the study's central conceptual contribution. Chapter Four sets out the methodological design, including the critical realist and abductive foundations, the logic of case selection, data collection, and analytic procedures. Chapter Five reports the empirical findings for each case and presents a cross-case synthesis. Chapter Six develops the discussion, specifying the mechanisms, pathways, and governance configurations that explain the observed paradoxes, and elaborating the Digital Constraint Paradox framework as a structured characterisation of digital transformation trajectories. Chapter Seven concludes by consolidating contributions, articulating implications for policy and practice, and specifying limitations and directions for further research.

### **1.11 Chapter conclusion**

This chapter has established the thesis problem framing: digital interventions in Nigeria's tomato supply chain operate within governance configurations that can generate simultaneous efficiency gains and constraint effects. It has specified the research questions and objectives that organise the dissertation, clarified the scope and comparative case design, and provided an updated chapter map aligned with the final thesis architecture.

The next chapter develops the intellectual foundations for this inquiry by synthesising scholarship on upstream food loss quantification, digital transformation and platform governance, and interventions for loss reduction. It builds the case for treating digital performance as contingent on governance and capability conditions and identifies the research gaps that motivate the theoretical framework developed in Chapter Three.

## **2 Chapter Two: Literature Review**

### **2.1 Introduction**

This chapter develops the analytical foundations for addressing the research questions by critically examining existing scholarship on digital transformation in agri-food supply chains, with particular emphasis on upstream food loss, the design of digital interventions, and governance arrangements. Rather than offering a descriptive survey of prior work, the chapter interrogates how dominant theoretical and empirical approaches conceptualise efficiency, coordination, and value creation, and where these approaches fall short in explaining post-implementation outcomes in low- and middle-income country contexts.

The review is structured around three interrelated bodies of literature. The first examines upstream food loss quantification and reduction, focusing on how loss is measured, modelled, and operationalised within production and early distribution stages. This strand reveals a persistent methodological bias towards static measurement and pre-adoption diagnostics, with limited attention to how digital tools interact with existing practices, incentives, and institutional constraints once deployed. As a result, explanations of realised performance remain under-theorised.

The second body of literature addresses digital transformation and digital interventions in agri-food and adjacent supply chains. While this literature documents the potential of digital technologies to improve traceability, coordination, and efficiency, it often treats digitalisation as a technical upgrade rather than a socio-technical reconfiguration. Consequently, it underplays how digital interventions reallocate decision rights, reshape information asymmetries, and introduce new dependencies that may simultaneously enable efficiency gains and generate new forms of constraint.

The third strand focuses on governance, including contractual arrangements, platform rules, data control, and enforcement mechanisms. This literature provides important insights into how coordination and compliance are organised across fragmented supply chains, yet it is rarely integrated with analyses of digital implementation outcomes. Governance is frequently examined as a background condition rather than as an active mechanism shaping how digital interventions perform in practice. By bringing these literatures into dialogue, the chapter identifies a set of interlocking research gaps. Most notably, existing studies provide limited explanation of why digital interventions that are designed to enhance efficiency frequently generate paradoxical outcomes during implementation and routine operation. There is also insufficient integration between digital transformation research and governance theory,

particularly in contexts characterised by informal coordination, weak enforcement, and uneven capability distribution.

These gaps motivate the need for a framework capable of explaining both efficiency gains and emergent constraints as endogenous outcomes of digital intervention design and governance configuration. The chapter therefore concludes by synthesising the reviewed literature to specify the precise theoretical and empirical lacunae that the thesis addresses. In doing so, it establishes the justification for the theoretical framework developed in Chapter Three, which conceptualises digital transformation in Nigeria's tomato supply chain through the lens of constrained efficiency and governance-mediated paradox.

## 2.2 Description of the agri-food supply chain

The literature review suggests a range of, and fragmentation in, definitions of agri-food supply chains, as highlighted in Table 1. The definitions of agri-food supply chains are categorised into eleven categories. A shift from linear, process-oriented approaches to agri-food supply chains (AFSCs) to multifaceted systems that account for social, technological, environmental, and governance dynamics was evident in many of the reviewed definitions of AFSCs. While earlier definitions, which focus on unidirectional flows of products from production to consumption (Renting et al., 2003; Ahumada and Villalobos, 2009; FAO, 2018), misrepresent the complexity of AFSCs, more recent definitions frame AFSCs as *complex, adaptive networks* connecting *heterogeneous actors* within broader governance networks, involving decision-making in conditions of uncertainty (Bryceson and Smith, 2008; Utomo et al., 2018; Hernandez et al., 2020).

Emerging digital technologies play significant roles, with blockchain, precision agriculture, and digital twins facilitating greater traceability, resilience, and real-time management (Kamble et al., 2020; Shahid et al., 2020; Guidani et al., 2024). Meanwhile, AFSCs are increasingly recognised as *socio-technical systems* grappling with ethical issues related to the distribution of labour, the inclusion of smallholders, and profit distribution (Marsden et al., 2020; Fair Trade International, 2019; Clapp, 2016). Sustainability represents another dimension, as circular models promote waste and pollution reduction, ecosystem regeneration, and resource efficiency (De Boer et al., 2020; Tumenbatur et al., 2022). AFSCs are also influenced by consumer preferences (Garcia Martinez et al., 2021), cultural values (Ploeg et al., 2019), post-harvest logistics (Hodges et al., 2011), and multilevel policy frameworks (Termeer et al., 2018). These definitions collectively suggest that AFSCs have evolved beyond mere logistical pathways and are integrated into broader socio-economic, environmental, and institutional frameworks, thereby necessitating integrated and adaptive approaches to governance and sustainability.



Table 1: Categorisation of the Definitions of Agri-food Supply Chain

| Category                               | Author(s)                             | Definition                                                                                                                                                                                                                                            |
|----------------------------------------|---------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Systems and Network Perspective</b> | Bryceson and Smith (2008)             | Agri-food chains are complex systems involving multiple multifaceted firms usually working together within specific industry sectors (e.g., grains, beef, wool, dairy) to satisfy increasingly globalised market demand for high-value food products. |
|                                        | Utomo et al. (2018)                   | Agri-food supply chains (ASC) comprise a network of heterogeneous actors working together in different processes and activities to deliver products and services to the market and satisfy customers' demands.                                        |
|                                        | Luo et al. (2018)                     | Agri-food supply chains are defined as a newly emerging network of producers, consumers, and other actors that embody alternatives to the more standardised industrial mode of food supply.                                                           |
|                                        | Qin (2010)                            | Agri-food supply chains are hybrid systems where authority emerges to coordinate complex relationships, particularly based on the importance and specificity of investments such as food safety and supply guarantees.                                |
|                                        | Guidani et al. (2024)                 | Agri-food supply chains are digitally managed ecosystems using "digital twins" to simulate and monitor agricultural, processing, distribution, and sustainability indicators from field to consumer.                                                  |
|                                        | Boudahri et al. (2013)                | Agri-food supply chains are regulated networks increasingly influenced by public health and ecological concerns, requiring optimized design to reduce CO <sub>2</sub> emissions and meet health standards.                                            |
|                                        | Hernandez et al. (2020)               | Agri-food supply chains are decision-intensive systems requiring collaborative, operations-focused management to address complexity and enhance resilience in global agri-food systems.                                                               |
|                                        | Tomasiello and Alijani (2021)         | Agri-food supply chains are risk-prone systems operating in volatile environments, where fuzzy-based approaches are useful for addressing uncertainties like perishability and sustainability trade-offs.                                             |
| <b>Process and Flow Perspective</b>    | Renting, Marsden, and Banks (2003)    | The agri-food supply Chain covers the interrelations between actors who are directly involved in the production, processing, distribution, and consumption of new food products.                                                                      |
|                                        | Ahumada and Villalobos (2009)         | The term agri-food supply chains (ASC) have been coined to describe the activities from production to distribution that bring the agricultural or horticultural product from the farm to the table.                                                   |
|                                        | Higgins et al. (2010)                 | An agri-food value chain is typically mapped as a linear sequence of activities, from primary production to consumption and waste management.                                                                                                         |
|                                        | Ting et al. (2014); Kuo et al. (2010) | The food supply chain is defined as "the total supply process from agricultural production, harvest or slaughter, through primary production and/or manufacturing, to storage and distribution to retail sale or use in catering and by consumers."   |
|                                        | Shukla and Jharkharia (2013)          | Agri-fresh supply chain management constitutes the processes from production to delivery of the agri-fresh produce, i.e., from the farmer to the customer.                                                                                            |

|                                            |                                             |                                                                                                                                                                                                                          |
|--------------------------------------------|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                            | FAO (2018); Zhao et al. (2020)              | Agri-food supply chains (AFSCs) are the linked events in the agricultural production of food, which involves all stages of production, processing, trading, distribution, and consumption – namely, "from farm to fork." |
| <b>Technology and Digitalization</b>       | Kamble et al. (2020)                        | Agri-food supply chains are digitally enabled ecosystems integrating farmers, processors, and consumers through real-time data sharing to enhance traceability and food safety.                                          |
|                                            | FAO (2021)                                  | Smart agri-food chains leverage precision agriculture and predictive analytics to optimize resource use and mitigate climate risks.                                                                                      |
|                                            | Shahid et al. (2020); Ibrahim et al. (2023) | Blockchain-enabled agri-food supply chains are secure, traceable, and decentralized systems that improve transparency, trust, and accountability from farm to fork.                                                      |
| <b>Social and Ethical Dimensions</b>       | Marsden et al. (2020)                       | AFSCs are socio-technical systems balancing economic efficiency with fair labor practices, equitable profit distribution, and animal welfare.                                                                            |
|                                            | Fair Trade International (2019)             | Ethical agri-food chains prioritize smallholder empowerment, gender equity, and living wages alongside environmental sustainability.                                                                                     |
| <b>Circular Economy and Sustainability</b> | De Boer et al. (2020)                       | Circular AFSCs prioritize closed-loop systems where waste is minimized, by-products are repurposed, and regenerative agricultural practices are institutionalized.                                                       |
| <b>Local vs. Global Dynamics</b>           | Ilbery and Maye (2005)                      | Short food supply chains (SFSCs) emphasize proximity, direct producer-consumer relationships, and reduced intermediation, contrasting with globalized chains dominated by corporate retailers.                           |
| <b>Policy and Governance</b>               | Termeer et al. (2018)                       | AFSCs are shaped by multi-level governance frameworks, including international trade agreements, national subsidies, and local food safety regulations.                                                                  |
| <b>Consumer-Centric Perspective</b>        | Garcia Martinez et al. (2021)               | Agri-food chains are evolving into demand-driven networks where consumer preferences (e.g., plant-based diets, organic foods) dictate production and processing strategies.                                              |
| <b>Resilience and Adaptation</b>           | Tendall et al. (2015)                       | Resilient AFSCs are characterized by diversified sourcing, adaptive capacity to shocks (e.g., pandemics, climate events), and redundancy in logistics networks.                                                          |
| <b>Cultural and Behavioural Dimensions</b> | Ploeg et al. (2019)                         | AFSCs are culturally embedded systems where traditional practices, dietary habits, and regional identities influence production and consumption patterns.                                                                |
| <b>Power and Equity Dynamics</b>           | Clapp (2016)                                | Corporate-dominated AFSCs often marginalize smallholders, reinforcing inequities in profit distribution and decision-making power.                                                                                       |
| <b>Post-Harvest Systems</b>                | Hodges et al. (2011)                        | AFSCs encompass post-harvest handling, storage, and preservation systems critical to reducing food loss (e.g., cold chains, solar drying).                                                                               |

## **2.3 Addressing Data Gaps in Upstream Agrifood Supply Chains: A Systematic Review of Food Loss Quantification**

### **2.3.1 Abstract**

Reducing food loss and waste is central to improving resource efficiency and advancing Sustainable Development Goal 12.3. Yet quantification remains fragmented, particularly in upstream stages, where losses are difficult to observe and are often poorly regulated. This study conducts a systematic literature review of 95 empirical studies on the quantification of upstream food loss. Following PRISMA-informed screening and structured coding, the review maps geographical and methodological patterns, synthesises recurring measurement limitations, and identifies institutional constraints on data availability and comparability. Findings indicate persistent definitional heterogeneity, heavy reliance on indirect coefficients and self-reported estimates, and limited capacity to capture cross-scale interactions and non-linear loss dynamics. Economic incentives, regulatory fragmentation, and power asymmetries further shape what is measured, by whom, and with what transparency. On this basis, the paper proposes an integrated framework combining Complex Adaptive Systems and Institutional Theory to support multi-method, cross-scale, and context-sensitive quantification strategies. The framework highlights the need to treat measurement as a socio-technical practice embedded in governance arrangements, and to prioritise adaptive, participatory designs capable of improving accuracy without assuming that perfect quantification is attainable.

### **Keywords**

food loss; food waste; quantification; systematic literature review; complex adaptive systems; institutional theory

### 2.3.2 Introduction

Efforts to reduce food loss and waste are central to food security, resource conservation, and climate mitigation, yet the empirical basis for policy and investment remains fragile because upstream losses are poorly measured and unevenly reported (Ishangulyyev et al., 2019; FAO, 2019). Global estimates that 13–14 per cent of food is lost between post-harvest and distribution, and a further 17–19 per cent is wasted at retail and consumer levels conceal major uncertainty in how losses are defined, located and quantified along supply chains (FAO, 2019; UNEP, 2024; Kummu et al., 2012). This uncertainty shapes which actors and stages are held responsible, which interventions are considered cost-effective, and how trade-offs among efficiency, equity, and environmental impacts are framed (Koester et al., 2018; Drabik et al., 2019).

A diverse toolbox of food loss and waste quantification methods has emerged, from direct measurements and surveys to material flow analysis and hybrid models based on food balance sheets and economic statistics (Kummu et al., 2012; Caldeira et al., 2019). This has improved the mapping of loss magnitudes and hotspots. Yet, estimates remain highly sensitive to system boundaries, data sources and classification rules, so that the same food system can yield divergent loss values depending on whether losses are inferred from mass balances, self-reported coefficients or process-level audits (Chaboud, 2017; Corrado and Sala, 2018; Hoehn et al., 2023). Reviews consistently highlight three weaknesses: no operational methodology jointly satisfies global monitoring, national statistics and local decision-making needs; empirical coverage is biased towards high-income, downstream contexts; and existing approaches struggle to capture quality-related losses, gradual degradation and diversion to low-value uses (Abiad and Meho, 2018; Sheahan and Barrett, 2017; Do et al., 2021; Delgado et al., 2023; O'Connor et al., 2023).

Upstream agrifood stages exemplify these problems. Studies in Sub-Saharan Africa and other low and middle-income regions identify limited cold chain infrastructure, volatile markets and transport bottlenecks as key drivers of loss, yet quantification often relies on small surveys, dated experiments or expert judgement that cannot be scaled or generalised (Sheahan and Barrett, 2017; Abiad and Meho, 2018; Totobesola et al., 2022). Regional and commodity-specific analyses show that upstream losses are frequently treated as residuals in mass balances or as fixed coefficients in models, rather than as empirically measured phenomena with their own drivers and dynamics, and that quality-related losses and informal transactions remain particularly under-

documented even though they often dominate farmers' economic exposure to loss (Chaboud, 2017; Corrado and Sala, 2018; Rahayu et al., 2020; Delgado et al., 2023; O'Connor et al., 2023). These empirical patterns reflect a predominantly linear, stage-based conceptual framework for quantifying food loss and waste. Global accounting exercises typically model the food system as a pipeline in which losses are assigned to discrete nodes, with limited representation of feedback, behavioural adaptation or cross-scale interactions (Corrado and Sala, 2018; Kummu et al., 2012). Economic and circular economy studies, while advancing analysis of downstream waste treatment and valorisation, often treat upstream loss coefficients as exogenous and rarely interrogate how those numbers are produced, reinforcing a view of food loss as a technical residual rather than as a product of system design and governance (Drabik et al., 2019; Teigiserova et al., 2019; Principato et al., 2019; Delgado et al., 2023).

A more adequate account of upstream loss generation and measurement must link system dynamics with governance. Complex Adaptive Systems theory conceptualises agrifood supply chains as networks of interacting agents whose decisions and learning generate emergent patterns, including loss, that cannot be reduced to individual components or stages (Holland, 1995; Bryceson and Ross, 2020). Empirical work on food loss and waste shows that small perturbations in upstream environments, such as weather shocks, price shifts or grading decisions, can cascade through storage, logistics and processing in non-linear ways, making loss an emergent outcome rather than a fixed stage-specific parameter (Dora et al., 2021; Stathers and Lamboll, 2023). Institutional theory adds that standards, reporting templates and statistical classifications interact with norms and power relations to determine which losses are recognised, who generates data and how numbers are mobilised in governance, so that simplified frameworks adopted for compliance and comparability can systematically understate losses in informal and low income settings (Meyer and Rowan, 1977; DiMaggio and Powell, 1983; Caldeira et al., 2019; Cattaneo et al., 2020; Delgado et al., 2023).

Existing reviews and methodological studies have not yet brought these systems and institutional perspectives together in a systematic assessment of upstream food loss quantification. Method-focused work tends to appraise tools in terms of technical robustness and uncertainty, while bracketing how data generation is shaped by incentives, capacities and governance arrangements (Chaboud, 2017; Corrado and Sala, 2018; Hoehn et al., 2023). Analyses of food loss drivers and interventions often treat measurement frameworks as exogenous, even when they acknowledge that data on upstream losses are weak or missing (Do et al., 2021; Delgado et

al., 2023). There is therefore limited synthesis of how different quantification methods perform in complex, data-poor agrifood systems, or of how institutional configurations condition both the availability and strategic use of upstream loss data.

This study addresses these gaps through a systematic review of peer-reviewed research on food loss quantification in upstream agrifood supply chains, interpreted through a combined Complex Adaptive Systems and institutional lens. It has three objectives. First, it classifies and compares the methods used to quantify upstream food loss across regions, commodities and chain stages, distinguishing macro-level and micro-level approaches and assessing the extent to which they capture key system features such as feedbacks, cross-scale interactions and emergent patterns. Second, it synthesises methodological and institutional barriers that limit the accuracy, comparability, and decision-relevance of existing upstream loss estimates, with particular attention to informal markets and low- and middle-income contexts where data infrastructures are weakest. Third, it develops an integrative framework for quantifying upstream food loss that links specific measurement challenges to design principles for multi-method, complexity-aware, and institutionally grounded quantification strategies.

These objectives guide the following research questions:

RQ1. How effective are existing methods of upstream food loss quantification in representing complex system interactions and emergent properties in agrifood supply chains?

RQ2. What systemic barriers, including methodological, institutional and economic factors, hinder precise and policy-relevant quantification of upstream food loss, particularly in developing regions?

The following sections outline the review methodology, present descriptive and thematic findings and develop the proposed framework for upstream food loss measurement.

### **2.3.3 Methodology**

#### **2.3.3.1 Search strategy and data sources**

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) to ensure methodological transparency and replicability. The search protocol was developed iteratively through pilot searches and refined following established systematic review methodology in management and sustainability research (Tranfield et al., 2003).

### 2.3.3.2 Electronic databases

A comprehensive search was conducted across five electronic databases selected for their complementary disciplinary coverage: Web of Science and Scopus provided broad multidisciplinary coverage encompassing environmental science, engineering, and food systems; EBSCO (Business Source Complete) enabled access to supply chain management and business logistics literature; CAB Abstracts offered specialised coverage of agricultural sciences and post-harvest research; and AgriEcon captured agricultural economics and food policy studies. This multi-database strategy was adopted to maximise retrieval across the fragmented disciplinary landscape characterising food loss research (Tranfield et al., 2003).

### 2.3.3.3 Search terms and Boolean logic

Search terms were derived through a systematic process combining: (i) terminology analysis from seminal food loss quantification studies, particularly the FAO global estimates (Gustavsson et al., 2011), the comprehensive supply chain review by Parfitt et al. (2010), and the World Resources Institute framework (Lipinski et al., 2013); (ii) controlled vocabulary from database thesauri; and (iii) iterative refinement based on pilot search precision and recall. Terms were organised into five conceptual categories representing the core constructs of the research questions (Table 1).

Table 2: Keyword taxonomy for systematic literature search

| Concept category | Search terms                                                                                                                                                                                                           |
|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Food Loss        | "food loss*" OR "food loss prevention" OR "food loss reduction" OR "food deterioration" OR "food spoilage" OR "food damage" OR "food quality loss" OR "food quantity loss" OR "food degradation"                       |
| Quantification   | "quantif*" OR "measur*" OR "assess*" OR "evaluat*" OR "calculat*" OR "estimat*" OR "monitor*" OR "track*" OR "record"                                                                                                  |
| Supply Chain     | "supply chain*" OR "value chain*" OR "food chain*" OR "agri-food*" OR "agrifood*" OR "agricultural*" OR "farming" OR "production" OR "processing" OR "distribution" OR "logistics" OR "post-harvest*" OR "postharvest" |
| Upstream focus   | "upstream" OR "pre-retail" OR "producer*" OR "farmer*" OR "processor*" OR "manufacturer*" OR "distributor*" OR "wholesaler*" OR "pre-consumer" OR "production stage*" OR "processing stage"                            |
| Methodology      | "method*" OR "technique*" OR "approach*" OR "framework*" OR "model*" OR "system*" OR "tool*" OR "protocol*" OR "procedure*" OR "assessment"                                                                            |

Note: Asterisk (\*) denotes truncation to capture morphological variants.

The final Boolean search string combined categories using AND operators:

("food loss\*" OR "food deterioration" OR "food spoilage" OR "food damage") AND (measur\* OR quantif\* OR assess\* OR estimat\*) AND ("agri-food\*" OR "value chain\*" OR "supply chain\*" OR "post-harvest\*") AND (producer\* OR upstream OR "pre-retail" OR farmer\* OR processor\*)

#### 2.3.3.4 Eligibility criteria and screening

Studies were included if they were peer-reviewed journal articles published in English between January 2012 and December 2024 that presented primary empirical data or methodological frameworks for quantifying upstream food loss. The temporal boundary captures the post-Rio+20 period during which global measurement efforts intensified following FAO's seminal estimates (Gustavsson et al., 2011). Review articles, book chapters, conference proceedings, and studies focused exclusively on consumer-level waste were excluded. Quality assessment employed a modified CASP checklist evaluating methodological clarity, sampling adequacy, and measurement validity. Studies were drawn from supply chain management, agricultural economics, food science, environmental science, and development studies; purely clinical nutrition or food chemistry studies without a supply chain focus were excluded.

The search yielded 5,183 records. Following duplicate removal (n=2,668) and two-stage screening against eligibility criteria, 95 peer-reviewed studies were retained for synthesis. Fig. 1 presents the PRISMA flow diagram documenting this process.



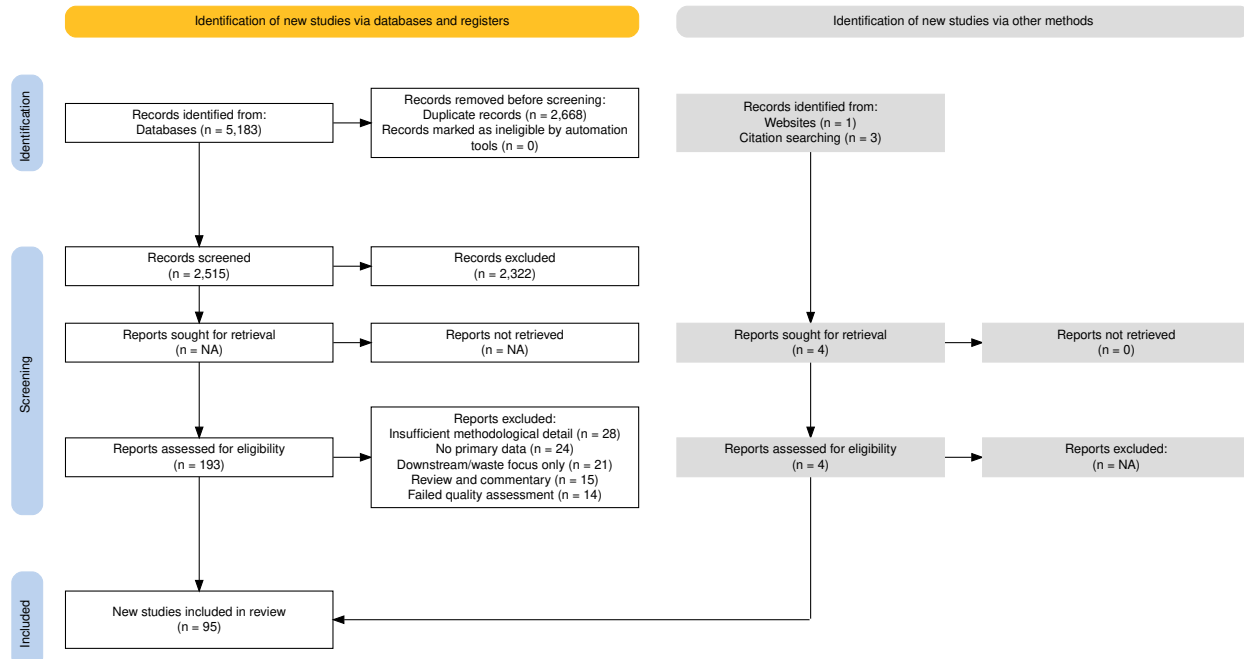


Fig. 1: PRISMA flow diagram for Food Loss Quantification literature (Source: Haddaway et al., 2022)

#### 2.3.3.5 Data extraction, coding and synthesis

Data extraction followed a standardised template designed to consistently capture the contextual and methodological features most relevant to upstream food loss quantification. The structure of this template was informed by recent systematic reviews of food loss and waste (FLW) quantification, which coded studies by stage, method, data type and reported limitations to enable comparable mapping and synthesis across heterogeneous designs (Soloha and Dace, 2025; Teigiserova et al., 2019; Yu et al., 2022). For each article, bibliographic details and year of publication were recorded together with the geographical context and the main commodity or product group, reflecting the way geographical coverage and product scope are used to interrogate representativeness and bias in existing FLW evidence.

Upstream stages were coded using a common stage classification that distinguishes pre-harvest and harvest activities, on-farm handling and storage, aggregation and early processing, and pre-retail distribution, consistent with the treatment of AP-1, AP-2, PP and PM in earlier European FLW reviews (Soloha and Dace, 2025). Where information allowed, the formal or informal character of the supply chain segment was also recorded, recognising that informal and smallholder-dominated systems tend to be under-represented in measurement initiatives and often require different data-collection approaches than highly formalised supply chains (Delgado

et al., 2023; O'Connor et al., 2023). For each study, data sources were categorised as field measurements, diaries, surveys, administrative statistics, secondary datasets or model outputs, and quantification methods were coded according to whether they relied on direct measurement, diary or self-report, waste composition analysis, coefficients and production statistics, material flow analysis, mass balance, statistical or process modelling, or explicit hybrid combinations. This classification aligns with the distinction between direct and indirect FLW methods and the specific techniques listed in the FLW Standard and EU delegated decision, which are widely used to structure reviews of quantification practices (Hanson et al., 2016; EC, 2019; Soloha and Dace, 2025).

Definitions of food loss, units of measurement and stated system boundaries were extracted for each article, given the central role of definitional scope and boundary choices in driving variability in reported loss estimates and comparability across studies (Corrado and Sala, 2018; Caldeira et al., 2019). Particular attention was paid to whether studies distinguished between quantitative and qualitative losses, how non-edible fractions and by-products were treated, and whether informal flows and alternative destinations (for example animal feed, on-farm reuse) were included or excluded from the loss category. Methodological assumptions and limitations as reported by the authors were also collected verbatim, since these statements provide primary evidence on where researchers themselves identify weaknesses in current FLW quantification and are crucial for constructing a synthesis of structural constraints and opportunities for improvement (Soloha and Dace, 2025; Baquero et al., 2023). The main categories used to code study characteristics and methods are summarised in the coding framework, mirroring the treatment of stages, processes and data types adopted in recent RCR and RCR Advances reviews.

Two levels of synthesis were undertaken. First, a descriptive mapping characterised the sample of 95 studies by geography, commodity group, coverage of supply chain stages, chain formality, data sources, and quantification methods. This mapping generated cross-tabulations of methods by region and stage. It highlighted the dominance of particular approaches (for example, survey-based estimation and mass balance) in specific contexts, as well as the relative absence of direct measurement in many upstream and informal settings, echoing patterns observed in European FLW quantification work (Soloha and Dace, 2025; Hoehn et al., 2023). Second, a thematic synthesis was conducted using a hybrid deductive-inductive coding approach. The initial coding framework drew deductively on established analytical categories from prior systematic reviews of food loss and waste quantification. Specifically, Soloha and Dace's (2025) framework for

categorising methodological limitations across the quantification process (sampling and recruitment, data acquisition, interpretation and comparability) provided the foundational structure, whilst Spang et al.'s (2019) taxonomy of institutional and economic barriers to measurement informed codes relating to governance and incentive structures. These pre-determined categories enabled systematic comparison with existing FLW scholarship and ensured theoretical coherence with the CAS and Institutional Theory lens outlined in Section 2.3.

The deductive coding framework comprised six primary code categories derived from the literature: (i) definitional and boundary inconsistencies; (ii) data source limitations and coefficient dependence; (iii) methodological fragmentation across scales; (iv) quality-related and informal flow coverage; (v) institutional and governance constraints; and (vi) economic incentive misalignments. Within this deductive structure, inductive coding was applied to identify emergent sub-themes specific to upstream agrifood contexts that were not captured by existing frameworks, including novel patterns related to smallholder data gaps, climate-driven variability in loss, and cross-scale integration challenges.

To ensure analytical rigour, a two-stage coding validation process was implemented. First, a pilot coding exercise was conducted on a randomly selected subset of fifteen articles (approximately 16 per cent of the corpus) to test the applicability of the deductive framework and refine code definitions. This pilot phase identified the need to expand the codes for informal market flows and quality-related losses, which were subsequently incorporated into the final coding scheme. Second, to enhance reliability, a proportion of articles ( $n = 20$ , representing 21 per cent of the sample) was independently double-coded by a second researcher. Inter-coder agreement was assessed using Cohen's kappa, yielding a coefficient of  $\kappa = 0.81$ , indicating substantial agreement (Landis and Koch, 1977). Discrepancies were resolved through discussion and, where necessary, refinement of code definitions to improve clarity and consistency.

Through this iterative process, codes were consolidated around six main themes: definitional heterogeneity; dependence on generic coefficients and secondary data; data quality constraints; scale mismatches between methods and system behaviour; insufficient treatment of quality-related and informal flows; and the influence of governance arrangements and incentive structures on measurement practice. These themes informed the hierarchical structure of the thematic findings presented in Section 4, with sub-themes identified inductively within each primary category.

The outputs of this descriptive and thematic work provide the empirical foundation for the results presented in Sections 3 and 4 and underpin the conceptual framework for upstream food loss quantification developed in the later sections of the paper.

#### 2.3.3.6 Analytical Framework

This review adopts Complex Adaptive Systems (CAS) theory as its primary analytical lens, complemented by Institutional Theory to illuminate governance dimensions of food loss measurement. CAS theory provides a robust framework for understanding agrifood supply chains as dynamic networks characterised by emergent properties arising from agent interactions, non-linear dynamics, adaptive capacities, and contextually determined boundaries (Preiser et al., 2018; Choi et al., 2001). Agrifood systems exemplify CAS characteristics: they comprise heterogeneous actors whose localised decisions generate system-wide patterns that cannot be predicted from individual behaviours alone, whilst feedback loops between social and environmental subsystems shape sustainability transitions (Bodin et al., 2024; Jørgensen et al., 2024). Recent systematic reviews in adjacent domains have demonstrated the analytical power of CAS for reconceiving food loss not as an isolated inefficiency but as an emergent outcome of interacting interventions across supply chain domains (Velasco-Sánchez et al., 2025). This perspective moves beyond linear, stage-based accounting to capture the non-linearities, cross-scale dynamics, and path dependencies that conventional quantification frameworks struggle to represent (Nesheim et al., 2015; DeLonge et al., 2017).

Institutional Theory complements CAS by explaining how regulative, normative, and cultural-cognitive pillars shape measurement practices and create systematic invisibilities in food loss data (DiMaggio and Powell, 1983; Scott, 2014). The three pillars of institutional theory (regulative pressures from governments, normative expectations from industry bodies, and mimetic behaviours copying successful competitors) provide explanatory power for understanding why firms in agrifood supply chains engage differentially in quantification activities (Brun et al., 2024; Glover et al., 2014). Institutional pressures motivate sustainability performance measurement heterogeneously along supply chains, with dominant actors (particularly retailers) shaping what is measured, how measurement occurs, and which losses remain invisible (Lazzarini et al., 2023; Gassler and Spiller, 2022). Power asymmetries embedded in institutional frameworks explain why policies relying on voluntary action may prove insufficient to address inter-stage food loss drivers, as incentives for dominant actors to bear measurement costs remain weak (Gassler and Spiller, 2022). By integrating CAS and Institutional Theory, this review positions food loss quantification as simultaneously a technical measurement challenge and a governance problem shaped by the

institutional contexts within which supply chain actors operate. This dual theoretical lens guided both the data extraction protocol (particularly the coding of system dynamics and institutional factors) and the thematic synthesis presented in Sections 4 and 5.

#### **2.3.4 Descriptive analysis**

This section provides an overview of the 95 studies included in the review, focusing on geographical coverage, methodological approaches, outlet distribution and temporal trends. The aim is not only to describe the sample, but to indicate how existing work is spatially and methodologically skewed, which is central to the argument that upstream food loss is unevenly measured.

##### **2.3.4.1 Geographical distribution**

Fig. 2 summarises the geographical distribution of the selected studies by region and by country. Africa accounts for the largest share of publications (53 per cent,  $n = 50$ ), followed by Asia (18 per cent,  $n = 17$ ) and Europe (17 per cent,  $n = 16$ ). North America contributes 7 per cent ( $n = 7$ ), with South America, global or multi-regional studies, and Oceania together accounting for the remaining 5 per cent. This distribution diverges from earlier systematic reviews of food loss and waste, which have typically focused on European and North American contexts (Corrado and Sala, 2018; Hoehn et al., 2023). The prominence of African studies reflects the upstream and post-harvest focus of this review, which captured substantial work on smallholder farming systems often absent from reviews centred on downstream waste. At the country level (Fig. 2), Ethiopia is the most represented country (15 per cent,  $n = 14$ ), consistent with its prominence in post-harvest loss research driven by cereal production systems and development investments. Kenya, Uganda, the United States and South Africa each contribute 6–7 per cent ( $n = 6–7$ ), whilst Nigeria accounts for 5 per cent ( $n = 5$ ). China and India each contribute 3–4 per cent. The remaining studies span 25 further countries, each appearing once or twice. This concentration of empirical work in East African agricultural systems, with comparatively limited coverage of South Asia, Latin America and Southeast Asia, indicates that the evidence base for upstream loss quantification remains geographically uneven despite stronger African representation than previous reviews suggested.

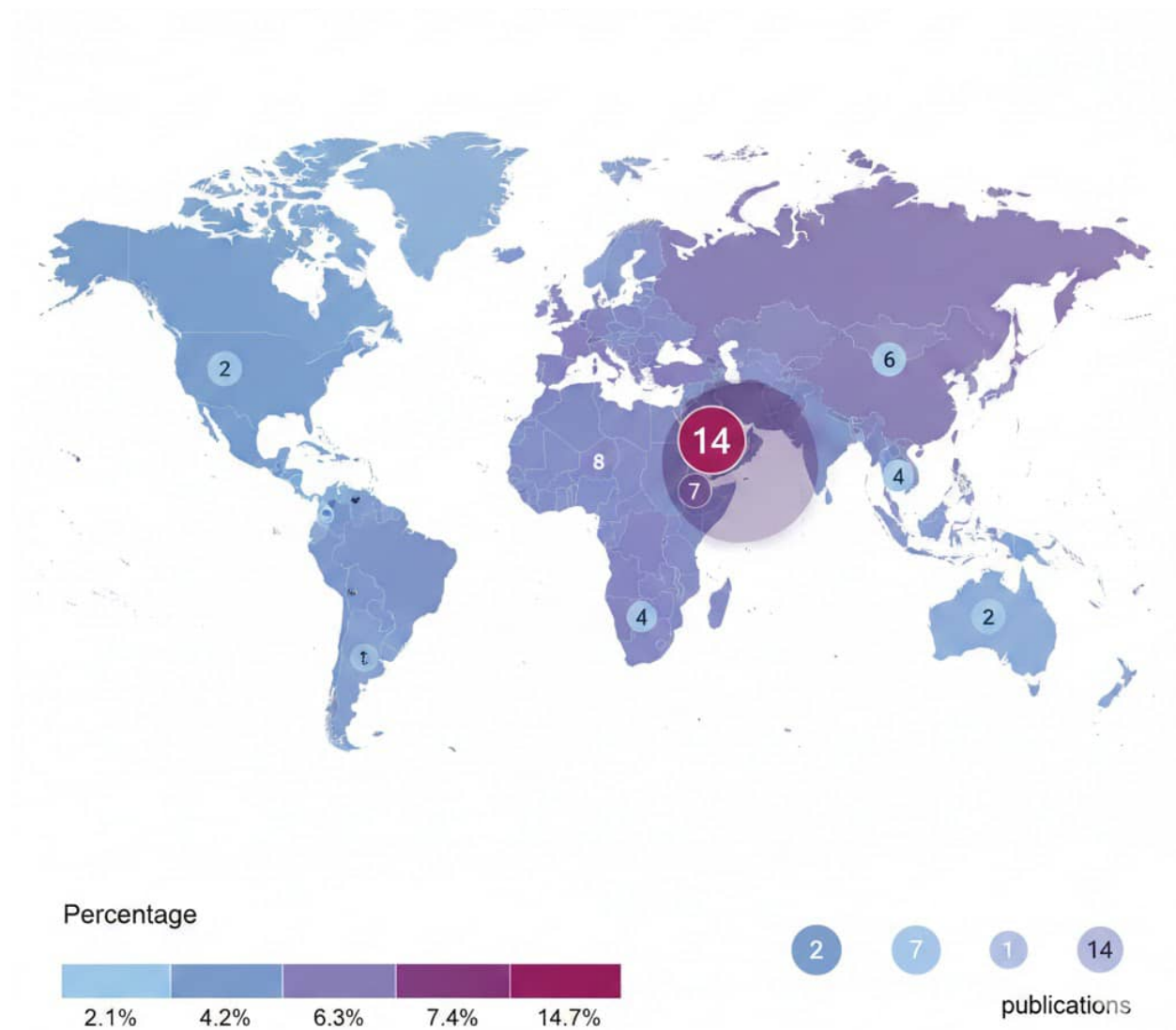


Fig. 2: Summary of Geographical distribution of Selected Papers by Region and Country

#### 2.3.4.2 Research methods

Fig. 3 presents the distribution of research methods used in the selected studies. For classification purposes, each study was assigned to one of five methodological categories based on its primary data collection approach: survey, modelling, case study, experimental, or direct measurement. Survey-based designs dominate the sample, accounting for 56 per cent of studies ( $n = 53$ ). These papers typically use structured questionnaires to collect self-reported information on quantities lost, causes of loss and handling practices from farmers, processors or traders. Modelling approaches constitute the second-largest category at 26 per cent ( $n = 25$ ), encompassing material flow analysis, mass balance, statistical modelling, and life-cycle-based assessments. Case

studies account for 7 per cent ( $n = 7$ ), providing in-depth analyses of commodities, supply chains or localities. Experimental designs account for 6 per cent ( $n = 6$ ) and employ controlled interventions to measure loss under specified conditions. Direct measurement studies, involving physical weighing and observation at specific chain points, represent only 4 per cent of the sample ( $n = 4$ ), reflecting the resource-intensive nature of this approach.

The dominance of survey-based approaches (56 per cent) indicates that much of the empirical base relies on self-reported evidence, which is vulnerable to recall error and social desirability bias. The limited use of direct measurement (4 per cent) and experimental designs (6 per cent) suggests that physically verified loss estimates remain rare, constraining the validation of survey-derived figures. Whilst modelling studies provide system-level perspectives, their dependence on coefficients often derived from the same survey literature creates circularity in the evidence base. This methodological imbalance is a key reason why upstream loss estimates lack robust empirical grounding.

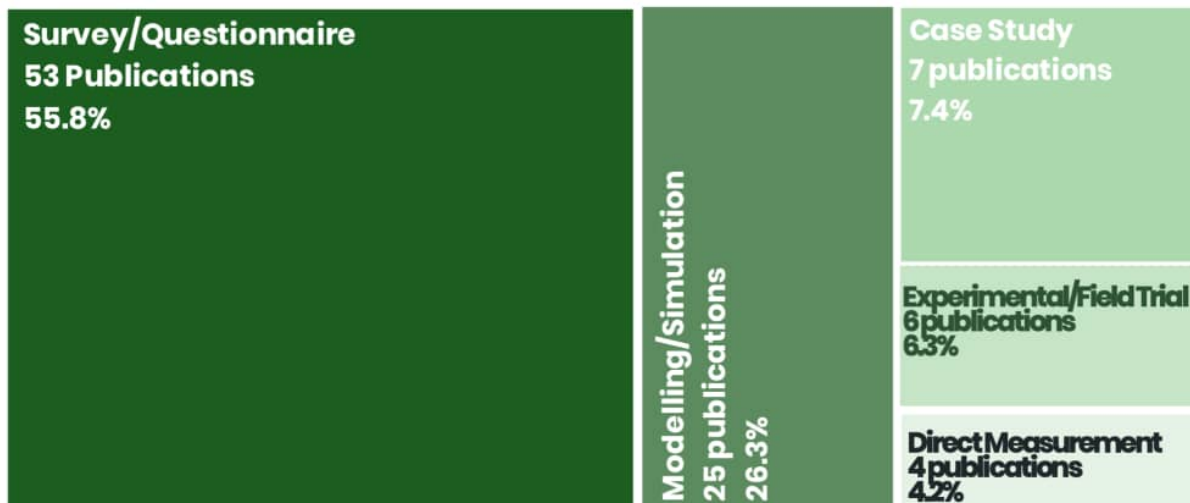


Fig. 3: Distribution of Research Methods of Selected Papers

#### 2.3.4.3 Distribution of journals

The 95 articles are distributed across 39 journals spanning agricultural science, sustainability, food security and environmental management. The highest number of articles appears in Resources, Conservation and Recycling (10 papers; 11 per cent), reflecting the growing treatment of food loss as a resource-efficiency issue within circular economy discourse. The Journal of Stored Products Research accounts for nine papers (10 per cent), representing the technical postharvest literature on storage, pest management, and preservation. Sustainability and Food

Security each contribute eight papers (9 per cent), together providing outlets for interdisciplinary work connecting loss quantification to broader sustainable development agendas.

Other prominent journals include Journal of Cleaner Production and Waste Management, each publishing four papers (4 per cent), alongside the MDPI journal Agriculture (4 papers). The remaining studies are distributed across 32 additional journals, including Heliyon, Agricultural Systems, Cogent Food and Agriculture, and Frontiers in Sustainable Food Systems (each with 3 papers), as well as specialist outlets such as Crop Protection, Food Policy, and Agricultural Economics. The spread across disciplinary boundaries, from agricultural sciences (35 per cent of papers) through sustainability and environmental management (33 per cent) to food-focused journals (17 per cent) and multidisciplinary outlets (15 per cent), suggests that upstream food loss quantification remains a methodologically fragmented field. Nevertheless, the concentration of nearly half of the sample in just four journals indicates that core publication venues are beginning to consolidate around the nexus of resource conservation and food systems.

Table 3: Journal Distribution of Selected Papers

| Journal Name                               | n         | %            |
|--------------------------------------------|-----------|--------------|
| Journal of Stored Products Research        | 9         | 9.5          |
| Sustainability                             | 9         | 9.5          |
| Resources, Conservation and Recycling      | 9         | 9.5          |
| Food Security                              | 8         | 8.4          |
| Journal of Cleaner Production              | 5         | 5.3          |
| Waste Management                           | 4         | 4.2          |
| Frontiers in Sustainable Food Systems      | 4         | 4.2          |
| Heliyon                                    | 3         | 3.2          |
| Agricultural Systems                       | 3         | 3.2          |
| Cogent Food and Agriculture                | 3         | 3.2          |
| Agriculture                                | 3         | 3.2          |
| Agriculture and Food Security              | 2         | 2.1          |
| Crop Protection                            | 2         | 2.1          |
| Horticulturae                              | 2         | 2.1          |
| Other journals (29 journals, 1 paper each) | 29        | 30.5         |
| <b>TOTAL (43 unique journals)</b>          | <b>95</b> | <b>100.0</b> |



#### 2.3.4.4 Publication trends

Fig. 4 presents the temporal distribution of reviewed studies from 2014 to 2025. The earliest included papers date from 2014, with minimal output in the initial years: only three studies (3 per cent) were published between 2014 and 2015. Publication activity increased markedly from 2016, coinciding with the adoption of SDG Target 12.3 and growing international attention to food loss measurement. The period 2016 to 2018 accounts for 24 papers (27 per cent), with annual output rising from three papers in 2016 to ten in 2017 and eleven in 2018.

The most substantial growth occurred from 2019 onwards, with nearly 70 per cent of the sample ( $n = 62$ ) published in the subsequent six years. Annual output peaked in 2022 with 15 papers (17 per cent), likely reflecting the lag between data collection activities initiated in response to SDG monitoring frameworks and eventual publication. The years 2019 and 2021 each contributed 13 and 11 papers, respectively, whilst 2020 showed a modest dip to seven papers, potentially attributable to pandemic-related disruptions to fieldwork. Recent years (2023 to 2025) show continued activity, though lower annual counts may reflect publication pipelines still in progress rather than declining interest.

This temporal concentration confirms that upstream food loss quantification is an emerging field, with over half the evidence base (55 per cent) produced in the last five years alone. The recency of the literature carries methodological implications: conclusions drawn from this corpus necessarily reflect the first generation of responses to global measurement agendas, and important regions, commodities and methodological approaches remain under-represented as the field continues to develop.

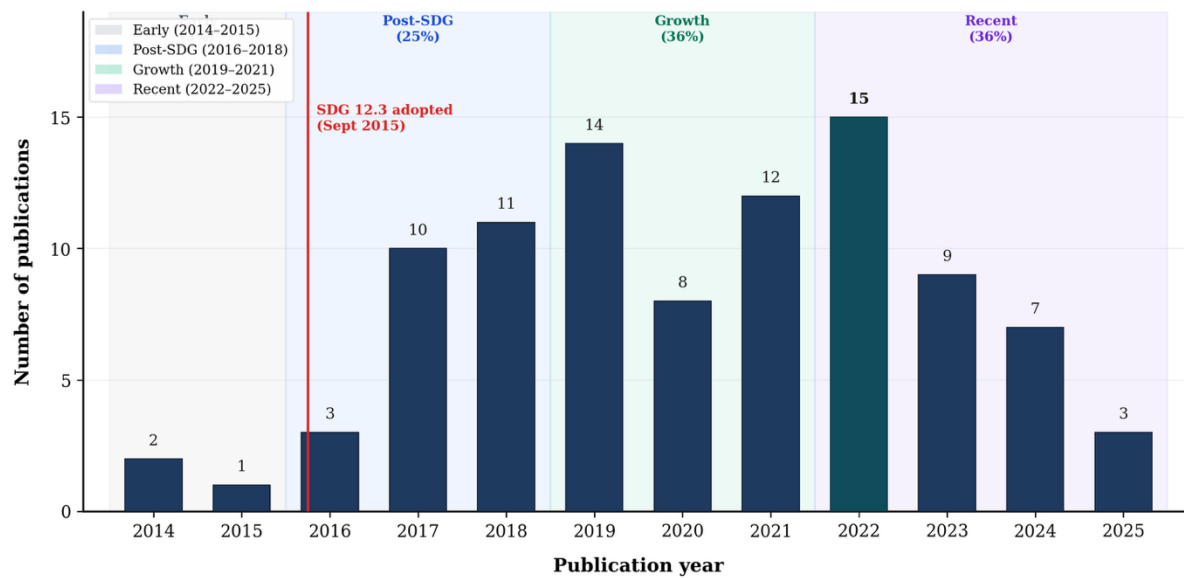


Fig. 4: Temporal Distribution of Reviewed Studies (n=95)

### 2.3.5 Thematic analysis

Descriptive mapping indicates that quantification of upstream food loss is geographically uneven and methodologically concentrated. To examine how these patterns organise the evidence base, this study conducted a structured co-word analysis of author keywords and salient terms extracted from titles and abstracts. Following current guidance on integrating bibliometric mapping with systematic evidence synthesis, terms were cleaned and normalised, a keyword co-occurrence network was constructed, and communities were identified using network clustering; importantly, cluster outputs were used as sensitising concepts and triangulated against the full-text coding described in Section 2.2, rather than treated as a substitute for interpretive synthesis (Zupic and Čater, 2015; Donthu et al., 2021; Haghani, 2023; Marzi et al., 2025). The resulting network (Fig. 5) reveals three partially overlapping thematic configurations: (i) measurement methodologies, centred on food loss, food waste, quantification and method-specific terms; (ii) systemic complexity, linking supply chain structures with post-harvest dynamics and environmental drivers; and (iii) economic and political constraints, connecting waste management, governance and resource use. These configurations structure the thematic synthesis that follows and directly address RQ1 (effectiveness and limitations of current methods) and RQ2 (systemic barriers to precise quantification).

### 2.3.5.1 Measurement Methodologies

#### Definitional and Data Collection Inconsistencies

Across the 95 studies, the most fundamental limitation is the lack of definitional and procedural consistency. In the reviewed corpus, 17 studies explicitly adopt an externally defined loss and waste standard or harmonised protocol, whereas 78 employ study-specific definitions or boundary rules. Key terms such as "food loss", "food waste", "avoidable", "unavoidable" and "by-product" are applied differently across and within regions, commodities and stages (Hartikainen et al., 2017; Emana et al., 2017; Corrado and Sala, 2018). Some frameworks distinguish loss and waste strictly by stage or intention, others treat them as interchangeable, and others still differentiate quantitative losses (mass) from qualitative losses (nutritional or economic value) (Caldeira et al., 2019; Redlingshöfer et al., 2017; Parmar et al., 2018). Studies that experiment with alternative classifications show that choices about whether, for example, diversion to animal feed or downgrading is treated as loss can shift estimated loss rates by more than ten percentage points, and in some cases by 12–18 per cent (Ju et al., 2017; Johnson et al., 2018).

These conceptual ambiguities propagate into data-collection practice. While processing losses can often be derived from input–output comparisons, upstream losses at farm and aggregation levels are commonly estimated using farmer or trader surveys, expert judgement or generic coefficients rather than standardised tracking systems (Wesana et al., 2019; Łaba et al., 2022). Across the corpus, survey-based self-reporting and coefficient-based estimation dominate farm and aggregation-stage measurement ( $n = 62$ ), whereas direct measurement studies remain comparatively rare ( $n = 26$ ). Field-measurement studies demonstrate that self-reported losses are often far below physically measured values, especially for perishable crops and cosmetic rejection (Johnson et al., 2018; Schneider et al., 2019). Baker et al. (2019) corroborate this finding, showing that measured losses in California vegetable fields exceeded grower estimates substantially. Cultural norms and local notions of what counts as "waste" lead to systematic under-reporting in some contexts, particularly where diversion to informal channels or non-food uses is socially accepted (Alshabanat et al., 2021).

At the national scale, many baselines draw heavily on FAO-style coefficients and global mass-balance templates, with limited empirical validation (Mingione et al., 2021; Alexander et al., 2017). Through an institutional theory lens, this can be interpreted as consistent with a form of institutional isomorphism: governments adopt internationally sanctioned methodologies to signal compliance and legitimacy even when those frameworks poorly reflect local supply chain

structures and informal flows (Meyer and Rowan, 1977). Mingione et al. (2021) demonstrate through Bayesian modelling how FAO data constraints propagate uncertainty across cereal loss estimates globally. Heterogeneous definitions combined with heterogeneous data sources create a patchwork of estimates that cannot easily be aggregated or compared, which is a central reason why upstream loss remains weakly characterised in the global evidence base.

#### Macro- and Micro-Level Quantification Approaches

To examine how methods contribute to this fragmentation, studies were grouped into macro-, micro- and cross-scale categories. Table 4 synthesises the resulting taxonomy, adapted from the methods identified in the review. The categories in Table 4 reflect predominant applications in the reviewed studies and are not mutually exclusive: individual studies sometimes combine methods or apply them at multiple scales. Reported outputs vary across the corpus (for example, tonnes or kilograms, percentage loss rates, monetary values, and environmental footprints), which further complicates aggregation and comparison. Across the corpus, macro-level approaches were used in 8 studies, micro-level approaches in 90, and cross-scale approaches in 28.

Table 4: Quantification Methods for Food Loss

| Scale              | Category                | Method                         | Brief Description                                              | Key references                                                                                  | Key Strengths                                             | Key Limitations                                                      |
|--------------------|-------------------------|--------------------------------|----------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-----------------------------------------------------------|----------------------------------------------------------------------|
| <b>Macro level</b> | Food balance approaches | National food balance sheets   | Use of national or regional statistics with conversion factors | Ju et al. (2017); Alexander et al. (2017)                                                       | Comprehensive coverage; supports international comparison | Poor granularity; outdated coefficients; weak informal flow coverage |
|                    |                         | Regional/global estimations    | Extrapolated estimates across regions or globally              | Alexander et al. (2017); Abass et al. (2014); Mingione et al. (2021)                            | Big picture perspective; highlights regional patterns     | Masks local variability; sparse sampling                             |
|                    | Economic accounting     | Input–output analysis          | Uses monetary IO tables to infer physical losses               | Caldeira et al. (2019)                                                                          | Links economic and physical flows                         | Difficult to disentangle flows; aggregation bias                     |
|                    |                         | Economic value estimations     | Converts financial metrics to loss quantities                  | Pietrangeli and Cicatiello (2024); Boiteau and Pingali (2022)                                   | Monetises impacts; useful for business cases              | Sensitive to price volatility                                        |
|                    | Policy-level assessment | Food security metrics          | Relates losses to nutritional and food security indicators     | Martindale et al. (2020); Bechoff et al. (2022)                                                 | Connects loss to nutrition; policy relevant               | Complex causal chains; data intensive                                |
| <b>Micro level</b> | Direct measurement      | On-site weighing/observation   | Direct measurement at specific chain points                    | Schneider et al. (2019); Johnson et al. (2018); Baker et al. (2019); Opara et al. (2021)        | High accuracy; process-specific insights                  | Labour intensive; sampling issues                                    |
|                    |                         | Waste composition audits       | Sorting and weighing of waste streams                          | Eriksson et al. (2017); Blanckenberg et al. (2021)                                              | Detailed compositional data                               | Costly; limited coverage                                             |
|                    | Self-reporting          | Commodity-specific assessments | Crop-specific measurements during production                   | Johnson et al. (2018); Herrera-Quinteros and Jara-Rojas (2023); Fernández-Zamudio et al. (2020) | Rich context; high precision                              | Poor scalability; single-commodity focus                             |
|                    |                         | Surveys and questionnaires     | Actor-reported losses                                          | Hartikainen et al. (2017); Mebratie et al. (2015); Lu et al. (2022)                             | Cost-effective; scalable                                  | Recall bias; definitional variance                                   |
|                    |                         | Diaries                        | Daily record-keeping by participants                           | Yigezu et al. (2021); Khader et al. (2019)                                                      | Temporal patterns; behavioural insight                    | Participant burden                                                   |
|                    |                         | Business waste tracking        | Internal monitoring systems                                    | Łaba et al. (2022); Principato et al. (2019)                                                    | Operational relevance                                     | Proprietary data; incentive misalignment                             |
|                    |                         |                                |                                                                |                                                                                                 |                                                           |                                                                      |

| Scale              | Category                 | Method                                   | Brief Description                              | Key references                                                         | Key Strengths                         | Key Limitations                            |
|--------------------|--------------------------|------------------------------------------|------------------------------------------------|------------------------------------------------------------------------|---------------------------------------|--------------------------------------------|
|                    | Process-based analysis   | Material flow analysis (MFA)             | Tracks mass flows through specified boundaries | Amicarelli et al. (2021); Parmar et al. (2018); Caldeira et al. (2019) | System perspective; mass conservation | Data intensive; boundary sensitive         |
|                    |                          | Mass balance                             | Input–output differences at process level      | Ju et al. (2017); Caldeira et al. (2019)                               | Clear attribution at specific nodes   | Limited quality treatment                  |
|                    |                          | Loss coefficients                        | Application of fixed coefficients              | Wesana et al. (2019); Teferra (2022)                                   | Simple and inexpensive                | Ignores contextual variation               |
|                    | Quality-based assessment | Moisture/quality metrics                 | Use of moisture meters or quality parameters   | Hengsdijk and de Boer (2017); Kebede et al. (2024)                     | Objective quality indicator           | Single-attribute focus                     |
|                    |                          | Grading and rejection                    | Quality-based rejection statistics             | Ortiz-Gonzalo et al. (2021); Pietrangeli and Cicatiello (2024)         | Direct link to standards              | Subjective criteria; power-driven          |
|                    |                          | Shelf-life indicators                    | Time–temperature and deterioration metrics     | Liu et al. (2024); Tansuchat et al. (2023)                             | Connects quality and time             | Product-specific; limited to formal chains |
| <b>Cross-scale</b> | Advanced technologies    | Internet of Things (IoT) sensor networks | Real-time monitoring                           | Shoji et al. (2022)                                                    | Continuous data; reduced human error  | High cost; digital divide                  |
|                    |                          | Machine learning                         | Predictive/classification models               | Jia et al. (2023)                                                      | Handles complex patterns              | Data requirements; opacity                 |
|                    | Integrated assessment    | Life cycle assessment (LCA)              | Multi-impact environmental assessment          | Liu et al. (2024); Gummert et al. (2020)                               | Systemic impact view                  | Method choices influence outcomes          |
|                    |                          | Hybrid modelling                         | Combinations across scales                     | Wesana et al. (2019); Boiteau and Pingali (2022)                       | Compensates single-method weaknesses  | Complexity; high resource needs            |
|                    |                          | Supply-chain-wide frameworks             | Loss tracking across all stages                | Redlingshöfer et al. (2017); Principato et al. (2019)                  | Holistic perspective; hotspot ID      | High coordination requirements             |
|                    | Resource footprinting    | Water/carbon/land footprints             | Resource impacts of loss                       | Jia et al. (2023); Winans et al. (2020)                                | Connects loss to resource pressure    | Allocation and boundary challenges         |

Table 4 shows an apparent depth–breadth trade-off: macro approaches provide coverage and comparability but obscure subnational heterogeneity and informal flows. Micro approaches generate rich, context-specific evidence but lack the statistical power and standardisation needed for national or global accounting. Cross-scale methods are still relatively rare and methodologically demanding. This fragmentation is a central reason why aggregate upstream loss estimates remain both contested and weakly actionable. Consistent with this pattern, survey-based approaches feature in 46 of the included studies and hybrid or multi-method designs in 18, whereas life cycle assessment and footprinting appear in nine and four studies, respectively; explicit use of real-time sensing appears in only one study.

### 2.3.5.2 Methodological Gaps in Capturing System Complexity

Most methods in Table 4 treat loss as a static parameter at a specific stage, implicitly assuming linear propagation. The review, however, indicates that upstream losses arise in complex adaptive systems in which feedback, thresholds, and cross-scale interactions are essential (Alexander et al., 2017; Boiteau and Pingali, 2022). Table 5 summarises how major measurement approaches align with key system features.

Table 5: Measurement approach and system features

| Measurement Approach   | System Feature Captured                        | System Feature Missed                                     | Regional Applicability                                    | Illustrative studies                                                  |
|------------------------|------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------------------|
| Material flow analysis | Physical throughputs; stage-wise mass balances | Feedback loops; adaptive behaviour; quality dynamics      | Formal, data-rich markets                                 | Ju et al. (2017); Amicarelli et al. (2021); Caldeira et al. (2019)    |
| Self-report surveys    | Actor perceptions; some behavioural drivers    | Systemic under-reporting; power relations; informal flows | Variable; widely used in low- and middle-income countries | Johnson et al. (2018); Hartikainen et al. (2017); Emanu et al. (2017) |
| Life cycle assessment  | Multiple environmental impacts                 | Dynamic market responses; emergent behaviours             | Predominantly formal economies                            | Liu et al. (2024); Gummert et al. (2020)                              |
| Direct measurement     | Process-specific losses                        | System-wide propagation; temporal dynamics                | Case studies, pilot sites                                 | Baker et al. (2019); Schneider et al. (2019); Opara et al. (2021)     |
| Economic modelling     | Market value implications                      | Non-economic drivers; social factors                      | Formal market contexts                                    | Caldeira et al. (2019); Boiteau and Pingali (2022)                    |
| IoT/sensors            | Real-time quality parameters                   | Accessibility barriers; data asymmetries                  | Digitally connected segments                              | Shoji et al. (2022)                                                   |
| Hybrid approaches      | Multiple dimensions; triangulation             | Integration and cost challenges                           | Context-dependent                                         | Wesana et al. (2019); Boiteau and Pingali (2022)                      |

The table highlights that no single method captures the full set of system properties relevant for upstream loss. Material flow analysis (MFA) and life cycle assessment (LCA) remain largely static; surveys and diaries are sensitive to bias; direct measurements are narrow in scope; advanced technologies are unevenly distributed. Several studies show that cumulative system-wide losses exceed the sum of independently measured stage losses, indicating that additive models under-represent emergent effects (Alexander et al., 2017; Ju et al., 2017; Caldeira et al., 2019). This pattern can arise where stage-specific studies apply inconsistent system boundaries, omit quality-related degradation, or fail to observe informal diversions and reclassifications, such that errors and uncertainty propagate and compound across stages. This is particularly evident in long, multi-actor chains such as animal products and horticulture, where small inefficiencies compound across stages (Wang et al., 2023; dos Santos et al., 2020).

#### 2.3.5.3 Systemic Complexity of Food Loss Patterns Cross-Scale Interaction Challenges

A second theme concerns the difficulty of relating measurements at one scale to outcomes at others. Farm-level measurements are hard to aggregate to national statistics because cropping systems, storage conditions and market channels vary considerably within single regions (Hengsdijk and de Boer, 2017; Herrera-Quinteros and Jara-Rojas, 2023). Short measurement windows and irregular sampling further complicate scaling (Eriksson et al., 2017). This is particularly acute in informal markets, where a substantial share of produce flows through channels that leave no trace in official statistics (Balana et al., 2022; Falola et al., 2023). Here, 'informal' refers to trading and handling activities that are not routinely captured in official registries, formal contracts, or routine reporting systems, including cash-based transactions and small-scale aggregation.



Table 6: Cross-scale measurement challenges in formal and informal contexts

| Scale Challenge            | Formal Supply Chain Context                                                                    | Informal Supply Chain Context                                    | Key Studies (Revised)                                        |
|----------------------------|------------------------------------------------------------------------------------------------|------------------------------------------------------------------|--------------------------------------------------------------|
| Data aggregation           | Standardised reporting systems; digital records and enterprise resource planning (ERP) systems | Fragmented or absent records; paper-based or verbal transactions | dos Santos et al. (2020); Balana et al. (2022)               |
| Temporal alignment         | Regular reporting cycles; long time series                                                     | Seasonal variability; limited historical data                    | Baker et al. (2019); Emanu et al. (2017)                     |
| Sampling representation    | Registries of firms and farms; stratified sampling frames                                      | Unknown population parameters; hard-to-reach actors              | Herrera-Quinteros and Jara-Rojas (2023); Ansah et al. (2018) |
| Economic integration       | Contractual prices; formal accounts                                                            | Cash-based, relationship-driven exchanges                        | Caldeira et al. (2019); Boiteau and Pingali (2022)           |
| Environmental attribution  | Product traceability; life-cycle databases                                                     | Multiple small actors; unclear system boundaries                 | Liu et al. (2024); Gummert et al. (2020)                     |
| Institutional coordination | Regulatory reporting mandates; industry associations                                           | Weak or fragmented governance; overlapping mandates              | Hartikainen et al. (2017); Łaba et al. (2022)                |

Formal chains benefit from standard frameworks, digital infrastructure, sampling frames and traceability systems, which allow cross-scale integration even if implementation is imperfect. Informal chains, by contrast, operate with minimal documentation and weak institutional coordination, making it extremely difficult to scale micro-level measurements or to attribute losses to specific actors. The gap between these contexts helps explain why global and national accounts often capture only a subset of actual upstream losses.

#### Environmental Variability and Climate Impacts

Environmental variability and climate change introduce further non-linearities that most quantification methods only partially address. Several studies document how rainfall variability, temperature extremes and pests lead to highly variable pre-harvest and post-harvest losses that cannot be captured by single-season measurements or static coefficients (Hengsdijk and de Boer, 2017; Ortiz-Gonzalo et al., 2021; Liu et al., 2024). Jia et al. (2023) demonstrate through footprint analysis that resource impacts of food loss respond in non-linear ways to production conditions, implying that small changes in loss patterns can have disproportionate environmental impacts.

Conventional tools such as material flow analysis (MFA) and life cycle assessment (LCA) handle average conditions but struggle with stochastic or threshold behaviour and seldom represent adaptive responses by farmers or traders (Ju et al., 2017; Caldeira et al., 2019). Emerging applications of sensor networks and machine learning provide more dynamic representations of deterioration and risk (Shoji et al., 2022; Jia et al., 2023), but as noted above, their deployment remains highly unequal and may deepen existing data divides

(Wesana et al., 2019; Adams et al., 2023). The thematic evidence therefore supports a complex adaptive systems (CAS)-informed reading of upstream loss as the product of interacting environmental, behavioural and institutional dynamics rather than as a stable parameter.

#### 2.3.5.4 Economic and Political Constraints on Quantification

The third cluster concerns economic incentives, regulatory frameworks and power relations. Many firms treat loss as a normal cost of doing business rather than as a performance indicator, which limits willingness to invest in measurement or prevention (Principato et al., 2019; Eriksson et al., 2017). March et al. (2019) show that in dairy processing, technological losses during cleaning cycles are accepted as unavoidable; improved monitoring is perceived as adding cost without clear financial returns. Where measurement might reveal commercially sensitive information or trigger regulatory scrutiny, there are clear incentives to under-report or to keep data proprietary (Minten et al., 2021; Wang et al., 2023). Across the corpus, proprietary data constraints and incentives to under-report or selectively report losses are explicitly discussed in 7 studies.

Regulatory frameworks often reinforce these disincentives. Studies of European and Middle Eastern contexts reveal fragmented, sometimes contradictory policies that create inconsistent reporting requirements and methodological guidance (Łaba et al., 2022; Alshabanat et al., 2021; Caldeira et al., 2019). Municipal waste directives may mandate reporting by local authorities but impose no obligations on primary producers, traders or processors. National strategies frequently focus on consumer behaviour and downstream waste, while upstream stages remain weakly regulated and poorly measured (Redlingshöfer et al., 2017). Alexander et al. (2017) demonstrate through global modelling that loss reduction targets can have distributional consequences, which may reduce the political appetite to push for stronger reporting standards or more intrusive measurement requirements.

Power asymmetries along supply chains further distort measurement practices. Retailers and large processors can set cosmetic standards and contractual terms that shift risk upstream, rejecting products without counting these volumes in their own loss statistics (Eriksson et al., 2017; Ortiz-Gonzalo et al., 2021). Empirical work on vegetable and cereal chains shows that producers, who often lack bargaining power and alternative markets, absorb these losses while having limited capacity or incentive to document them (Yigezu et al., 2021; Khader et al., 2019). Institutional norms and confidentiality practices in sectors such as animal products similarly limit transparency and hinder independent quantification (Wang et al., 2023).

In combination, economic disincentives, regulatory fragmentation, power imbalances and institutional weaknesses create a structural environment in which under-measurement and selective reporting are rational responses for many actors. These constraints shape not only the incidence of loss but also the feasibility of quantification methods and the accessibility of data sources, reinforcing the methodological fragmentation discussed above. The thematic analysis, therefore, indicates that improving upstream food loss quantification will require not only methodological innovation but also changes in incentive structures, governance arrangements and regulatory design, issues that are taken up in the framework and future-research sections that follow.

### **2.3.6 Framework for Food Loss Quantification**

The systematic review and thematic analysis show that definitional heterogeneity, fragmented methods and weak alignment between measurement systems and governance structures constrain current approaches to upstream food loss quantification. These limitations are consistent with the methodological concerns raised in leading work on food loss and waste accounting, which highlights inconsistent system boundaries, reliance on indirect coefficients and limited coverage of upstream stages (Chaboud and Daviron, 2017; Caldeira et al., 2019; Hoehn et al., 2023). In particular, the evidence confirms that dominant tools such as food balance sheets, survey-based estimates and static material flow analyses often treat loss as a stage-specific parameter and abstract away from the feedbacks, adaptive behaviours and power relations that shape both losses and the data used to describe them (Drabik et al., 2019; Corrado and Sala, 2018).

Throughout this manuscript, 'upstream' refers to stages from primary production through post-harvest handling, storage, aggregation and processing before retail, recognising that supply-chain boundaries differ by commodity and context. In line with the review findings, whether diversions such as animal feed, downgrading or non-food uses are categorised as loss is treated as an explicit boundary choice and should be reported transparently.

To respond to these limitations, the proposed framework combines Complex Adaptive Systems (CAS) theory with Institutional Theory to reconceptualise upstream food loss quantification as a dynamic, multi-scale and politically embedded process. CAS offers a vocabulary for representing non-linear interactions, feedback loops, path dependence and emergent behaviour in agrifood systems, emphasising how small perturbations can cascade through networks of actors and processes (Kuhmonen, 2017; Angeler et al., 2015). Institutional Theory foregrounds how formal rules, informal norms and power asymmetries

shape what is counted as loss, which methods are adopted and whose information is considered legitimate (Meyer and Rowan, 1977; Guptill and Peine, 2021). Integrating these perspectives supports a shift from viewing quantification as a neutral technical exercise to seeing it as a co-evolving configuration of methods, incentives and governance arrangements.

Fig. 5 positions this framework at the interface among three sets of challenges identified in the review: definitional and data-collection inconsistencies, methodological fragmentation, and economic–political constraints. It proposes four interlinked responses: systems thinking to recognise complex interactions; multi-method, cross-scale measurement to balance breadth and depth; institutional analysis of incentives and power; and adaptive, participatory design supported by systemic modelling. These four interlinked responses serve as strategic pillars. They are operationalised through the seven core components outlined in Section 6.1, which specify definitional alignment, nested multi-method designs, institutional analysis, adaptive participation, systemic modelling, and an implementation process. The review shows that ignoring these elements yields systematic mismeasurement. For example, minor inefficiencies in perishable supply chains have been shown to propagate across storage, logistics, and market stages, generating cumulative losses exceeding the sum of individual-stage estimates (Alexander et al., 2017; Ju et al., 2017). Likewise, institutional analyses of European and national loss accounts demonstrate that data gaps are not merely technical but reflect who bears costs and who defines the rules of measurement (Caldeira et al., 2019; Łaba et al., 2022).

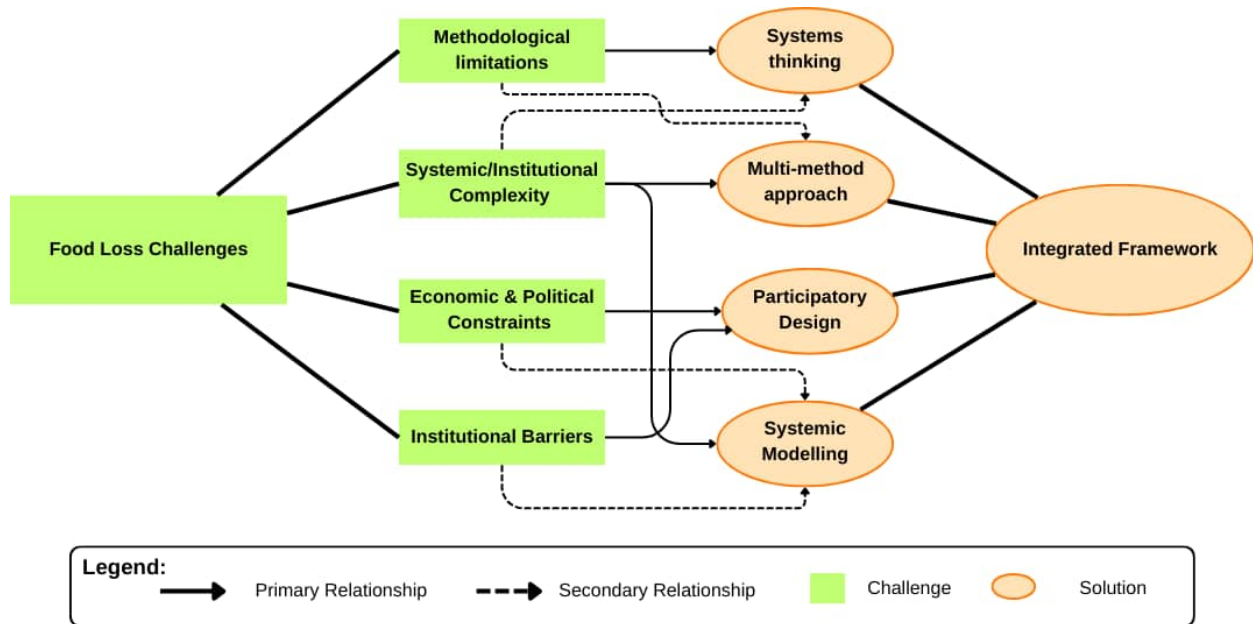


Fig. 5: Relationship between Food Loss Challenges and Proposed Framework

The framework, therefore, aims not only to refine existing methods but to reorient quantification towards a more reflexive and context-sensitive practice. It is designed to be modular and adaptable: components can be implemented incrementally in settings with limited resources while still moving measurement closer to the systemic, complexity-aware and institutionally grounded standards increasingly called for in Resources, Conservation and Recycling (RCR)'s FLW scholarship (Hoehn et al., 2023; Spang et al., 2019).

#### 2.3.6.1 Theoretical Foundations

Fig. 6 summarises the theoretical foundations of the framework, showing how CAS and Institutional Theory intersect in the context of upstream food loss. CAS conceptualises agrifood systems as networks of heterogeneous agents whose interactions under uncertainty generate outcomes that cannot be inferred from individual components alone (Holland, 1995; Bryceson and Ross, 2020). Losses arise from evolving combinations of climatic shocks, production choices, grading and pricing rules, storage capacities and infrastructural constraints, and interventions can have counter-intuitive consequences when feedbacks and adaptations are ignored (Alexander et al., 2017; Boiteau and Pingali, 2022). This view aligns with recent RCR work arguing that static mass-balance and coefficient-based approaches are inadequate for capturing the complexity of FLW dynamics and their environmental impacts (Hoehn et al., 2023; Caldeira et al., 2019).

Institutional Theory complements this systems lens by explaining why certain losses are measured while others remain invisible. Formal regulations, standard-setting initiatives, and corporate reporting schemes create intense pressures for harmonisation and legitimacy, but they can also encourage the adoption of simplified frameworks that underrepresent upstream and informal contexts (Caldeira et al., 2019; Redlingshöfer et al., 2017). Informal norms, path-dependent infrastructures and power asymmetries along the chain influence which data matter and who has the capacity to shape metrics, a point emphasised in governance-oriented analyses of FLW and circular economy transitions (Spang et al., 2019; Teigiserova et al., 2019). In institutional terms, food loss quantification is not just a measurement problem; it is a site where interests, symbols and resources intersect.

Bringing CAS and Institutional Theory together allows the framework to link three levels of analysis. At the micro level, it considers how farmers, traders, processors and retailers adapt to changing conditions and incentives. At the meso level, it examines how sectoral organisations, supply chain partnerships and information systems mediate data flows. At the macro level, it interrogates how national strategies, international standards and market structures shape both losses and measurement architectures. This multi-level integration is consistent with calls in RCR for frameworks that can relate micro evidence, such as on-site measurements or case studies, to macro debates on resource productivity and policy design (Drabik et al., 2019; Caldeira et al., 2019; Teigiserova et al., 2019).

#### 2.3.6.2 Core Components of the Integrated Framework Systems Thinking and Complexity

The first component is explicit adoption of systems thinking in the design of measurement strategies. Rather than treating each stage as a separate analytical unit, the framework encourages users to map interdependencies and feedback between production, storage, transport and market processes. CAS-informed tools such as causal loop diagrams, influence maps and qualitative system dynamics can be used with stakeholders to identify potential reinforcing and balancing feedbacks, for example, how post-harvest losses influence market prices and subsequent planting decisions, or how stringent cosmetic standards create rejection cascades upstream (Bryceson and Ross, 2020; Sengupta et al., 2024). This component responds to critiques of dominant FLW accounting pathways that reduce complex chains to linear loss coefficients (Hoehn et al., 2023) and aligns with broader system-oriented work in food waste and circular economy research (Teigiserova et al., 2019; Principato et al., 2019).

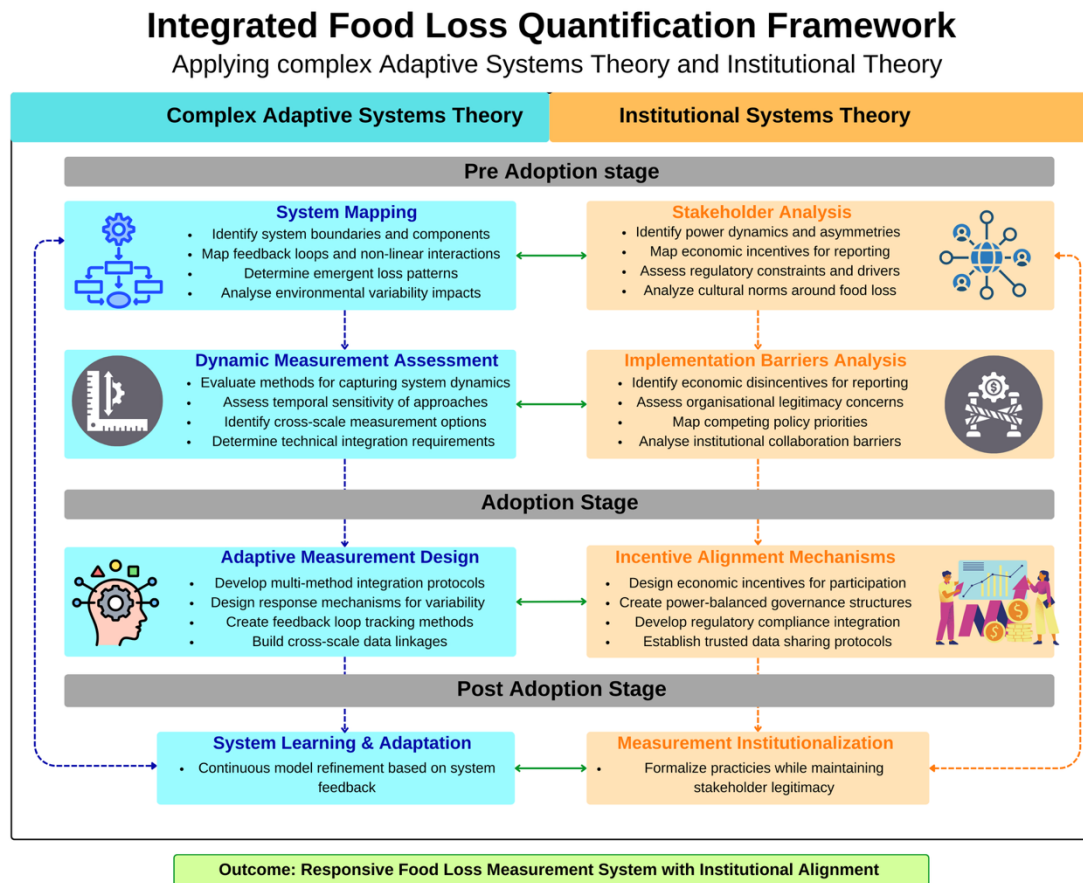


Fig. 6: Integrated Food Loss Quantification Framework

#### Standardised Definitions and Measurement Protocols

The second component addresses definitional fragmentation by promoting standardised yet adaptable concepts and protocols. Building on FAO and FLW Standard definitions and the experience from European mass-flow work (Hanson et al., 2016; Caldeira et al., 2019; EC, 2019), the framework advocates a core set of definitions for loss, waste, avoidable and unavoidable fractions, and quality-related versus quantitative losses, while encouraging context-specific refinements where necessary. The aim is to provide a stable reference point that can be used across studies, sectors and regions without suppressing important differences in local practice. Establishing such a common definitional core directly responds to calls from RCR scholars for harmonised accounting frameworks that can support monitoring and comparative assessment (Corrado and Sala, 2018; Caldeira et al., 2019).

#### Multi-Method Measurement Approach

The third component is a deliberate multi-method design that combines macro, micro and cross-scale approaches in ways that exploit their respective strengths while mitigating their weaknesses. As the review shows, macro methods such as food balance sheets and national MFA provide coverage but lack granularity, while micro methods such as on-site measurement

and case studies offer detail but do not scale (Amicarelli et al., 2021; Alexander et al., 2017). Building on the methodological toolbox articulated by Chaboud and Daviron (2017) and on integrated approaches in RCR (Caldeira et al., 2019; Drabik et al., 2019), the framework proposes sequencing and nesting methods rather than choosing a single "best" tool.

For example, food balance sheets or national waste statistics can be used to identify broad hotspots; targeted field measurements and waste audits can then be implemented in these hotspots to refine estimates; surveys and diaries can explore behavioural and institutional drivers; and MFA or hybrid models can integrate these layers into a coherent picture. Where feasible, digital tools such as IoT sensors, low-cost data loggers and machine learning models can support continuous monitoring and pattern recognition, although the framework emphasises that adoption should be sensitive to local capacities and inequalities (Shoji et al., 2022; Jia et al., 2023; Łaba et al., 2022). The principle is methodological pluralism guided by system logic rather than convenience.

#### Institutional Analysis

A fourth component is systematic institutional analysis of measurement contexts. This involves mapping which actors collect data, for what purposes and under which incentives; how regulations, standards and reporting schemes shape these practices; and where power asymmetries create blind spots or distortions. Techniques can include policy analysis, stakeholder interviews, document review and participatory institutional mapping (Spang et al., 2019; Hook and Soma, 2022). Case evidence from both high- and middle-income settings shows that misaligned policies, fragmented mandates and confidentiality concerns regularly limit data availability and comparability (Alshabanat et al., 2021; Redlingshöfer et al., 2017). By making these constraints explicit, the institutional component identifies leverage points for reform, such as targeted reporting requirements, data-sharing agreements or incentive mechanisms that encourage more accurate measurement.

#### Adaptive and Participatory Design

The fifth component emphasises adaptive and participatory design of measurement systems. Rather than imposing fixed protocols, the framework recommends collaborative design processes that involve producers, traders, processors, regulators, civil society and technical experts. Participatory techniques, including co-design workshops, community-based monitoring and feedback sessions, can help align measurement with local priorities, build trust and enhance data quality, particularly in informal and data-poor contexts (El Bilali et al., 2022; dos Santos et al., 2020). This component also supports incremental adaptation: measurement systems are periodically reviewed in light of new information, changing conditions or



stakeholder feedback, an approach consistent with CAS notions of learning and adaptation and with open, reflexive methodologies advocated in recent RCR debates (Fabi et al., 2021; Teigiserova et al., 2019).

### Systemic Modelling

The sixth component uses systemic modelling tools, such as system dynamics and agent-based models, to integrate data across scales and explore the consequences of alternative interventions. These tools can simulate how shocks or policy changes propagate through supply chains, how feedbacks might amplify or dampen losses, and which actors and stages are most sensitive to change (Sengupta et al., 2024). In line with concerns raised by Hoehn et al. (2023) about the limitations of static quantification pathways, systemic models can be used to stress-test measurement assumptions, identify where additional data would most improve understanding and reveal where apparently minor interventions could have system-wide effects. They also offer a bridge between physical loss accounting and impact assessment, enabling integration with LCA or footprint analyses (Liu et al., 2024; Jia et al., 2023).

#### 2.3.6.3 Implementation Process

Finally, the framework outlines an implementation process that moves from diagnosis to pilot testing and institutionalisation. The diagnostic phase applies the components above to identify current methods, data gaps and institutional constraints. Pilot studies then test tailored multi-method packages in selected supply chains or regions, using both quantitative metrics and qualitative feedback to evaluate feasibility, accuracy and acceptance. Successful pilots can be scaled up through policy integration, capacity-building programmes and incorporation into national reporting systems. Throughout, iterative learning loops are maintained so that experiences in one context inform adjustments elsewhere, consistent with CAS principles and with continuous improvement approaches used in RCR case work on waste prevention and resource efficiency (Caldeira et al., 2019; Drabik et al., 2019; Teigiserova et al., 2019).

### 2.3.7 Future Research Directions

The framework and review together suggest several priority directions for future work.

First, there is a clear need to develop complexity-aware yet standardised metrics for food loss that reconcile the demands of comparability and context sensitivity. This aligns with the framework's emphasis on standardised definitions and measurement protocols (Section 6.1.2) and multi-method, cross-scale designs (Section 6.1.3). Empirically, this calls for validation studies that compare alternative definitions and boundary rules within the same supply chain and across seasons, and that report sensitivity of estimates to classification choices. Building on current efforts to harmonise definitions and accounting methods in Europe and

internationally (Caldeira et al., 2019; EC, 2019), future research should test metrics that integrate physical quantities with economic, nutritional and environmental dimensions, and that can be operationalised through multi-method designs. Work in RCR on nutritional and economic valuation of FLW provides promising starting points (Drabik et al., 2019).

Second, digital technologies require more nuanced evaluation and co-design. While Internet of Things (IoT) applications, remote sensing and machine learning can substantially improve temporal resolution and predictive power, their deployment raises questions about cost, control over data and distribution of benefits (Shoji et al., 2022; Jia et al., 2023; Hoehn et al., 2023). This corresponds to the framework's focus on adaptive and participatory design (Section 6.1.5) and on institutional analysis of data governance (Section 6.1.4). Methodologically, comparative field trials and co-design studies can evaluate not only technical performance but also data ownership arrangements, incentives for truthful reporting, and distribution of benefits across actors. Future studies should not only test technical performance but also examine governance models that ensure equitable access and prevent concentration of informational power in a few corporate or state actors.

Third, further work is needed on institutional reforms that align incentives with accurate measurement and loss reduction. This includes comparative analyses of regulatory frameworks, experiments with mandatory and voluntary reporting schemes, and evaluation of financial instruments such as subsidies, penalties or performance contracts that might support more honest and granular data (Spang et al., 2019; Alexander et al., 2017). In line with the framework's institutional component (Section 6.1.4), study designs could include comparative policy analysis across jurisdictions, natural experiments around reporting reforms, and evaluations of data-sharing agreements or incentive mechanisms. RCR is particularly well placed for such research given its focus on policy-relevant resource governance.

Fourth, the development and testing of multi-scale, hybrid quantification frameworks should become a methodological priority. Integrating field measurements, surveys, national statistics and modelling within coherent CAS-informed designs will require methodological innovation and careful validation across commodity chains and regions. Cross-case comparisons and meta-analyses could help identify which combinations of methods perform best in which contexts, extending the critical reviews already emerging in the FLW literature (Chauhan et al., 2021; Hoehn et al., 2023). This corresponds to the framework's multi-method and systemic modelling components (Sections 6.1.3 and 6.1.6). Priority designs include multi-site comparative case studies that apply the same nested measurement package across

contrasting contexts, as well as uncertainty quantification and out-of-sample validation when modelling is used.

The broader socio-economic and environmental impact assessment of upstream loss remains underdeveloped. Future research should integrate LCA, footprinting, and distributional analysis to understand who ultimately bears the costs of loss and how reductions interact with other sustainability goals, such as livelihoods, resilience, and biodiversity (Jia et al., 2023; Boiteau and Pingali, 2022). This agenda is strengthened when coupled with qualitative inquiry into who bears the costs of loss and who benefits from loss reduction, consistent with the framework's attention to power and governance. Such work would move the field beyond a narrow focus on tonnes lost toward a more holistic evaluation of the stakes.

### **2.3.8 Conclusion and Contributions**

This review has synthesised evidence from 95 empirical studies on upstream food loss quantification and shown that current practice is marked by definitional heterogeneity, methodological fragmentation and strong institutional constraints. The review contributes (i) a taxonomy of upstream food loss quantification methods (Table 4); (ii) a synthesis of the implications of system complexity and cross-scale measurement gaps (Tables 5 and 6); and (iii) an integrated framework linking methodological choices to institutional incentives and governance structures. Many of the concerns raised in RCR's leading FLW contributions, such as inconsistent system boundaries, limited method transparency, and a focus on downstream waste, were confirmed and extended to new regions and commodities (Chaboud and Daviron, 2017; Caldeira et al., 2019; Hoehn et al., 2023). The analysis suggests that mismeasurement is not an incidental problem but a structural feature of how agrifood systems and their governance have evolved.

By combining CAS and Institutional Theory, the paper proposes an integrated framework that repositions upstream loss quantification as a dynamic, multi-scale and politically embedded process. The framework contributes conceptually by articulating how feedback, emergence and power relations jointly structure what is measured and what remains invisible; methodologically by outlining multi-method, cross-scale and participatory strategies that can be tailored to diverse contexts; and practically by identifying leverage points for policy and institutional reform. These contributions align with and extend RCR's priority agenda on resource-efficient and evidence-based transitions in food systems.

The study has limitations. It focuses on peer-reviewed, English-language literature and may therefore under-represent local studies and grey literature, particularly in low and middle-

income contexts. The framework is conceptual and requires empirical testing across different supply chains and governance settings. Nevertheless, by synthesising state-of-the-art research from RCR and related journals, and by situating measurement problems within a broader systems and institutional perspective, the paper provides a foundation for more rigorous, reflexive, and equitable approaches to quantifying and ultimately reducing upstream food loss.

## **2.4 The Digital Transformation of Agri-food Supply Chains**

### **2.4.1 Overview**

Digital technologies have become central to contemporary discussions on food system reform, particularly as proposed solutions to persistent challenges of food loss across agri-food supply chains. The progressive stages of digitisation, digitalisation, and digital transformation are frequently presented through a lens of techno-optimism that emphasises linear efficiency gains and sustainability improvements. However, this narrative requires critical interrogation as it often obscures the complex socio-political, infrastructural, and ecological contexts within which these technologies operate.

Digitisation, converting analogue data into digital formats, is often positioned as the foundational step toward efficiency in agri-food contexts. Examples include digitising yield records or implementing basic sensors in storage units that reportedly reduce food loss (Onwude et al., 2020). Yet, this process frequently amounts to mere data accumulation rather than actionable insight. If data remain siloed, inaccessible, or inequitably distributed, digitisation serves primarily as a technological credential rather than a substantive intervention (Anastasiadis et al., 2018). Small-scale farmers face significant barriers to adoption due to cost constraints and limited technological infrastructure (Achieng, 2023), raising questions about who benefits from even this most basic level of digital transformation.

Digitalisation builds upon digitisation by embedding digital tools into operational workflows, IoT-enabled temperature tracking, AI-powered spoilage prediction, and cloud-based inventory management systems that promise process efficiencies with documented food loss reductions (Jagtap and Rahimifard, 2019; Achieng, 2023). However, these claims warrant scepticism. Digitalisation introduces new inefficiencies, including data overload, limited interoperability between systems, and frequently misaligned incentives between supply chain actors. Most crucially, digitalisation presumes a stable technological environment with reliable connectivity, consistent power supply, and adequate technical support, conditions largely absent in resource-constrained or rural contexts where significant food loss occurs (Müller et al., 2018).

Furthermore, the interoperability challenges between different IoT systems often prevent seamless integration across supply chains (Ibrahim et al., 2023), creating digital islands rather than cohesive systems. Emerging concerns around data privacy in AI-driven food logistics, job displacement in manual logistics roles, and the creation of new dependencies on external technology providers also undermine the promised efficiency gains.

Digital transformation, the most far-reaching stage, involves the systemic reconfiguration of supply chains and business models using advanced technologies, blockchain, digital twins, and predictive analytics. It claims to reduce food loss by an impressive 40-60% (Tzachor et al., 2022). However, these technologies require sophisticated infrastructure, high levels of technical literacy, and institutional reform that remain largely inaccessible to smallholders and cooperatives, particularly in the Global South (Annosi et al., 2020; Akyazi et al., 2020).

The resultant risk is a two-speed food system wherein digital elites, typically large corporations and well-resourced actors, reap efficiency gains while peripheral actors become increasingly marginalised. As Tzachor et al. (2022) acknowledge, large corporations often dominate digital transformation initiatives, potentially widening wealth gaps and excluding smaller players from the purported benefits. This *corporatisation* of digital agriculture raises profound questions about power, control, and equity in future food systems. A summary of the differences between digitisation, digitalisation and digital transformation is presented in the Comparative Table 7 below.

Table 7: Digitisation, Digitalisation, and Digital Transformation in Agrifood Supply Chains (Food Loss Focus)

| Aspect                                   | Digitisation                                                                                                                                 | Digitalisation                                                                                                                       | Digital Transformation                                                                                                                                                  |
|------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Definition</b>                        | Basic conversion of analogue inputs (e.g., farm records, temperature logs) into digital formats for storage and transmission (Jamous, 2018). | Integration of digital tools (e.g., sensors, software) to enhance and automate existing processes (Wibowo and Article Info, 2023).   | System-wide redesign using advanced technologies to create new business models and data ecosystems (Trevisan and Formentini, 2024).                                     |
| <b>Theoretical Focus</b>                 | Information encoding and digitised data availability; foundational for further interventions (Blahun, 2023).                                 | Process efficiency, monitoring, and control via digital tools, leading to incremental operational improvement (Onwude et al., 2020). | Strategic transformation of operations through predictive, interconnected systems and AI-driven decision loops (Tzachor et al., 2022).                                  |
| <b>Scope</b>                             | Narrow, affects data recording and access only.                                                                                              | Moderate, optimises specific stages like storage, transport, or inventory.                                                           | Broad, reconfigures relationships, value creation, and governance across the entire supply chain.                                                                       |
| <b>Technologies Used</b>                 | Barcode scanners, RFID, IoT temperature loggers (Fernandez et al., 2023).                                                                    | Cloud platforms, AI-based demand prediction, IoT networks, ERP systems (Achieng, 2023).                                              | Blockchain, Digital Twins, autonomous logistics, distributed ledgers, platform economies (Tzachor et al., 2022).                                                        |
| <b>Impact on Food Loss Reduction</b>     | Minimises human error and ensures basic compliance in storage/transport (Onwude et al., 2020).                                               | Improves responsiveness, shelf-life prediction, and demand alignment (Achieng, 2023).                                                | Enables dynamic traceability, systemic transparency, and waste-preventing simulations (Tzachor et al., 2022; Kayikci et al., 2020).                                     |
| <b>Example Applications</b>              | Farmers log harvest yields via mobile apps; cold storage units use RFID tags (Fernandez et al., 2023).                                       | AI-based cold chain monitoring flags failures before spoilage occurs; cloud ERP tools align supply with demand (Achieng, 2023).      | Blockchain used to verify origin and freshness; Digital Twins model end-to-end supply chain scenarios for loss mitigation (Ibrahim et al., 2023; Verdouw et al., 2021). |
| <b>Policy and Regulatory Constraints</b> | Lack of uniform digital recordkeeping standards; weak national ICT policies (Trevisan and Formentini, 2024).                                 | Fragmented food safety and data privacy laws; absence of mandates on IoT interoperability (Ibrahim et al., 2023).                    | Jurisdictional uncertainty on blockchain legality, cross-border traceability, and AI accountability (Tzachor et al., 2022).                                             |
| <b>Ethical and Social Concerns</b>       | Risk of digital exclusion for smallholder farmers lacking digital tools (Achieng, 2023).                                                     | Displacement of low-skilled labour due to automation in storage/logistics (Ibrahim et al., 2023).                                    | Consolidation of power among large agri-tech firms; data asymmetry may marginalise less-digitised actors (Annosi et al., 2020).                                         |
| <b>Industry-Specific Variation</b>       | Effective in grain supply chains where weight/volume tracking matters most.                                                                  | Perishable goods (e.g., dairy, seafood) benefit from IoT-based monitoring for cold chain integrity.                                  | Aquaculture and meat processing adopt predictive AI and digital twins for end-to-end spoilage prevention (Pylianidis et al., 2021; Marvin et al., 2022).                |

### 2.4.2 Digital Transparency and Power Asymmetries in Agri-food Systems: An Example of Blockchain Technology

Blockchain technology exemplifies both the promise and contradictions of digital transformation in agri-food supply chains. Proponents emphasise its capacity to ensure farm-to-fork transparency, reduce food fraud, and build stakeholder trust (Ibrahim et al., 2023; Zhao et al., 2019). Kamilaris et al. (2019) present a clear illustration of adopting blockchain technology across AFSC as depicted in Fig. 7. Yet critical examination reveals substantial implementation challenges beyond technical complexity.

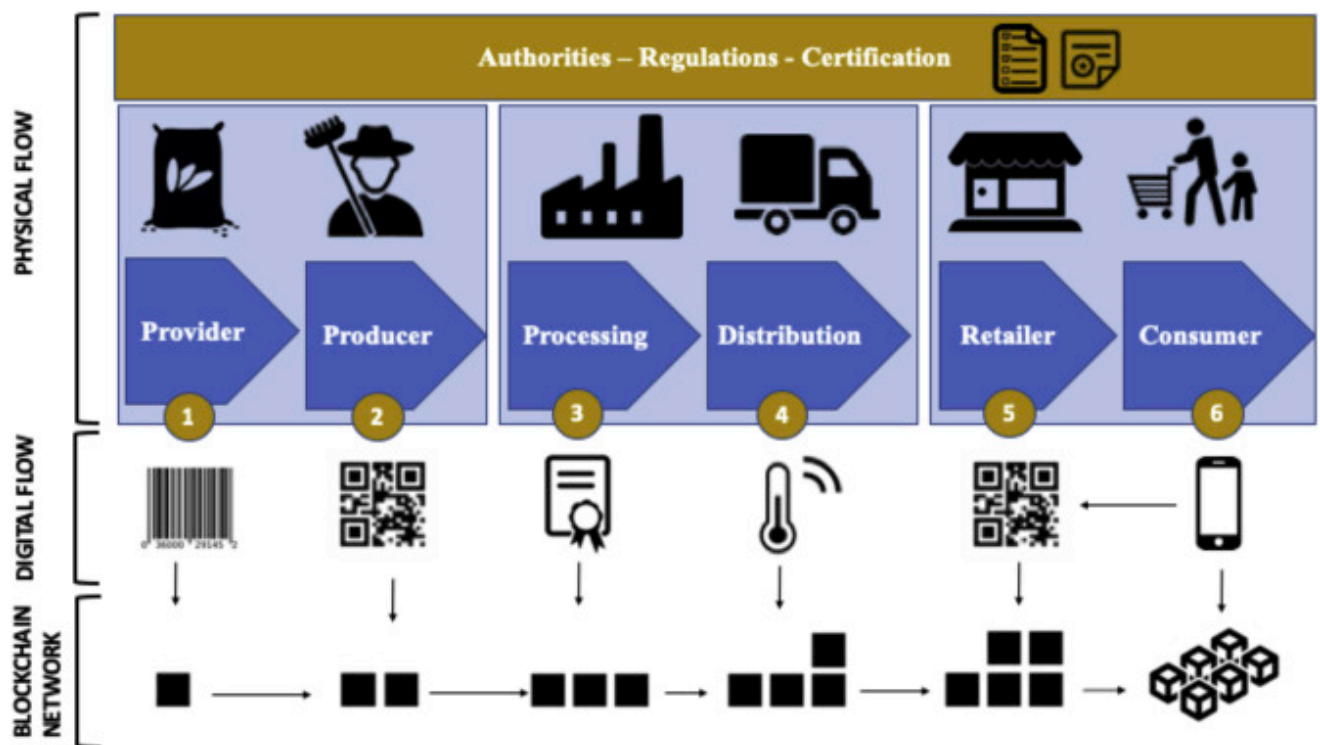


Fig. 7: A simplified Agri-food Supply Chain System (Source: Kamilaris et al., 2019)

Blockchain systems typically involve high computational costs, demand complex interfaces, and require robust connectivity, and prerequisites rarely met in the diverse contexts of global food production. Furthermore, the irreversible nature of blockchain transactions and unclear regulatory frameworks raise serious concerns about farmer data privacy and system governance (Kayikci et al., 2020; Trevisan and Formentini, 2024).

While Blockchain-as-a-Service (BaaS) platforms are lowering entry barriers, they simultaneously centralise control in the hands of service providers, creating new forms of digital dependency. The ethical issues related to control, transparency, and power

asymmetries persist largely unaddressed in mainstream blockchain discourse, which tends to privilege technical possibilities over social impacts.

### **2.4.3 Efficiency as Conditional and Contextual**

The techno-optimistic framing of digital technologies as efficiency drivers obscures their deeply contextual outcomes. In poorly connected regions, IoT systems frequently malfunction or fail. Where trust deficits exist between supply chain actors, data sharing breaks down regardless of technical capabilities. Even more troubling, high-tech systems often displace locally adaptive practices without offering robust alternatives, creating new vulnerabilities in food systems.

Furthermore, efficiency gains in one supply chain node may simply displace inefficiencies elsewhere rather than eliminate them. Improved harvesting technologies, for example, may increase production volume without corresponding enhancements in cold storage capacity, thus shifting spoilage downstream rather than preventing it (Chauhan et al., 2021). This reveals efficiency not as a linear outcome but as contingent, fragmented, and mediated by complex sociotechnical factors that resist technological quick fixes.

### **2.4.4 The Environmental Costs of Digital Solutions**

While digitisation is frequently positioned as a sustainability tool for reducing food loss and its associated environmental impacts, the ecological footprint of the digital infrastructure itself remains conspicuously absent from most analyses. Blockchain validation consumes significant energy; IoT devices contribute to mounting e-waste; and data centres demand constant cooling and substantial water usage (Aschemann-Witzel and Stangherlin, 2021). These environmental costs may partially or entirely offset the ecological gains achieved through food loss reduction, creating a sustainability paradox rarely acknowledged in techno-optimistic accounts.

Moreover, the extractive processes required for manufacturing digital devices, including mining for rare earth minerals, create additional environmental and social harms at sites of extraction that remain invisible within most food system analyses. A nuanced accounting of digital transformation must include these distributed ecological costs rather than externalising them from evaluation frameworks.

### **2.4.5 Toward Critical Digital Transformation**

What emerges from this critical examination is the urgent need to challenge the assumption that digitalisation is inherently beneficial or universally applicable in agri-food contexts. Rather than prescribing technology-first interventions, future strategies must begin with contextual



diagnostics, localised needs assessments, and co-designed solutions that centre marginalised voices.

Digital tools should augment rather than override Indigenous knowledge systems, informal market structures, and local adaptive capacities that have evolved in specific ecological and social contexts. Critically, digital transformation should not be evaluated solely through narrow efficiency metrics like throughput or return on investment but by its ability to build resilient, inclusive, and ethically governed agri-food systems that serve the interests of producers and consumers alike.

Implementing digital technologies, including blockchain and AI-driven forecasting, introduces unforeseen challenges that undermine supply chain resilience rather than enhancing it. Predictive models that do not account for specific agricultural settings lead to algorithmic inefficiencies through inaccurate forecasting and resource misallocation (Mishra et al., 2021). Workforce-related inefficiencies, such as resistance to digital adoption and limited digital literacy among farmers, impede effective implementation (Brunetti et al., 2020). The accessibility and utility of digital solutions are constrained by data governance challenges, such as interoperability constraints and power imbalances across digital platforms, thereby perpetuating existing inequalities (Klerkx and Rose, 2020). Table 8 synthesises these digital transformation inefficiencies, categorising the key drivers, impacts, and illustrative examples across nine distinct categories of operational and systemic challenges.

Table 8: Digital Transformation Inefficiencies in Agri-Food Supply Chains

| Category of Inefficiency                    | Description                                                                   | Key Drivers                                                                                                                                                                                                                   | Impact                                                                                                                                                 | Examples                                                                                              |
|---------------------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| 1. Process and Workflow Inefficiencies      | Digital solutions are introduced without reengineering operational processes. | Digital tools are layered onto existing workflows without optimization. Underlying processes are not critically examined. There is a disconnect between digital capabilities and operational realities (Kamble et al., 2020). | Redundant work streams emerge. Multiple data entry is required. Traditional paper-based systems often persist alongside digital systems.               | Blockchain-based traceability systems implemented without redesigning inventory management workflows. |
| 2. Data and Interoperability Inefficiencies | Fragmented data and incompatible digital systems hinder integration.          | Disparate digital platforms lack communication pathways. Standardized data formats and protocols are missing. Information silos prevent effective knowledge sharing (Lin et al., 2020).                                       | Data collected in one area cannot be used in others. Critical information is not shared across actors. The value of collected data remains unrealized. | IoT sensors collect temperature data in cold storage but cannot integrate it with transport systems.  |

|                                                                   |                                                                      |                                                                                                                                                                                                              |                                                                                                                                                         |                                                                                                                              |
|-------------------------------------------------------------------|----------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
| 3. Workforce and Cultural Inefficiencies                          | Organizational culture and skill gaps impede digital adoption.       | Training and skills development are inadequate. Resistance to change is widespread. Digital tools often conflict with traditional work habits (Brunetti et al., 2020).                                       | Technology is underutilized. Data-driven decisions are resisted. Parallel reliance on experiential judgment persists.                                   | Digital insights are ignored in favor of traditional judgment in agricultural settings.                                      |
| 4. Economic and Incentive Misalignment Inefficiencies             | Digital transitions impose unequal costs and benefits across actors. | Mandated adoption disregards smaller actors' economic constraints. Costs and benefits are unevenly distributed. Implementation costs often outweigh perceived benefits (Agarwal et al., 2021).               | Stakeholders adopt technologies reluctantly. Engagement remains minimal. Digital solutions are superficially implemented.                               | Smaller partners bear costs of digital transition without realizing significant benefits.                                    |
| 5. Algorithmic and Automation Inefficiencies                      | Digital tools fail to reflect complex, context-specific realities.   | AI and machine learning lack contextual adaptability. Training data are biased. Local standards and cultural variation are overlooked (Mishra et al., 2021).                                                 | Edible produce may be misclassified as waste. Forecasting errors distort supply decisions. Interconnected systems replicate and amplify these errors.   | Automated quality systems misclassify produce due to training data bias; AI demand models ignore local consumption patterns. |
| 6. Cybersecurity and Data Governance Inefficiencies               | Weak data protection and governance discourage information sharing.  | Security protocols are often incomplete. Data governance practices are insufficient. Stakeholders hesitate to share sensitive data. Regulatory fragmentation complicates compliance (Tsolakis et al., 2021). | Systems are vulnerable to breaches. Trust in digital platforms erodes. Information sharing is constrained. Cross-border coordination becomes difficult. | Varying privacy laws and data sovereignty issues obstruct international data sharing.                                        |
| 7. Policy Implementation and Regulatory Compliance Inefficiencies | Digital adoption is poorly aligned with regulatory frameworks.       | Regulatory implications are poorly understood. Technology and compliance efforts are uncoordinated. Multiple legal frameworks overlap in cross-border trade (Hobbs, 2021).                                   | Compliance becomes redundant and burdensome. Administrative load increases. Regulatory uncertainty stifles innovation.                                  | Digital tools are underused due to unclear regulatory expectations in international supply chains.                           |
| 8. Network Coordination and Collaboration Inefficiencies          | Digital platforms fail to support collaborative governance.          | Synchronization of digital adoption across actors is weak. Adoption remains fragmented. Stakeholder engagement is insufficient (Gonela and Zhang, 2019).                                                     | Isolated solutions do not address systemic inefficiencies. Collaboration is limited. Integrated supply chain benefits are unrealized.                   | Digital platforms fail to foster meaningful collaboration due to weak engagement strategies.                                 |
| 9. Investment and Resource Allocation Inefficiencies              | Poor prioritization and implementation of digital investments.       | Resources are spent on complex tools while basic needs go unmet. Investment decisions lack strategic alignment. Change management support is inadequate (Klerkx and Rose, 2020).                             | Technologies are underused. Returns on investment are low. Expected benefits are not delivered.                                                         | High-cost digital systems fail due to limited training and poor implementation planning.                                     |

The synthesis of constraints and inefficiencies in digital transformation reveals complex interdependencies that significantly impact food loss reduction efforts in AFSCs. This classification framework contributes to both theoretical understanding and practical implementation by highlighting how different categories of constraints and inefficiencies interact to influence digital transformation outcomes.

The interaction between constraints and inefficiencies creates a dynamic environment where addressing one category often reveals or amplifies challenges in others. For instance, while infrastructural constraints may limit digital connectivity, inefficiencies in data governance and system integration often prevent organisations from maximising value from available digital capabilities. This interconnected nature of digital transformation barriers suggests that successful food loss reduction requires a systemic approach that simultaneously addresses both structural limitations and operational inefficiencies. The framework provides a theoretical foundation for understanding how different barriers to digital transformation manifest across various contexts and supply chain configurations (Akkerman et al., 2020; Christopher, 2016).

The classification framework extends existing theory by incorporating the unique characteristics of AFSCs into digital transformation discourse. Traditional approaches to digital transformation often fail to account for the biological nature of food products, the complexity of agricultural production systems, and the social dimensions of food supply chains. This research addresses this gap by explicitly considering how these sector-specific factors influence constraints and inefficiencies in digital adoption. The framework demonstrates that successful digital transformation in AFSCs requires careful consideration of technical and socio-technical elements, challenging simplified technology-centric approaches to digital innovation (Tilson et al., 2010; Klerkx and Rose, 2020).

From a practical perspective, the classification framework provides organisations with a structured approach to analysing and addressing barriers to digital transformation. The framework enables more targeted and effective intervention strategies by distinguishing between constraints that require systemic intervention and inefficiencies that can be addressed through operational improvements. This distinction is crucial in resource-constrained environments where organisations must carefully prioritise digital transformation investments. The framework suggests that while constraints may require long-term strategic initiatives and multi-stakeholder collaboration, many inefficiencies can be addressed through

improved process design, better change management, and enhanced coordination mechanisms (Tsolakis et al., 2021).

#### **2.4.6 Summary**

Digitisation, digitalisation, and digital transformation are frequently presented as a linear, progressive trajectory toward agri-food optimisation. However, their success in reducing food loss and achieving sustainable efficiency depends on a complex web of infrastructural, institutional, social, and ecological variables that resist technological determinism. Without explicitly addressing structural inequality, governance gaps, and ecological costs, digital strategies risk reproducing and potentially amplifying the very inefficiencies and injustices they purport to resolve.

Therefore, a fundamentally recalibrated digital agenda is needed, one that privileges adaptive digital ecosystems over technocratic blueprints, centres equity and environmental limits in technology design, and evaluates digital interventions not by their technical sophistication but by their contribution to just and sustainable food futures. Only through such critical engagement can digital transformation fulfil its potential as a tool for genuine food system reform rather than merely reinforcing existing power structures under a veneer of technological innovation.

### **2.5 Multisided Platforms in Agri-food Supply Chains**

#### **2.5.1 Overview**

Digital platformisation has increasingly contributed to the steady transformation of industry market structures (Gawer, 2022), redefining how value is created and distributed (Lehdonvirta et al., 2020; Sauvagerd et al., 2024). Platforms are digital intermediaries that bridge the gap between technical infrastructure and organisational elements (Gawer, 2014) to enable exchanges and interactions (Hagiu and Wright, 2015). These platforms can be two-sided or multi-sided if they facilitate interactions between different groups of users (for example, by sharing information or conducting commerce) to generate value and maximise resource flows (Lehdonvirta et al., 2020). The technical layer of platforms provides a digital infrastructure through APIs, analytics and cloud services to facilitate transactions and algorithmic coordination (Sauvagerd et al., 2024). These digital platforms support interoperability among user communities across multiple market segments (Brynjolfsson and McAfee, 2014; McAfee, 2018; McIntyre et al., 2021).

MSPs are transforming agriculture by connecting farmers, suppliers, agribusinesses, and consumers through digital tools that improve resource management, precision farming, and market access (Hagiu and Wright, 2015). Platforms like Bayer's Climate FieldView and John Deere Operations Centre facilitate data-driven decision-making. African platforms such as Hello Tractor and Twiga Foods enhance mechanisation and supply chain efficiency (Hermans et al., 2017). Despite their advantages, MSPs present challenges such as high adoption costs, vendor lock-in, and data privacy concerns (Evans, 2013). Smallholder farmers' reliance on MSPs can also exacerbate power asymmetries, consolidating control among large agribusinesses that dictate pricing, market access, and data usage (Belleflamme and Peitz, 2017).

MSPs follow distinct business models, primarily transaction-based, innovation-driven, and integrated approaches (Yablonsky, 2018). Transaction-based models, which facilitate direct exchanges between farmers and service providers, are more scalable in Africa due to lower entry barriers (Nobrega et al., 2023). In contrast, integrated models, common among large multinational agribusinesses, combine data analytics, supply chains, and digital services. However, they often require significant investment and infrastructure, limiting accessibility for smallholder farmers (Yang et al., 2017).

As digital platforms continue to evolve, addressing scalability, power dynamics, and data governance will be critical to ensuring inclusive growth and sustainable development in agriculture (Hagiu, 2007). Multi-Sided Platforms (MSPs) in agriculture vary widely in scope, features, business models, advantages, and limitations. While global MSPs often focus on large-scale agribusinesses and data-driven farming, African MSPs address smallholder farmers' needs, supply chain inefficiencies, and market access challenges. While MSPs demonstrate significant potential for transforming agrifood supply chains, their practical implementation faces several operational and structural challenges. Understanding these challenges requires examining how platforms operate and their limitations in different market contexts.

### **2.5.2 Current State and Challenges**

Platforms operate in three distinct ways: *transaction platforms* (such as Farmers' Market Online or Too Good To Go) create value by facilitating direct transactions between buyers and sellers; *innovation platforms* (such as John Deere's Developer Platform or IBM Food Trust) provide back-end technology for further digital innovation; and *integrated platforms* (such as Alibaba's Rural Taobao or Pinduoduo's Agriculture Initiative) blend the two strategies, aggregating transactional data for innovation with their tech platform to scale marketplaces (Gawer, 2014; Evans and Gawer, 2016; Parker et al., 2016). Sauvagerd et al. (2024) define

platformisation as reshaping market dynamics through digital platforms where data analytics, artificial intelligence (AI) and cloud computing serve as operations' bases.

Beyond being technology-dependent, multisided platforms act as market controllers, adopting governance mechanisms and policies that govern participation, data flows, and revenue allocation (Rahman et al., 2024). Historically conceptualised as physical and digital structures (Sabourin, 2016), MSPs have become central in the digital economy, with firms such as Uber, Amazon, and the iOS App Store exemplifying their organisational architecture (Gawer, 2022). Such organisational structures, such as pricing or data practices, can lead to power differentials that privilege platform owners over others (Rahman et al., 2024). MSPs do not simply reduce transaction fees; they change market governance, restricting access, pricing, and data flow between participants, often reinforcing platform owner dominance (Rahman et al., 2024). This control dynamic is particularly evident in financial services platforms where data-based pricing and service models exacerbate market dependence on platform owners (Agarwal and Assenova, 2023).

In AFSCs, MSPs are increasingly positioned as strategic enablers of digital transformation (Buyssens and Viaene, 2024; Gupta et al., 2024), offering potential solutions to minimise food loss, enhance collaboration, and increase market access (Principato et al., 2023; Chandrasiri et al., 2024). Platforms provide farmers and supply chain participants more convenient access to pricing information, agronomic data, and input markets (Suali et al., 2024). For instance, digital tools facilitating e-commerce food sales have increased supply chain resilience in response to exogenous shocks. MSPs reduce disruptions and streamline logistics through improved structural flexibility and data sharing (Suali et al., 2024).

However, the idealisation of MSPs as agents of market efficiency is tempered by practical drawbacks. According to Sauvagerd et al. (2024), agriculture demonstrates how platformisation can reinforce, not undermine, market concentration. As Big Tech companies create digital platforms together, monopolising agrifood data networks and marginalising small players. This control tends to create fragmented data environments to which few influential individuals have access. Rahman et al. (2024) deepen this critique by highlighting structural power inequalities in MSP design. Platform providers are typically in charge of algorithms and data flows, setting market entry rules and denying data access to those who lack the power. This is the same dynamic observed in financial services platforms where data-based pricing and service models exacerbate market dependence on platform owners (Agarwal and Assenova, 2023).

Some studies challenge the presumption that MSPs uniformly improve market efficiency, noting that platform algorithms tend to be short-term and short-lasting (Malgonde et al., 2022). Other studies caution against market lock-in, in which platforms dominate market access to block competition (Hagiu, 2014). These issues are most acute in agri-food supply chains, where smallholder farmers face institutional impediments to technology use and data ownership (Suali et al., 2024). Existing theoretical models do not consider that MSPs act as enablers and guardians. Hagiu and Wright (2020) state that MSPs operate on a spectrum between co-creating value and generating profits. In agriculture, this double purpose manifests itself in data platforms providing decision-support tools and reselling aggregated farm data, sometimes without fair value redistribution.

The balance between efficiency benefits and structural risks is a key consideration when deploying MSPs in agri-food supply chains. Sauvagerd et al. (2024) emphasise how the agrifood industry's historical concentration magnifies the platformisation threat, where powerhouses strengthen their market position. Meanwhile, Rahman et al. (2024) advocate for more accountable structures, pointing towards multi-level accountability systems that balance the power of platform owners and more minor market actors. MSPs can transform supply chain visibility, productivity, and resilience, but they pose structural threats in agri-food chains, especially in resource-poor settings (such as the tomato supply chain in Nigeria). Theoretical models of network effects, institutional gaps, and platform power dynamics both support and warn us about the necessity of fair governance and data availability when designing digital platforms for agri-food supply chains.

This study's section explores multisided platforms (MSPs) on three fronts. First, it explores MSPs' conceptual underpinnings and pillars and outlines gaps in the available contextual knowledge and conceptual frameworks. Second, it focuses on how MSPs are strategically deployed within agrifood supply chains and emerging trends. Finally, it ranks MSPs in two critical areas: the digitalisation of AFSCs and their ability to improve food security through reduced food loss and waste.

These identified challenges in MSP implementation and governance highlight the need for a robust theoretical framework to explain platform dynamics in agricultural contexts. A unified theoretical approach combining network effects, institutional void considerations, and platform governance principles can help address these operational complexities.

### **2.5.3 Theoretical Framework for Agrifood MSPs**

Theoretical understanding of MSPs in the AFSCs requires a new, multilayered conceptual model that unifies three primary theoretical perspectives: network effects (Øverby and

Audestad, 2021), institutional void (Agarwal and Assenova, 2024) and platform governance (Chen et al., 2022). These theories have historically been applied to digital platforms in isolation, but their interaction in agrifood contexts generates distinct dynamics unaccounted for by conventional platform models (Hagiu and Wright, 2015; Rochet and Tirole, 2003; Gawer, 2022). This part creates a synergistic theoretical framework for how these perspectives fit together in a dynamic triangle in which each reflects on and affects the others.

According to Øverby and Audestad (2021), network effects on MSPs are positive feedback mechanisms in which participants are more likely to participate in their own group (same-side effects) or between different user groups (cross-side effects), following earlier models of Caillaud and Jullien (2003) and Parker and Van Alstyne (2005). However, studies have observed that network effects among agrifood MSPs differ significantly from the more conventional digital platforms because of the nature of agrifood production and market dynamics (Hermans et al., 2017; Wang, 2019). Unlike continuous digital services, agrifood network effects are seasonal and induce surges and declines in platform usage at intervals (Rochet and Tirole, 2003; Hagiu and Wright, 2015; Tavalaei et al., 2024). This seasonality contradicts the traditional network effect theory that assumes continuous value production from growing platform usage (Øverby and Audestad, 2021). In agrifood settings, the importance of network effects varies from season to season and requires platforms to sustain user engagement during production interruptions. Fig. 8 illustrates the network effects operating within typical multi-sided platforms, depicting how same-side and cross-side effects generate value across user groups.

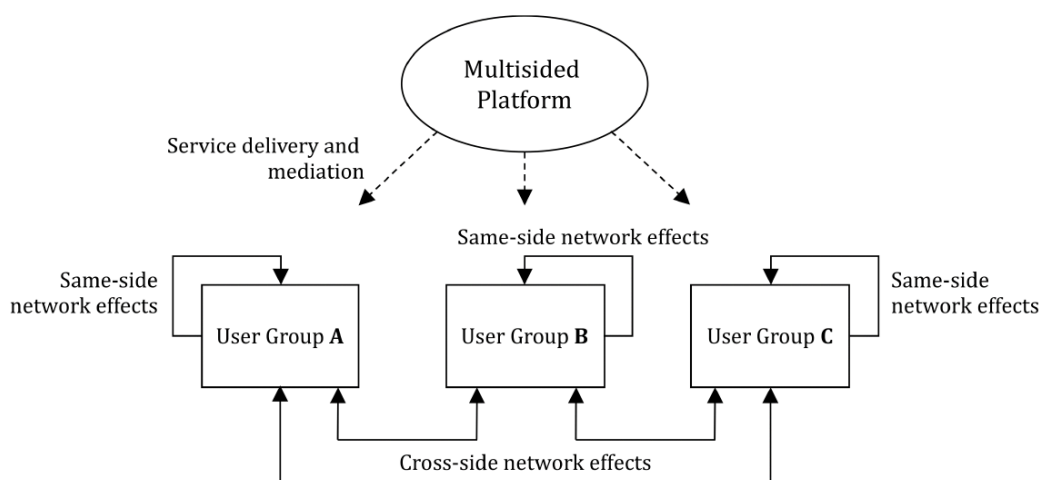


Fig. 8: Network Effects in Typical MSPs (Øverby and Audestad, 2021)



The intersection of oligopolistic markets and platform dynamics in agriculture further strains classical MSP views. While the MSP theoretical argument assumes positive feedback loops for growth and value creation from network effects (Parker et al., 2016; Evans and Schmalensee, 2016), oligopolistic platformisation in agriculture illustrates how these can be effectively limited and managed. As Sauvagerd et al. (2024) maintain, dominant firms actively regulate access to the market, data visibility, and value distribution, creating bounded network effects in which strategic data-sharing decisions among dominant actors limit the flow of value. This breaks with the traditional MSP theory regarding decentralised communication and participation (Cutolo and Kenney, 2021).

The concentration market effect of oligopolistic platformisation allows incumbent companies to build selective network effects by specifying which actors have access to which features or data on the platform. This matches Hagiu's (2014) point that MSPs manage infrastructure and access systems but goes even further by illustrating how oligopolies can de-emphasise those systems to enhance market control. Cross-platform network effects in agrifood platforms are very explicitly constrained by a strategic oligopolistic rivalry that creates silos of data and diminishes overall network value (Sauvagerd et al., 2024). This goes against traditional MSP theory's focus on creating value through mass network participation (Rochet and Tirole, 2003).

These network effects dynamics interact continuously with institutional voids, usually present in upstream agrifood markets (Khanna and Palepu, 1997), forming another side of the dynamic triangle that describes MSPs in AFSCs. Institutional voids in multisided platforms are the gaps in market-enabling intermediaries that connect buyers and sellers in digital platform markets (Khanna and Palepu, 2010; Malik et al., 2021). These manifest in three forms: lack of credibility enhancement systems to build trust between parties, inadequate information analysis infrastructure, which creates asymmetries, and limited transaction facilitation mechanisms to make market transactions possible (Malik et al., 2021). Particularly in emerging markets, these institutional voids can potentially reinforce power imbalances between platform users even as platforms try to address these vacuums (Khanna and Palepu, 2010; Malik et al., 2021).

Agrifood MSPs address institutional voids using digital infrastructure that keeps pace with seasonal cash flows, verifying perishable goods and determining prices in a regionally diverse environment (Agarwal and Assenova, 2023; Mair and Marti, 2009). However, value creation through these institutional solutions relies critically on network effects. For example, price discovery mechanisms are more predictable when the network participation grows, but seasonal production constrains this participation. This creates a dynamic where institutional

void-filling must balance the seasonality of agrifood production with the need for continuous platform engagement (Nobrega et al., 2024; Chen et al., 2021).

Platform governance, forming the third side of the dynamic triangle, takes on new dimensions when integrated with these agrifood network effects and institutional void considerations. Conventional MSP governance describes the practices and regulations that platform owners employ to orchestrate interactions among platform users by both incentive elements (share of resources, dissemination of information, allocation of autonomy, reward systems) and control elements (regulation of access, output monitoring, shaping of behaviour, relationship management). These are mainly implemented through digital design elements to balance value creation and appropriation while addressing market frictions (Chen et al., 2022; Malik et al., 2021). Therefore, AFSC MSPs must develop governance structures considering inclusive participation, equitable value distribution, and varying technological capabilities among participants (Chen et al., 2021; Gawer, 2014). In addition, AFSC platform governance needs to address power asymmetries among stakeholders and market-concentration risks (Gawer, 2014). Fig. 9 presents the MSP Dynamic Triangle, illustrating the interplay between network effects, institutional void-filling, and platform governance that characterises agri-food multi-sided platforms.

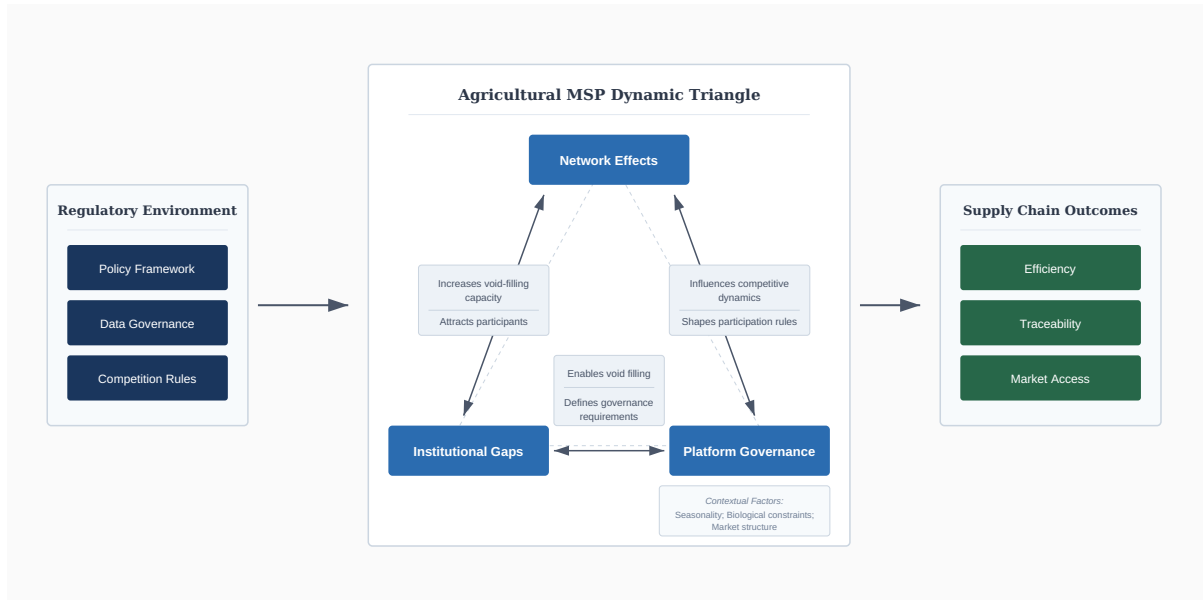


Fig. 9: The MSP Dynamic Triangle

These governance challenges play out differently across the three agrifood MSPs: transaction, innovation, and integrated platforms. Every platform is an individual mix of network effects, institutional void-filling, and governance (Gawer, 2014; Evans and Gawer, 2016; Parker et al., 2016). Therefore, each platform type requires specific configurations of:

1. Safeguards against the exploitation of small actors.
2. Equitable pricing and revenue sharing to mitigate production risk.
3. Data rights and privacy mechanisms that avoid information asymmetry exploitation.
4. Transparent decision-making across stakeholder groups.
5. Competition policies to prevent platform capture by dominant actors.
6. Guidelines for sustainability and resource use.
7. Efforts to create supportive environments for technology adoption and capability development (Chen et al., 2022; Gawer, 2014; Malik et al., 2021)

These governance features enable AFSC MSPs to balance value-creation and capture in a way that drives fair development outcomes and avoids harmful market concentration.

#### **2.5.4 Critical Synthesis of Digital Agrifood MSPs**

Digital MSPs reshape agrifood value chains through distinct evolutionary pathways in developed and emerging markets. In Africa, the platforms exhibit a clear dichotomy between globally oriented, technology-intensive solutions and regionally adapted, accessibility-focused platforms. This structural divergence reflects deeper systemic challenges in agrifood digitization.

Global MSPs predominantly pursue integrated business models combining IoT sensors, AI, and predictive analytics (Hussein et al., 2024; Gul and Banday, 2024). Platforms like Climate FieldView and John Deere Operations Center exemplify this approach, embedding sophisticated data analytics within existing agribusiness infrastructure. However, this integration-centric model presents significant barriers for smaller stakeholders, particularly regarding adoption costs and data governance (Issa et al., 2024). African MSPs, conversely, have evolved distinct characteristics addressing local constraints. These platforms prioritise mobile-first solutions and transaction-based models, exemplified by Hello Tractor's mechanisation services and Twiga Foods' supply chain optimisation (Mabaya and Porciello, 2022). This adaptation reflects both infrastructure limitations and the predominance of smallholder farming in African agriculture.

A critical analysis reveals three emergent patterns in MSP evolution:

1. Business model innovation shows increasing divergence between transaction-based and integrated approaches. While global platforms leverage data monetisation and subscription models, African MSPs focus on immediate value creation through direct service provision (Omulo and Kumeh, 2020). This divergence suggests that platform economics in agriculture are not globally uniform but rather highly context-dependent.
2. Second, technological architecture choices reflect distinct development trajectories. Global platforms emphasise comprehensive data integration and advanced analytics, while African MSPs prioritise mobile accessibility and offline functionality (Gavrilova, 2022). This architectural divide raises important questions about the scalability of agrifood digitisation across different contexts.
3. Third, power dynamics within agrifood MSPs reveal concerning trends in data control and market access. Large agribusinesses increasingly leverage platform dominance to consolidate market position, while smallholder farmers face potential disintermediation (Mapanje et al., 2023). This asymmetry challenges assumptions about platforms' role in democratising agrifood markets.

The synthesis of available evidence suggests that agrifood MSPs are not merely technical innovations, but socio-technical systems shaped by regional contexts. Their evolution reflects broader tensions between technological advancement and accessibility, data-driven agriculture and smallholder inclusion, platform economics and agrifood sustainability. These findings contribute to platform theory by demonstrating how sector-specific characteristics influence platform evolution and adoption patterns. They also challenge prevailing assumptions about platform scalability and standardisation in agriculture, suggesting that successful agrifood MSPs must balance technological sophistication with contextual adaptation.

The patterns revealed in platform evolution and adoption highlight specific implementation barriers that must be addressed. These challenges manifest differently across technological, economic, and sociocultural dimensions.

### **2.5.5 Implementation Challenges in Agrifood Supply Chains**

The deployment of multisided platforms in agrifood supply chains faces several distinct challenges that affect platform adoption and sustained engagement. These challenges are particularly salient given the unique characteristics of agrifood production and the diverse stakeholder ecosystem involved in agrifood supply chains. This section examines four primary

categories of implementation challenges: technological infrastructure limitations, economic barriers, sociocultural resistance, and regulatory complexity.

The implementation challenges are highlighted in Table 9, and successful agrifood MSPs must address the following limitations as outlined in Table 9

Table 9: Approaches to Address MSP Challenges

| Approach to Address Limitation                                                              | Description of Approach                                                                                                                             | References                                                                                      |
|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Infrastructure resilience through offline functionality and low-bandwidth operational modes | Implementation of multi-stakeholder platforms (MSPs) to enhance network governance in agrifood systems and improve resilience strategies.           | Thorpe et al. (2021); Hermans et al. (2017); Sartas et al. (2018); Stone and Rahimifard, (2018) |
| Cost structures that accommodate seasonal revenue patterns and varying scales of operation  | Development of adaptive pricing models and flexible financial mechanisms to align with seasonal revenue fluctuations and scalability.               | Wallbach et al. (2019); Teece et al. (2022)                                                     |
| User interface design that considers varying levels of digital literacy                     | Design of inclusive digital platforms with simplified navigation, multilingual support, and assisted user interactions.                             | Hein et al. (2019); Stummer et al., (2018)                                                      |
| Governance frameworks that respect local cultural norms while promoting innovation          | Implementation of culturally sensitive governance models that integrate traditional leadership structures while encouraging digital transformation. | La Sala et al., (2024)                                                                          |
| Compliance mechanisms that can adapt to evolving regulatory requirements                    | Establishment of modular compliance frameworks that enable real-time updates to regulatory policies while ensuring operational continuity.          | Jhaveri et al., (2021); Ti et al., (2022)                                                       |

The interplay between these challenges suggests that successful implementation requires a holistic approach considering both technical and socioeconomic factors. Platform designers must balance the need for sophisticated functionality with the practical limitations of agrifood contexts, while governance structures must accommodate both formal regulatory requirements and informal cultural norms. This analysis of implementation challenges reinforces the importance of considering agrifood MSPs within their specific contextual framework, as discussed in the theoretical model presented earlier. Successfully deploying agrifood MSPs requires technological solutions and careful attention to economic sustainability, social acceptance, and regulatory compliance.

While implementation challenges are universal, their intensity and characteristics vary significantly across regions. Understanding these geographical variations is crucial for developing effective platform strategies.

## **2.6 Strategic Interventions for Minimising Food Loss in Agri-food Supply Chains: A Systematic Literature Review and Conceptual Framework Development** *(Published journal article)*

### **2.6.1 Abstract**

#### **Purpose**

Food loss in agrifood supply chains (AFSCs) drains one-third of global production, undermining food security, natural resources, and climate resilience. Interventions abound but are scattered, sector-bound, and rarely assessed comparatively. This paper develops a systemic benchmarking framework that reconceives food loss not as isolated inefficiency but as an outcome of interacting interventions across supply chain domains.

**Design/methodology/approach:** A systematic review of 102 peer-reviewed studies was conducted following the PRISMA protocol. Evidence was drawn from agricultural sciences, logistics, and operations management, then interpreted through General Systems Theory and Complex Adaptive Systems. This dual lens organised interventions into six domains: contractual, infrastructural, network-based, data-driven, behavioural, and governance, and layered them across enabling, execution, and adaptive tiers.

**Findings:** The framework crystallises into a benchmarking device that maps interventions by levers, metrics, and tools. Vertical readings provide diagnostic clarity within each domain; horizontal readings expose interdependencies that condition resilience. Three recurrent scenarios, adaptive informality, data-governance integration, and transitional hybrid, show how interventions cluster, generating feedback loops and emergent equilibria that shape system trajectories.

**Research limitations/implications:** The review consolidates fragmented evidence but future research must embed longitudinal, cross-regional, and equity-sensitive benchmarking to capture evolving dynamics.

**Practical implications:** The framework offers practitioners and policymakers a roadmap for sequencing and scaling interventions, diagnosing fragility, and aligning strategies to systemic conditions.

**Originality/value:** The study advances benchmarking in AFSCs by moving from static comparison to systemic diagnosis, establishing the first integrated framework for evaluating and orchestrating food loss interventions.

### 2.6.2 Introduction

Food loss across agrifood supply chains (AFSCs) represents one of the most pervasive systemic failures of the global economy. Nearly a third of food produced worldwide fails to reach consumption (Gurralla and Hariga, 2022), eroding food security, depleting natural resources, and accelerating environmental degradation. The literature attributes this to technological bottlenecks (Despoudi *et al.*, 2018), weak infrastructure (Gokarn and Kuthambalayan, 2017), fragmented cold chains, coordination failures (Vernier *et al.*, 2021), and persistent perishability challenges (Jonkman *et al.*, 2019). Each explanation is valuable, yet the persistence of loss points to deeper systemic dynamics rather than isolated deficiencies.

Recent work has begun to capture these dynamics through multiplier and stacking effects (Sengupta *et al.*, 2024). Multiplier effects arise when local inefficiencies cascade downstream, amplifying losses (Raut *et al.*, 2019; Rogers and Dora *et al.*, 2020). Stacking effects occur as small, repeated frictions in production, storage, and distribution accumulate into significant aggregate waste (Barrett *et al.*, 2022; Hamilton *et al.*, 2022). These insights frame food loss as an emergent phenomenon of complex interdependence.

Benchmarking research in this journal has made important inroads into this problem, though typically within bounded domains. Yakovleva, Sarkis and Sloan (2012) established the comparative logic of embedding sustainability in food supply chains. Chauhan *et al.* (2018) benchmarked the determinants of food waste, while Dania *et al.* (2019) developed tools for assessing collaboration quality. More recent studies have extended the scope: Kumar *et al.* (2020) and Aamer *et al.* (2021) benchmarked digital adoption, while Ramos *et al.* (2022) and Kumar *et al.* (2020) benchmarked commodity- and country-specific supply chains. Jacob-John *et al.* (2023) benchmarked alignment with SDG 12.3. Bag (2024) examined SME transitions to net zero, and Gupta and Shankar (2024) benchmarked blockchain-enabled traceability. Collectively, these studies demonstrate the versatility of benchmarking but also reveal its fragmentation: each illuminates a part of the system, yet together they lack an integrative framework.

This paper advances the field by embedding benchmarking within a systems-theoretical architecture. Complex Adaptive Systems (CAS) theory highlights the feedback, emergence, and path dependence that characterise AFSCs (Choi *et al.*, 2001; Surana *et al.*, 2005), while General Systems Theory (GST) positions them as interdependent subsystems within a wider hierarchy (Caddy and Helou., 2007). Taken together, they support a reconceptualisation of food loss as a design outcome, not simply an operational inefficiency, and they open benchmarking to systemic application. Rather than identifying “best practice” in isolation, benchmarking becomes a diagnostic device that reveals where enabling conditions, execution mechanisms, and adaptive capacities align, or fail to align, across the chain.

Guided by these perspectives, this study conducts a systematic literature review of 102 peer-reviewed papers to address two questions:

RQ1: What strategic interventions have been identified to mitigate food loss across production, processing, and logistics in AFSCs?

RQ2: How can these interventions be categorised and benchmarked to inform a coherent, adaptive framework for food loss management?

The contribution is fourfold: it consolidates interventions into six domains, contractual, infrastructural, behavioural, network-based, governance-oriented, and data-mediated; develops a benchmarking framework that renders these interventions comparable and sequenced; embeds the framework within established operations management logics of performance, process, and learning; and sets a future research agenda that integrates benchmarking, systems thinking, and adaptive governance. We convert food-loss interventions into benchmarkable dimensions with specific indicators that support cross-organisational comparison, before-and-after tracking, and diffusion of superior practices. This positioning aligns with recent treatment of traceability as a measurable performance architecture in agri-food chains, where design choices shape loss, quality and profit trajectories that can be compared across firms and periods (Dash *et al.*, 2023). It also connects to evidence that blockchain-enabled traceability closes information gaps in complex public distribution systems, creating auditable, comparable processes for managerial and policy benchmarking (Gupta and Shankar, 2024). In parallel, capability-oriented synthesis clarifies how organisational capabilities underpin the performance differentials that benchmarking seeks to reveal and explain, linking our intervention domains to capability-based performance paths (Orioli and Veríssimo, 2024). Related research on digital sourcing architectures shows how blockchain and smart contracts structure process metrics, provenance and cycle times in ways that are directly comparable across projects and suppliers, reinforcing our emphasis on indicator design for cross-case learning (Hastig and Sodhi, 2020).



### 2.6.3 Methods

This study used the systematic literature review approach articulated by Denyer and Tranfield (2009) and widely applied in management and operations research. The approach was chosen for its transparent and replicable sequence of steps that convert dispersed studies into a defensible body of cumulative knowledge suited to cross-study comparison and benchmarking (Denyer and Tranfield, 2009). Reporting followed PRISMA guidance to ensure procedural clarity from identification through inclusion (Liberati *et al.*, 2009; Haddaway *et al.*, 2022). To handle heterogeneous evidence that spans agricultural sciences, logistics, operations management, and policy, the protocol drew on established review handbooks in information systems and management to structure search, screening, and synthesis decisions in advance (Okoli and Schabram, 2010; Durach *et al.*, 2017).

The review proceeded through five linked phases, consistent with Denyer and Tranfield's (2009) logic: formulation of research questions, identification of studies, selection and evaluation of studies, analysis and synthesis, and presentation of results as depicted in Fig. 10. A versioned protocol specified the review questions, eligibility rules, data sources, and analysis plan before any searching commenced. Any operational refinements, such as minor adjustments to search strings and duplicate handling, were logged in an audit trail and do not alter the scope or inclusion standards.

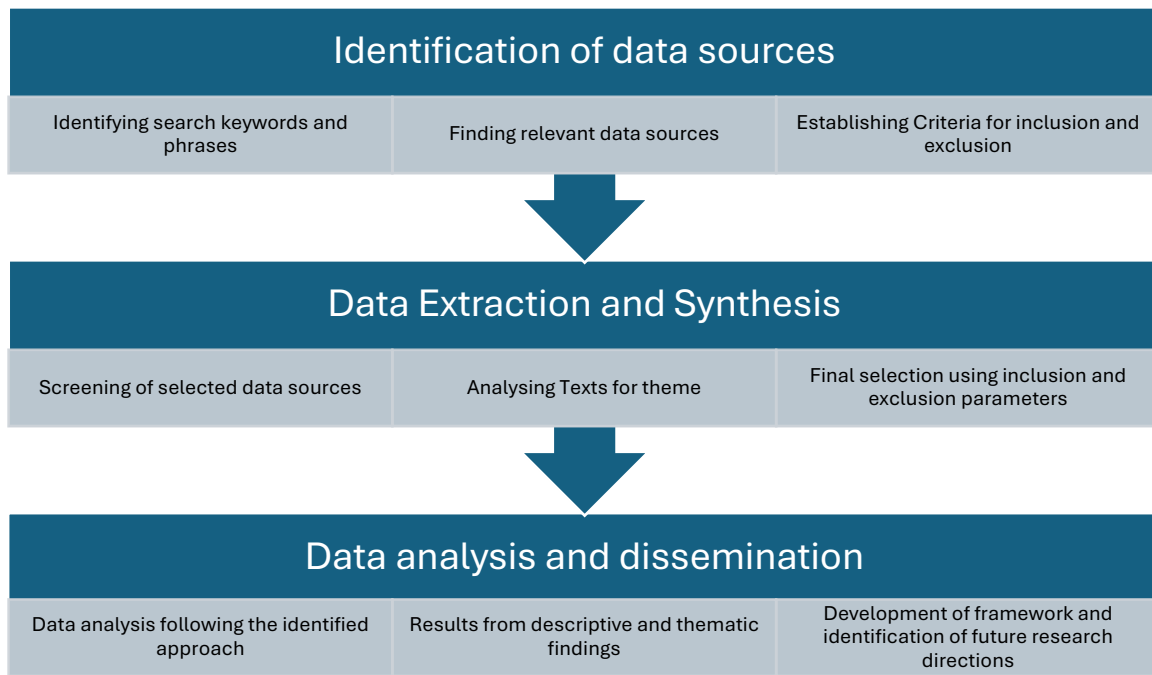


Fig. 10: Systematic Literature Review Process (Source: Denyer and Tranfield, 2009)

#### 2.6.3.1 Formulation of research questions

Guided by a scoping exercise conducted between August 2022 and February 2025, which confirmed fragmentation across technical, behavioural, and governance interventions in agrifood supply chains, the review asked three questions. First, which strategic interventions have been implemented at production, processing, and logistics stages to mitigate food loss, and with what measured effects. Second, how these heterogeneous interventions can be organised into a comparative framework that enables benchmarking across technological, organisational, and contextual dimensions. Third, which implementation conditions and system characteristics moderate effectiveness across regions and infrastructure settings. These questions set the boundaries of the review while retaining sufficient breadth to reflect upstream and midstream realities of agrifood chains (Arksey and O'Malley, 2005; Fabbe-Costes and Jahre, 2008).

#### 2.6.3.2 Identification of studies.

To ensure disciplinary breadth and index diversity, searches covered ScienceDirect, Scopus, Web of Science Core Collection, Wiley Online Library, Academic Search Complete, and Google Scholar. These sources were chosen to balance engineering and preservation literature with operations and policy outputs and to reduce the risk of database-specific blind spots. Search strings combined three keyword clusters corresponding to phenomenon, context, and intervention. The first cluster captured food-loss phenomena using terms such as food loss, post-harvest loss, pre-harvest loss, crop loss, and food degradation. The second captured the agrifood supply-chain context using agri-food supply chain, agricultural supply

chain, food production chain, supply chain logistics, food distribution, food processing, and harvest management. The third captured strategic responses using loss mitigation strategies, food loss prevention, waste reduction, risk management, and supply chain optimisation. Boolean operators integrated the three clusters in titles, abstracts, and keywords, with truncation or proximity used where platforms allowed. Searches were limited to English for feasibility. Following initial runs, citation chaining and database alerts were used to identify late-appearing items. The combined process generated 3,123 records prior to de-duplication.

#### 2.6.3.3 Selection and evaluation of studies.

Eligibility rules were aligned to the review questions and fixed a priori. Included studies were peer-reviewed empirical investigations that implemented and evaluated an intervention aimed at reducing food loss or improving preservation at production, processing, or logistics nodes. Publication years spanned 2012 to 2025. Studies had to report measurable outcomes relevant to loss, quality, efficiency, resilience, or closely related operational performance. Exclusions removed consumer-level or retail waste studies without upstream components, conceptual or review papers lacking primary evaluation, purely food-safety investigations without loss outcomes, ecological or agronomic trials with no supply-chain linkage, and non-food commodities. Screening proceeded in three passes consistent with PRISMA: titles, abstracts, and full texts. Two reviewers independently assessed each record at every pass. Disagreements were resolved through discussion and, where required, a third adjudicator. Inter-rater agreement statistics and the decision log are provided in an appendix. The PRISMA flow diagram records the movement from 3,123 records to 102 included studies (Fig. 11).

#### 2.6.3.4 Data extraction and coding.

Each included study was read in full and coded against a structured template that operationalised the Population–Exposure–Outcome model for comparability (Haddaway *et al.*, 2022). Extracted fields captured bibliographic details, country and region, commodity or sector, targeted node, intervention class and lever, study design and data sources, outcome indicators with measurement definitions, presence and nature of comparators or baselines, and the main quantitative or qualitative results. Contextual notes recorded infrastructure intensity, market characteristics, and regulatory conditions to support later stratification. Reference management was conducted in EndNote. Coded data were stored in a controlled workbook with validation rules and harmonised vocabularies to minimise classification drift. A second reviewer cross-checked a random sample and all entries that required interpretive judgement; discrepancies were reconciled to preserve internal consistency.

#### 2.6.3.5 Quality appraisal and risk of bias.

Methodological quality was assessed using the Mixed Methods Appraisal Tool, which offers design-sensitive criteria for qualitative, quantitative, and mixed-methods research, complemented by an evaluative scale adapted from management research to capture external

validity, construct clarity, and implementation fidelity (Hong *et al.*, 2018). Two reviewers independently appraised each study. Quality assessments did not serve as hard exclusion thresholds but informed analytic weighting, sensitivity analysis, and the interpretation of heterogeneity. When studies reported multiple outcomes or partial designs, appraisal considered the strongest eligible analysis relevant to the intervention effect.

#### 2.6.3.6 Analysis, synthesis, and benchmarking design.

Given heterogeneity across commodities, nodes, metrics, and designs, the synthesis used a convergent approach that joined structured narrative with quantitative summarisation where defensible. To enhance comparability, outcome data were harmonised where possible through percentage loss reduction relative to a baseline, simple standardised effect proxies, or consistent quality indices over aligned time windows. Where harmonisation could not be justified, findings were retained qualitatively with explicit notation of measurement differences. Results were then stratified by intervention class, supply-chain node, infrastructure intensity, region, and commodity.

To link evidence to decision support, a benchmarking matrix positioned interventions against criteria that matter for both operations and sustainability: effectiveness, resource or cost intensity, implementation complexity, scalability, and strength of evidence. The comparative logic was anchored in a three-level classification that preserves theoretical coherence while accommodating empirical variety. At the first level, intervention dimensions were mapped to process and activity integration, technology and system integration, actor and relationship integration, and flow integration. At the second level, scope distinguished dyadic, triadic, and network configurations. At the third level, variables captured concrete mechanisms and implementation modalities. Sensitivity checks re-examined patterns after excluding lower-quality studies and after restricting to designs with explicit counterfactuals or pre-post baselines. Only relationships that remained stable under these perturbations are carried forward into the results.

#### 2.6.3.7 Limitations and mitigations.

Restricting the search to English risks omitting relevant non-English evidence; this was partially mitigated by screening translated abstracts and consulting regionally focused syntheses. Although the database mix is broad, exhaustive capture cannot be guaranteed; citation tracking, alerts, and manual snowballing reduced the likelihood of omission. Publication bias towards positive findings remains a concern; inclusion of studies reporting null or mixed effects and the use of sensitivity analysis sought to limit distortion. Very recent field innovations in pilot phases may not yet be indexed; alerts were maintained until final synthesis to narrow this gap.

This protocol provides a transparent and replicable path from dispersed studies to a structured comparative assessment of interventions that reduce food loss in agrifood supply chains. It is aligned with PRISMA reporting and the Denyer and Tranfield (2009) tradition and is calibrated to produce benchmarking outputs that are usable by scholars and practitioners.

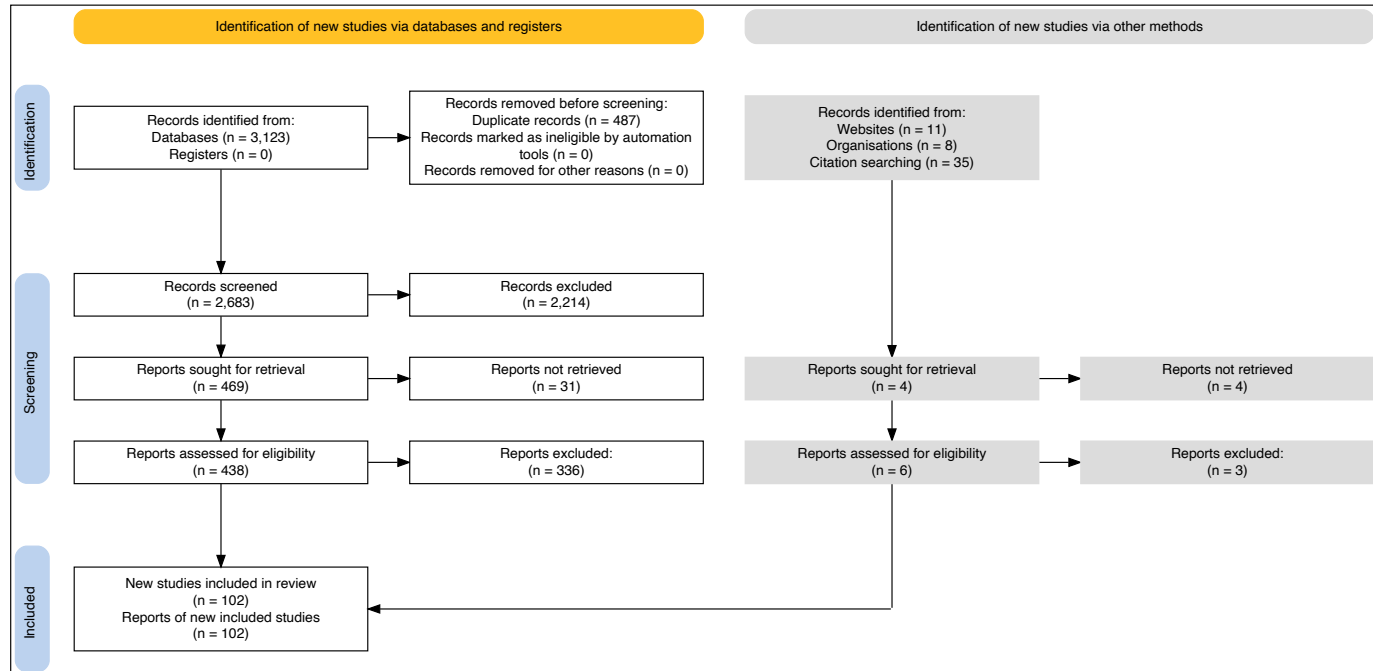


Fig. 11: PRISMA flow diagram for Strategic Interventions Literature (Source: Haddaway et al., 2022)

## 2.6.4 Results and findings

The analysis of the 102 included studies clarifies what is known about upstream and midstream interventions to reduce food loss in agrifood supply chains (RQ1), organises heterogeneous strategies into a comparative structure suitable for benchmarking, and identifies gaps and boundary conditions that shape implementation across contexts (RQ2). Studies were grouped by three main dimensions. Within each dimension, scopes were specified and studies were then assigned to concrete variables that represent implementable levers.

### 2.6.4.1 Analysis

#### Chronology

Publications were sparse from 2013 to 2016, rose from 2017, and accelerated after 2019, peaking in 2023 with 17 studies and remaining high in 2024 with 14 (Fig. 12). This pattern aligns with the consolidation of SDG 12.3, mounting food security concerns, and the shock of COVID-19 that exposed supply-chain fragilities, shifting interventions from isolated fixes to resilience strategies (Khader *et al.*, 2019; Gholami-Zanjani *et al.*, 2021; Totobesola *et al.*,

2022). For benchmarking, the temporal break matters, since estimates anchored in crisis conditions are not directly comparable to pre-pandemic baselines without explicit adjustment.

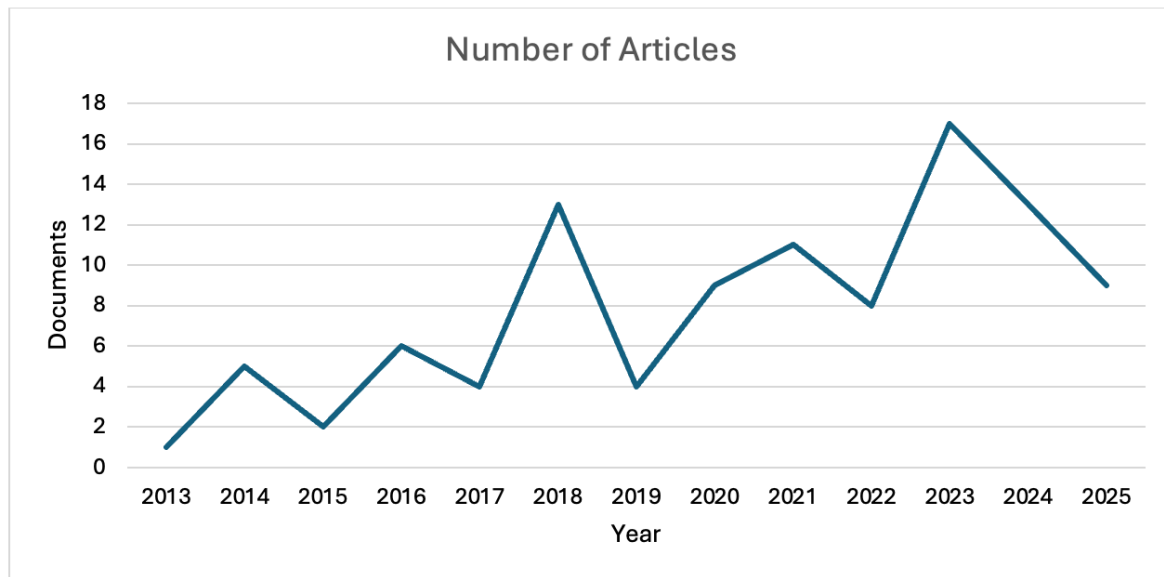


Fig. 12: Number of Research Articles Published Per Year (Source: Author's own work)

The portfolio is concentrated in a small set of regions. Sub-Saharan Africa accounts for 30.4 percent, Europe 20.6 percent, East Asia and the Pacific 14.7 percent, North America 6.9 percent, South Asia 4.9 percent, and Latin America and the Caribbean 8.8 percent, with 8.8 percent multi-country and 4.9 percent from the Middle East and North Africa. At country level, Kenya and Germany appear most frequently, followed by the United States and China, together contributing around one third of studies. This unevenness signals two cautions for transferability: first, interventions are more often tested where infrastructure is strong, which makes sensor-rich or energy-intensive options more visible than low-resource adaptations; second, effect sizes from high-infrastructure contexts are not sufficient grounds for adoption where cold-chain coverage, credit access, or dispute resolution are weak.

## Methods

Experimental designs dominate at 70.6 percent of studies, encompassing controlled laboratory experiments (20.6%), field experiments (15.7%), randomised controlled trials (7.8%), and various specialised experimental approaches. Mathematical modelling and simulation account for 10.8 percent of studies. Mixed-methods designs represent 5.9 percent, whilst literature reviews and meta-analyses comprise 3.9 percent (as depicted in Fig. 13). Cross-sectional surveys contribute 6.9 percent, with case studies representing 2.0 percent of the corpus.

The prevalence of experimental approaches reflects the applied nature of post-harvest loss research, where technological interventions require empirical validation. However, this emphasis on measurement-oriented designs may compress complex socio-technical interventions into simplified outcome metrics. Mathematical modelling provides systematic scenario analysis, though model assumptions may not fully capture institutional complexities and local variability. Mixed-methods approaches, whilst representing a smaller proportion of studies, demonstrate potential for integrating quantitative outcomes with qualitative insights about implementation contexts and mechanisms. The methodological distribution suggests robust capacity for intervention testing, yet reveals limited engagement with the contextual factors and causal mechanisms that determine intervention effectiveness across diverse settings.

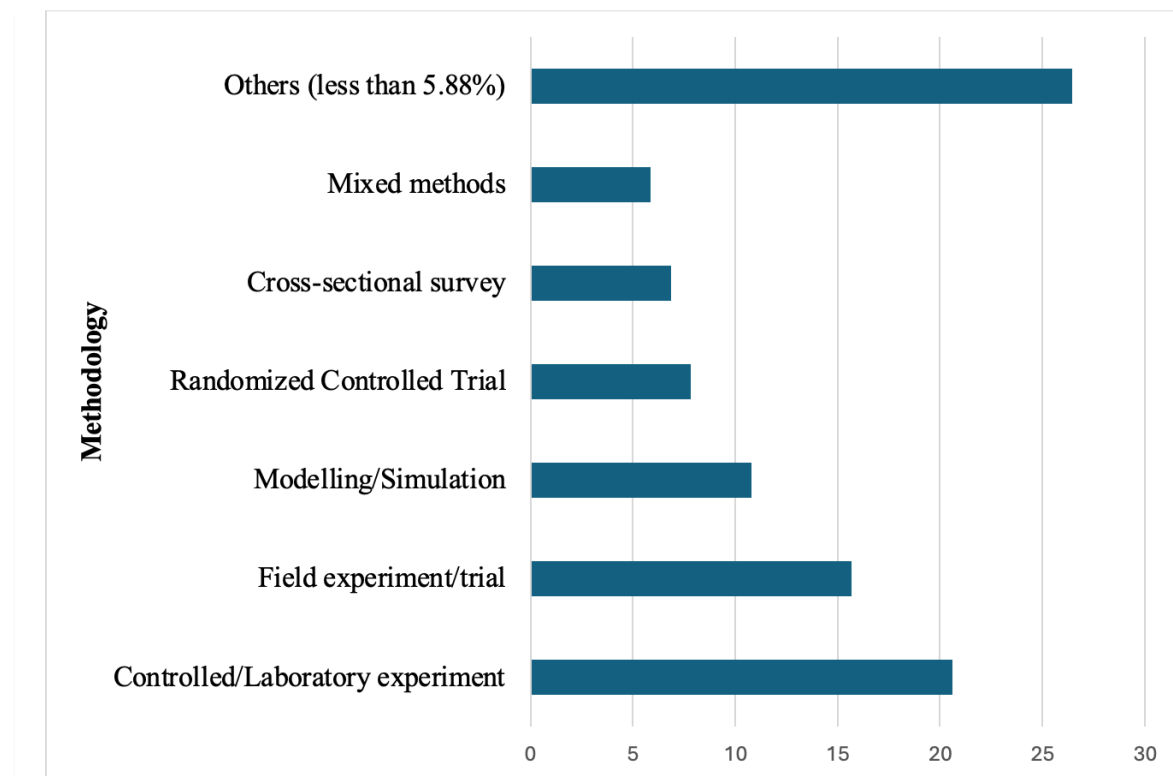


Fig. 13: Methodologies Used in Papers Analysed (Source: Author's own work)

### Outlets

The 102 studies are spread across 62 journals, with concentrations in Journal of Stored Products Research (n = 8), Postharvest Biology and Technology (n = 6), Journal of Cleaner Production (n = 5), and Food Policy (n = 4). Dispersion across food science, environmental management, operations, and policy outlets is advantageous for benchmarking because it

allows interventions to be assessed across economic, environmental, operational, and social criteria within a single comparative frame.

#### 2.6.4.2 Synthesis against the classification

Applying the classification schema to the corpus reveals that all six dimensions are represented, with the densest coverage in infrastructure and preservation technologies, as well as in data-driven and digital interventions, reflecting the emphasis on storage, cold-chain, sensing, and traceability. Contract management appears frequently but is uneven in design quality; many evaluations rely on pre–post comparisons without strong counterfactuals. Network coordination interventions are present but often embedded within broader programmes, which can blur attribution. Behavioural interventions are fewer in number but show consistent practical gains in basic handling and grading, especially where training is coupled with targeted incentives. Governance measures are under-reported relative to their likely system-wide effects, which suggests a gap for future evaluation.

#### 2.6.4.3 Implications for benchmarking

When interventions are positioned in a benchmarking matrix that balances effectiveness, resource intensity, implementation complexity, scalability, and strength of evidence, a consistent pattern emerges. Low-cost handling improvements, hermetic storage, and basic moisture management cluster as high-effect, low-complexity options suited to low-infrastructure contexts. Sensor-enabled cold-chain, electronic traceability, and machine-learning routing deliver strong effects where energy reliability and data governance are adequate but carry higher complexity and resource demands. Contractual levers and dispute-resolution mechanisms show promise for stabilising grades, payments, and delivery windows, but their effects are sensitive to local enforcement capacity and market structure. These gradients, rather than single headline effects, are the most policy-relevant outputs of the synthesis.

### 2.6.5 Findings

#### 2.6.5.1 Interventions at Production, Processing, and Logistics Nodes

The review identifies production, processing, and logistics as decisive nodes in agri-food supply chains, not as isolated stages of technical breakdown but as interdependent arenas where biological vulnerability, infrastructural fragility, and institutional asymmetry converge. Their significance lies in multiplier and stacking effects: small inefficiencies at these points reverberate across the system, compounding into large-scale loss.

At the earliest stages, pre-harvest strategies already establish benchmarks of coordination. Advanced seed varieties, digital monitoring of crop health, and precision pest control reduce potential loss before harvest (Ciccullo *et al.*, 2021; Soethoudt and Castelein, 2021; Zhang *et al.*, 2022). These interventions extend beyond agronomic benefit, for they enable performance



metrics that can be compared across contexts, allowing benchmarking of yield stability, resilience, and downstream alignment (Ciccullo *et al.*, 2021).

Production-stage interventions broaden this toolkit: information systems and analytics (Bag *et al.*, 2024), preservation technologies (Bernardi *et al.*, 2018; Dong *et al.*, 2023), edible coatings (Feng *et al.*, 2018), sensory and weight-loss monitoring, and systematic diagnosis of loss sources (Barons *et al.*, 2024; Ambler *et al.*, 2018; Beretta *et al.*, 2013). These measures not only reduce physical losses but also serve as diagnostic benchmarks that feed into continuous improvement frameworks. The classification of interventions and their benchmarking leverage is summarised in Table 10.

Table 10: Food Loss Interventions and Benchmarking Leverage (Source: Author's own work)

| Intervention Area                         | Occurrences | Benchmarking Insight                                                       |
|-------------------------------------------|-------------|----------------------------------------------------------------------------|
| <b>Production</b>                         |             |                                                                            |
| Information systems and analytics         | 8           | Core enabler of visibility; supports predictive benchmarks across nodes.   |
| Chemical preservation                     | 2           | Effective in niche crops; uptake limited by cost/regulation.               |
| Mechanical preservation                   | 10          | Promising in mid-income contexts; requires infrastructure alignment.       |
| Edible coatings                           | 6           | Underexplored; strong potential in perishables.                            |
| Sensory/weight-loss analysis              | 3           | Establishes measurement standards; weakly embedded in practice.            |
| Certified seeds and fertilisers           | 1           | Yield-oriented; indirect loss impact unless tied to logistics.             |
| Process improvement diagnostics           | 4           | Dominant theme; functions as benchmark for continuous learning.            |
| <b>Processing and Logistics</b>           |             |                                                                            |
| Post-harvest practices                    | 0           | Foundational; often generic; limited integration into systemic strategies. |
| Actor collaboration and coordination      | 2           | Widely evidenced; addresses network failures and multiplier effects.       |
| Improved storage (hermetic/cold chain)    | 40          | High leverage; adoption constrained by cost and access.                    |
| Modern processing technologies            | 1           | Productivity gains contingent on skills and infrastructure.                |
| Logistics optimisation                    | 1           | Persistent focus; hampered by infrastructural bottlenecks.                 |
| Advanced digital tools (RFID, AI, drones) | 10          | Future-facing; hindered by cost and standardisation gaps.                  |
| Management/governance frameworks          | 9           | Reflect behavioural-cultural focus; embed systemic change.                 |
| Economic/regulatory instruments           | 1           | Emerging; effectiveness varies by scope and enforcement.                   |
| Skills and awareness                      | 1           | Human capital critical; enables adoption of other levers.                  |
| Standardisation (packaging, quality)      | 1           | Sparse; efficiency gains clear from adjacent industries.                   |
| Addressing market power                   | 1           | Critical leverage point; under-theorised.                                  |
| Algorithms (optimisation models)          | 1           | Analytical sophistication evident; translation to practice limited.        |
| Composting/waste-to-energy                | 1           | Positioned as remedial; less effective for prevention.                     |

| Cross-Node                        |   |                                                                  |
|-----------------------------------|---|------------------------------------------------------------------|
| Circular economy strategies       | 1 | Conceptually rich; limited empirical grounding.                  |
| Consumer demand management        | 1 | Strikingly neglected despite upstream influence.                 |
| Contractual/economic incentives   | 2 | Latent leverage point; weakly linked to systemic outcomes.       |
| Risk/resilience strategies        | 1 | Emerging; underdeveloped in CAS perspective.                     |
| Circular supply chain innovations | 1 | Early but promising bridge between sustainability and logistics. |

Interventions in processing and logistics deepen this repertoire. Storage innovations such as hermetic bags and drying technologies (Baoua *et al.*, 2014; Hoffmann and Jones, 2021) extend shelf life, delivering both economic and environmental benefits (May and Guenther, 2020; Broeze *et al.*, 2023). Handling practices (Willersinn *et al.*, 2015), training programmes (Pretari *et al.*, 2019; Hoffmann and Jones, 2021; Treurniet, 2021), and infrastructural upgrades consistently reduce avoidable losses. Contractual and governance tools further align incentives: contract farming halves vegetable waste (Moradi *et al.*, 2025), while enforceable agreements raise compliance with safety standards (Ndambi *et al.*, 2023). Forecasting-integrated logistics (Springael *et al.*, 2018; Manouchehri *et al.*, 2020) and networked quality-control processes (Willersinn *et al.*, 2015; Totobesola *et al.*, 2022; Göransson *et al.*, 2018) anchor system coordination.

Beyond technical levers, circular economy strategies reframe waste as input (May and Guenther, 2020; Broeze *et al.*, 2023), consumer-facing approaches encourage behavioural adaptation (Gomez and Grady, 2023; Willersinn *et al.*, 2015), and advanced modelling tools inject predictive resilience into planning (Heising *et al.*, 2017; Springael *et al.*, 2018). In aggregate, these interventions exemplify benchmarking in practice: they are not merely fixes but reference points for comparison, sequencing, and replication across supply chains (Brockhaus *et al.*, 2016; Jacob-John *et al.*, 2023).

#### 2.6.5.2 Differential Impacts Across Actors

The weight of interventions lies in their differentiated impacts across the heterogeneous actors of AFSCs. These impacts extend across economic, environmental, social, operational, quality, technological, and regulatory domains. Benchmarking translates these heterogeneous outcomes into a coherent evaluative structure, rendering them comparable across contexts (Brockhaus *et al.*, 2016).

Economic impacts dominate as storage investments and improved seed varieties strengthen profitability through extended crop longevity and reduced post-harvest losses (Baoua *et al.*,

2014; Omotilewa *et al.*, 2018; Ndegwa *et al.*, 2016; Soethoudt and Castelein, 2021). Environmental dividends include reduced emissions, water use, and energy intensity, with scenario analyses showing that targeted interventions can lower total greenhouse gases per unit sold and that upcycling by-products can cut footprints while informing cost decisions (Broeze, Guo and Axmann, 2023; May and Guenther, 20). Social benefits emerge in employment, stabilised incomes, and enhanced food security; collaborative and market-access interventions raise sales and welfare indicators for smallholders (Tesfaye and Tirivayi, 2018; Brander, Bernauer and Huss, 2021; Safo *et al.*, 2023; Channa *et al.*, 2022).

Operational outcomes address lead times, inventory control, and efficiency. Evidence from factory and logistics settings shows that digital waste tracking, vibration-aware routing, and dynamic shelf-life modelling improve coordination and reduce losses (Jagtap and Rahimifard, 2019; Springael *et al.*, 2018; Göransson, Nilsson and Jevinger, 2018). Quality and safety impacts stem from preservation technologies: lemon essential oil extends citrus shelf life (Zhang *et al.*, 2022), while intelligent packaging and real-time monitoring reinforce traceability and temperature control (Albrecht *et al.*, 2020; Loisel *et al.*, 2022; Gillespie *et al.*, 2023).

Policy and regulatory effects crystallise institutional significance. Targeted measures stimulate collaboration, government engagement, and cohesive governance frameworks (Totobesola *et al.*, 2022; Ndambi *et al.*, 2023; Treurniet, 2021; Willersinn *et al.*, 2015). Here, benchmarking is indispensable: it enables interventions to be judged not only on local performance but also on alignment with governance architectures across contexts, as recent studies formalise cross-context observatories and multi-criteria indices that integrate governance, circularity and digital enablers (Butturi *et al.*, 2024; Bello *et al.*, 2024).

Thus, interventions should be read less as discrete impacts than as a constellation of performance dimensions that require benchmarking logics for synthesis. Only by comparative evaluation can leverage points across farmers, processors, retailers, regulators, and consumers be clarified.

#### 2.6.5.3 From Interventions to Systemic Benchmarking

The evidence demonstrates that interventions generate systemic effects through complementarities, tensions, and feedback loops. Their value lies in configuration rather than isolation. Previous reviews catalogued interventions as parallel strategies; the present synthesis reinterprets them as interacting subsystems. When seen through benchmarking, interventions become diagnostic markers of systemic performance, substrates that can be sequenced, scaled, and adapted (Butturi, Lolli and Gamberini, 2025; Pandey *et al.*, 2024).

Benchmarking thus bridges micro- and macro-dynamics. At the micro-level, it clarifies which interventions deliver efficiency or resilience gains; at the macro-level, it shows how these combine into systemic architectures (Bello *et al.*, 2024). In this way, interventions become intelligible as elements of a framework that supports both operational learning and strategic adaptation. By situating food loss interventions within benchmarking traditions, the review transforms dispersed evidence into an evaluative and operational device capable of guiding both scholarship and practice (Butturi, Lolli and Gamberini, 2025; Pandey *et al.*, 2024).

#### 2.6.5.4 Strategic Domains of Intervention

##### Contract Management Interventions

Contracts in agrifood supply chains are not neutral instruments but devices that distribute risk, encode incentives, and shape resilience. Evidence from export horticulture shows that governance features within written agreements, audits, and price expectations relate to rejection dynamics and market stability, with implications for waste (Kariuki and Loy, 2016). Production and marketing contracts among growers are associated with higher profits and lower post-harvest losses once selection is addressed (Dsouza, Mishra and Webster, 2023). Yet rigid cosmetic standards intensify waste, with on-farm losses rising where aesthetic grading is imposed rather than size-only grading, and with frequent rejections of suboptimal produce reported by European producers and retailers (Jia *et al.*, 2025; de Hooge, van Dulm and van Trijp, 2018). Contract clauses that embed verification and payment for quality alter behaviour along the chain, raising input use and quality investments but sometimes provoking resistance when techniques are imposed unilaterally (Saenger *et al.*, 2014; Ndambi *et al.*, 2023; Ciliberti, Frascarelli and Martino, 2023).

Relational continuity strengthens when agreements bundle technical assistance and decision-support, while coordination tools specified within contracts, such as RFID-enabled allocation and quality-driven routing, help protect perishables in transit (Gautam *et al.*, 2017; Mack *et al.*, 2014). Portfolio-style arrangements that integrate storage finance or receipt systems re-time sales and reduce exposure to distress losses (Safo *et al.*, 2023; Channa *et al.*, 2022). Benchmarking tools, including fairness indices, volatility absorption ratios, and efficiency frontier models, enable assessment of these designs for systemic robustness as well as private returns (Ramos *et al.*, 2022).

##### Infrastructure Management Interventions

Infrastructure establishes the physical backbone of supply chains, yet deficiencies remain a decisive constraint (Arias Bustos and Moors, 2018). Storage innovations such as hermetic

bags and controlled atmosphere systems extend shelf life (Baoua *et al.*, 2014; García-Lara *et al.*, 2020; Argenta *et al.*, 2024; Both *et al.*, 2018), though affordability curtails adoption amongst smallholders (Raut *et al.*, 2019). Transport optimisation reduces spoilage (Springael *et al.*, 2018; Gautam *et al.*, 2017), but weak infrastructures erode these gains. Forecasting tools and processing innovations (Akonor *et al.*, 2023; Bernardi *et al.*, 2018; Ahmed *et al.*, 2023) remain unevenly distributed, compounding fragility. Newer technologies, AI shelf-life prediction (Albrecht *et al.*, 2020; La Scalia *et al.*, 2016), IoT-enabled preservation (Gillespie *et al.*, 2023), and edible coatings (De Bruno *et al.*, 2023; Zhang *et al.*, 2022), expand capacity but demand capital and regulatory acceptance. Benchmarking spoilage rates, utilisation, and preservation costs reveals how infrastructure acts as a slow-moving attractor in CAS: stabilising when aligned, destabilising when absent.

#### Network-Focused Interventions

Networks form the relational tissue binding agrifood systems. Collaboration and trust reduce inefficiency and improve alignment (Arias Bustos and Moors, 2018; Treurniet, 2021). Cooperative logistics and digital platforms expand coordination (Arias Bustos and Moors, 2018; Gautam *et al.*, 2017), while information exchange proves more decisive than technology alone (Bai, 2025). Yet power asymmetries in contracting arrangements (Dsouza, Mishra and Webster, 2023; Kariuki and Loy, 2016), weak governance frameworks (Messner *et al.*, 2021), and structural lock-ins (de Hooge, van Dulm and van Trijp, 2018) undermine collaboration. Digital solutions enhance coordination through optimised routing (Springael *et al.*, 2018) and network traceability (Gautam *et al.*, 2017) but cannot substitute governance mechanisms. Quality-based payment systems demonstrate how aligned incentives foster trust (Ndambi *et al.*, 2023; Rao and Shenoy, 2023), while contract design preferences reveal producer needs for guaranteed pricing and technical assistance (Ciliberti, Frascarelli and Martino, 2023). Decision-support modelling expands adaptive capacity (Barons *et al.*, 2024), yet aesthetic grading standards and retailer requirements create systematic exclusions (Jia *et al.*, 2025). Benchmarking through trust indices and coordination cost ratios (Dania *et al.*, 2019) distinguishes networks that merely connect actors from those that reconfigure outcomes.

#### Data-Driven Interventions

Data systems act as feedback mechanisms in CAS and meta-systems in GST, extending supply chains' capacity to sense and adapt. Big data analytics and IoT systems enhance visibility (Deichmann *et al.*, 2016; Ciccullo *et al.*, 2021), with evidence from waste-tracking implementations demonstrating significant reductions through real-time monitoring (Jagtap and Rahimifard, 2019). RFID and sensor technologies refine monitoring capabilities (Gautam *et al.*, 2017; Gillespie *et al.*, 2023), whilst predictive tools reduce mismatch-driven waste through temperature-based quality models (Mack *et al.*, 2014; Albrecht *et al.*, 2020) and intelligent packaging systems (Heising *et al.*, 2017; Waldhans *et al.*, 2024). Machine learning

applications demonstrate potential for non-destructive quality assessment (Feng *et al.*, 2018; Vélez Rivera *et al.*, 2014), though neural network models require substantial experimental data for accuracy (Loisel *et al.*, 2022). Yet adoption remains constrained by costs, trust deficits, and technical complexity. Inconsistent reporting methods distort cross-regional comparisons, despite meta-analytical frameworks revealing systematic measurement gaps (Fabi *et al.*, 2021). Collaborative forecasting improves alignment (Gruzauskas *et al.*, 2019), while dynamic pricing demonstrates profitability alongside waste reduction (Chen and Chen, 2021; Kayikci *et al.*, 2022). Benchmarking metrics, forecast accuracy, traceability coverage, and error-detection rates make visible whether data sophistication produces systemic resilience or reinforces fragmentation.

#### Behavioural Interventions

Behavioural interventions foreground the human dimension. Training and managerial competence consistently shape intervention success (Dora *et al.*, 2020; Surucu-Balci and Tuna, 2021). Lean Six Sigma with reflexive learning embeds loss reduction into daily routines (Kolawole, 2020), while technical expertise underpins adaptive capacity (Emana *et al.*, 2017; Despoudi, 2021). Post-harvest handling (Hoffmann and Jones, 2021; Ambler *et al.*, 2018) and shifts in consumer norms (Jiang *et al.*, 2024; Gao *et al.*, 2024) demonstrate how micro-practices aggregate into resilience. Contract farming also acts behaviourally, stabilising expectations (Moradi *et al.*, 2025). Yet failures in communication or awareness undermine technology adoption (Omotilewa *et al.*, 2018; Eichenauer *et al.*, 2023). Benchmarking through training uptake, compliance scores, and cultural alignment indicators reveals how behaviours crystallise into systemic outcomes.

#### Governance Interventions

Governance supplies the institutional scaffolding for all other strategies. Robust frameworks configure conditions for success (Hanson *et al.*, 2022), yet fragmented regulation impedes progress (Ferrando and Mansuy, 2018). Standards, particularly aesthetic grading requirements, significantly influence waste generation, resulting in substantial on-farm losses averaging 17.1% of the harvest (Jia *et al.*, 2025). Meanwhile, cosmetic standards lead to approximately 20% rejection rates in retail chains (de Hooge, van Dulm, and van Trijp, 2018). Retailer dominance perpetuates upstream waste (Herzberg *et al.*, 2022), while voluntary initiatives rarely alter incentives. However, coordinated governance approaches demonstrate effectiveness: partnership-based interventions addressing structural inefficiencies across value chains (Arias Bustos and Moors, 2018), and contract farming scenarios reducing total waste from 39% to 16% through market coordination mechanisms (Moradi *et al.*, 2025). Regulatory enforcement mitigates spoilage (Richter and Bokelmann, 2016), and is identified as the most influential driver of loss reduction (Gokarn and Kuthambalayan, 2017). Retailers themselves can function as coordinators when properly incentivised (Lemos and Castro,

2021). Benchmarking governance through compliance, alignment, and enforcement indices clarifies whether it consolidates interventions or fragments them. Within CAS it steers adaptation; within GST it acts as the higher-order regulator ensuring system coherence.

#### **2.6.6 Synthesis**

The review consolidates this corpus into a systemic benchmarking device (Table 11), organising interventions by levers, metrics, and tools. Contracts can be assessed through fairness indices and dispute measures; infrastructure through spoilage rates and throughput efficiency; networks through trust and resilience indices; data systems through maturity and traceability coverage; behavioural interventions through training adoption and compliance; and governance through enforcement and alignment. Read vertically, the device provides diagnostic clarity within domains; read horizontally, it exposes interdependencies: contracts stabilise only when infrastructure is reliable, behavioural training generates resilience only with data scaffolding, and governance determines whether networks consolidate or collapse. In this way, benchmarking evolves from static measurement into systemic diagnosis, equipping scholars, policymakers, and practitioners with a comparative and adaptive frame for food loss reduction.

Table 11: Systemic Benchmarking Device for Food Loss Interventions in AFSCs (Source: Author's own work)

| Domain         | Illustrative Levers                                                                                                                                                                                                                                                    | Benchmarking Metrics                                                                  | Benchmarking Tools                                                                                                                                                                                                                                                                                                                                         | Key References                                                                                                                                                                                                                                                             |
|----------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Contracts      | Quality-based payment systems; production and marketing contracts; harvest loans; warehouse receipt systems; third-party verification; price signalling through labelling; team-based financial incentives                                                             | Fairness indices; volatility absorption; dispute frequency; farmer income stability   | Transaction cost analysis; efficiency frontier; contract simulation<br>Data Envelopment Analysis (DEA) with super-efficiency for contracting units; Analytic Hierarchy Process (AHP)–DEA hybrids for contract design evaluation; Malmquist Productivity Index for inter-year contract performance; Balanced Scorecard (BSC)-aligned procurement scorecards | Dsouza, Mishra, and Webster (2023); Ciliberti, Frascarelli, and Martino (2023); Kariuki and Loy (2016); Rashidi <i>et al.</i> (2020)                                                                                                                                       |
| Infrastructure | Hermetic storage systems; controlled/dynamic atmosphere storage; modified-atmosphere packaging; edible coatings; evaporative cooling; forced-air precooling; time-temperature management; processing technology optimisation                                           | Spoilage rates; throughput time; storage utilisation; preservation cost per tonne     | Cost-benefit benchmarking; capacity-gap analysis; readiness indices; Grey Technique for Order Preference by Similarity to Ideal Solution (Grey-TOPSIS); COMplex PROportional ASsessment with Grey relations (COPRAS-G); Multi-Objective Optimisation on the basis of Ratio Analysis (MOORA);                                                               | Baoua <i>et al.</i> (2014); García-Lara <i>et al.</i> (2020); Argenta <i>et al.</i> (2024); Both <i>et al.</i> (2018); Ahmed <i>et al.</i> (2023); De Bruno <i>et al.</i> (2023); Malaga and Vinodh (2021)                                                                 |
| Networks       | Partnership-based governance; supply chain coordination; algorithmic routing optimisation; digital traceability networks; integrated production-routing; cold-chain logistics coordination; resilience-oriented network design                                         | Trust indices; coordination costs; resilience scores; partnership longevity           | Social network analysis; relational capital benchmarking; collaboration quality assessment; Evidence-based benchmarking frameworks integrating operational, financial and resilience key performance indicators (KPIs, first use); indicator suites for longitudinal comparison across partner portfolios                                                  | Arias Bustos and Moors (2018); Moradi <i>et al.</i> (2025); Gautam <i>et al.</i> (2017); Springael <i>et al.</i> (2018); Manouchehri <i>et al.</i> (2020); Raut <i>et al.</i> (2019); Gomez and Grady (2023); Bardhan <i>et al.</i> (2021)                                 |
| Data Systems   | Time-temperature indicators; IoT sensor networks; smart packaging with dynamic expiry dates; predictive quality models; machine learning classification; wireless sensor networks; digital waste tracking; hyperspectral imaging; volatile organic compound monitoring | Forecast accuracy; traceability coverage; error-detection rate; decision latency; ROI | Digital maturity indices; predictive dashboards; blockchain audit trails                                                                                                                                                                                                                                                                                   | Albrecht <i>et al.</i> (2020); Gillespie <i>et al.</i> (2023); Göransson, Nilsson, and Jevinger (2018); La Scalia <i>et al.</i> (2016); Heising <i>et al.</i> (2017); Lin <i>et al.</i> (2025); Waldhans <i>et al.</i> (2024); Loisel <i>et al.</i> (2022); Feng <i>et</i> |



|             |                                                                                                                                                                                                                                     |                                                                                         |                                                                                                                                                                     |                                                                                                                                                                          |
|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|             |                                                                                                                                                                                                                                     |                                                                                         |                                                                                                                                                                     | <i>al.</i> (2018); Jagtap and Rahimifard (2019); Akhtar <i>et al.</i> (2022)                                                                                             |
| Behavioural | Farmer training programmes; technology adoption with demonstrations; post-harvest handling education; consumer information prompts; mental health support integration; moisture measurement training; storage technique instruction | Training uptake; compliance scores; adoption rates; error reduction; cultural alignment | Capability maturity models; continuous improvement benchmarking; behavioural audits                                                                                 | Brander, Bernauer and Huss (2021); Hoffmann and Jones (2021); Leavens <i>et al.</i> (2021); Pretari <i>et al.</i> (2019); Palaniappan <i>et al.</i> (2021)               |
| Governance  | Aesthetic versus size-based grading standards; cosmetic quality specifications; decision-support modelling for input reduction; dynamic pricing policies; measurement framework standardisation; food loss assessment methodologies | Compliance rates; alignment indices; enforcement consistency; inclusivity measures      | Policy coherence analysis; governance benchmarking frameworks; regulatory gap analysis; Domain-specific performance-measurement frameworks with indicator structure | Jia <i>et al.</i> (2025); de Hooge <i>et al.</i> (2018); Willersinn <i>et al.</i> (2015); Barons <i>et al.</i> (2024); Chen and Chen (2021); Menhat <i>et al.</i> (2023) |

## 2.6.7 Framework for the Implementation of Strategic Interventions

The synthesis of interventions demonstrates that food loss cannot be reduced by treating contracts, infrastructure, networks, data, behaviours, and governance as separate fixes. Their systemic impact arises from how they align, reinforce, or undermine one another across supply chain layers. To capture this, the study organises interventions into a three-tiered framework (Fig. 14) that escalates from foundational preconditions to mechanisms of execution to adaptive capacities. The framework advances the literature by showing how food loss interventions crystallise into distinct system states, and how benchmarking makes their complementarities and tensions visible.

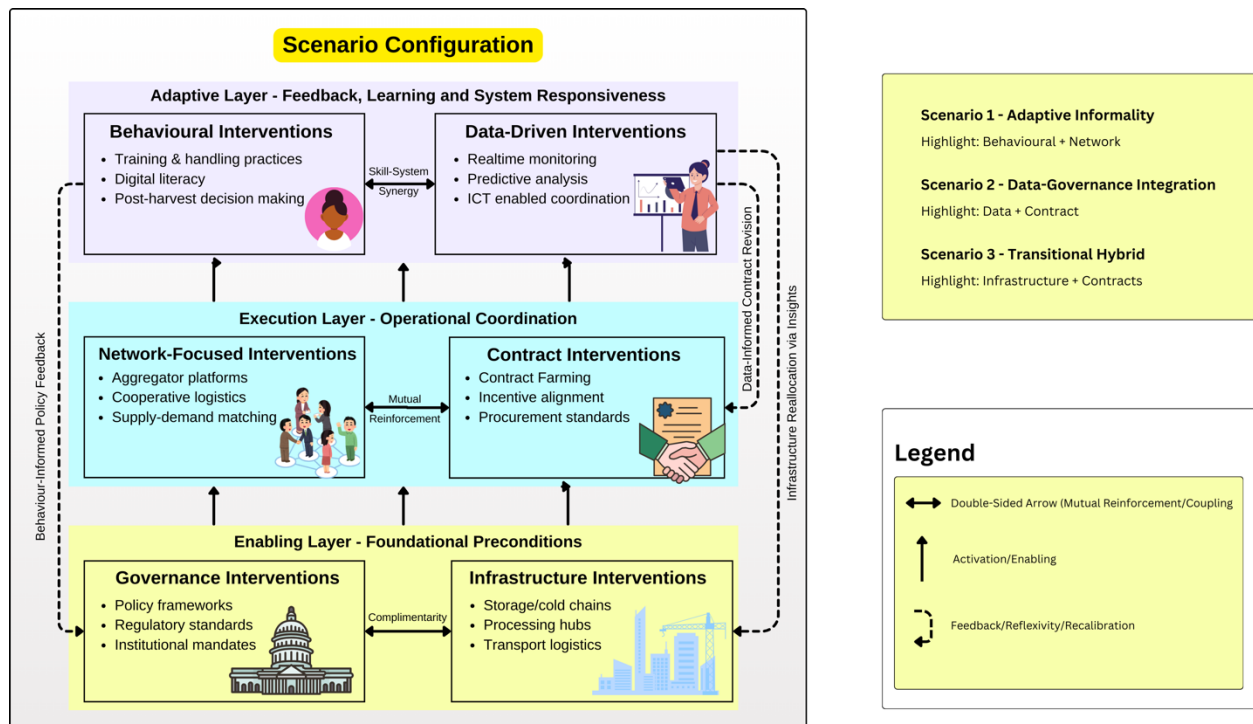


Fig. 14: Conceptual Framework for Strategic Interventions to Reduce Food Loss (Source: Author's own work)

### 2.6.7.1 The Enabling Layer: Preconditions of Resilience

At the foundation lie governance and infrastructure. Governance, regulatory standards, policy instruments, and institutional scaffolds set thresholds for compliance and accountability (Willersinn *et al.*, 2015; de Hooge, van Dulm, and van Trijp, 2018). CAS perspectives highlight its feedback sensitivity: fragmented regulation produces maladaptation (Tesfaye and Tirivayi, 2018), while coherent, multi-actor mandates foster emergent coordination (Totobesola *et al.*, 2022).

Infrastructure, cold chains, storage hubs, logistics networks, defines the material capacity of supply chains (Baoua *et al.*, 2014; García-Lara *et al.*, 2020; Wittkamp *et al.*, 2025). Fragility multiplies local shocks into systemic crises (Gitonga *et al.*, 2013); resilient platforms absorb volatility and stabilise flows. GST frames governance and infrastructure as substrate subsystems, CAS as attractors around which adaptive trajectories form. Their coupling constitutes the enabling layer of systemic resilience.

#### 2.6.7.2 The Execution Layer: Coordination in Practice

Execution is where contracts and networks convert enabling conditions into operational continuity. Contracts, production and marketing agreements, revenue-sharing, and risk-reward mechanisms stabilise vertical flows and reduce inefficiency (Dsouza, Mishra, and Webster, 2023; Ndambi *et al.*, 2023; Treurniet, 2021). Yet excessive rigidity provokes resistance, as farmers resist sustainability clauses they view as restrictive (Ciliberti, Frascarelli, and Martino, 2023). Networks, cooperatives, collaborative logistics, digital platforms, consolidate horizontal ties (Arias Bustos and Moors, 2018; Gautam *et al.*, 2017; Safo *et al.*, 2023). Their resilience derives from recursive trust and legitimacy, facilitated through partnership-based governance and information exchange mechanisms (Arias Bustos and Moors, 2018; Kariuki and Loy, 2016), though asymmetrical power can destabilise collaboration when techniques are imposed unilaterally rather than through collaborative arrangements (Ciliberti, Frascarelli, and Martino, 2023). Benchmarking confirms that systems combining strong contracts with robust networks outperform those that privilege one axis alone, as demonstrated by integrated approaches linking financial mechanisms with storage technologies and market coordination (Channa *et al.*, 2022; Moradi *et al.*, 2025).

#### 2.6.7.3 The Adaptive Layer: Feedback and Learning

At the apex sit behavioural and data-driven interventions, which supply the adaptive intelligence of the system. Training, post-harvest handling, and digital literacy build capacities for responsiveness (Hoffmann and Jones, 2021; Brander, Bernauer and Huss, 2021; Omotilewa *et al.*, 2018). Data-driven tools, predictive analytics, IoT monitoring, blockchain traceability, extend supply chains' sensing and coordination capacity (Ahmed *et al.*, 2023; Gillespie *et al.*, 2023; Gautam *et al.*, 2017). CAS frames these as feedback loops that recalibrate flows; GST as cybernetic subsystems regulating performance. Their interdependence is decisive: data has no traction without behavioural competence, while training achieves scalability only when data scaffolding supports it. This synergy differentiates adaptive supply chains from stagnant ones.

#### 2.6.7.4 Feedback Loops and Scenario Configurations

Layered together, interventions converge into recurrent configurations rather than a single trajectory. Three archetypes are visible in the literature when Table 11 is read vertically and horizontally alongside Fig. 14.

Adaptive Informality emerges in contexts with thin formal scaffolds yet strong behavioural and network capacities. Farmer cooperatives, training programmes, and informal trading arrangements sustain continuity despite infrastructural gaps (Brander, Bernauer and Huss, 2021; Hoffmann and Jones, 2021; Arias Bustos and Moors, 2018). Benchmarks register high trust and skill retention but persistent deficits in contract fairness, storage utilisation, and compliance. Agility is generated by human and relational capital, though shocks beyond local absorptive capacity expose systemic fragility.

Data–Governance Integration defines systems anchored in digital infrastructure and regulatory enforcement. Blockchain traceability, monitoring platforms, and stable contracts deliver measurable gains in efficiency and compliance (Albrecht *et al.*, 2020; Gillespie *et al.*, 2023; Gautam *et al.*, 2017; Ndambi *et al.*, 2023). Benchmarks score strongly on accuracy, enforcement, and dispute reduction, yet plateau in behavioural uptake and trust. Stability is secured, but adaptability narrows when coordination rests primarily on technological and legal instruments.

Transitional Hybrid characterises supply chains undergoing incremental reform. Cold storage expansion combined with revenue-sharing contracts demonstrates how infrastructure gains traction when aligned with equitable agreements (Channa *et al.*, 2022; Dsouza, Mishra, and Webster, 2023). Benchmarks record steady improvement in spoilage reduction, throughput, and income stability, though governance coherence and training scalability lag behind. Progress is tangible yet uneven, exposing the risk of stalled transformation if domains are not progressively synchronised.

These scenarios demonstrate how food loss interventions are not discrete solutions but systemic configurations shaped by feedback loops and dependencies. Benchmarking provides the comparative lens to diagnose strengths, expose vulnerabilities, and calibrate trajectories. Adaptive informality demonstrates agility rooted in skills and trust; data–governance integration demonstrates stability anchored in regulation and technology; transitional hybrids demonstrate gradual evolution through layered reforms. Together they embody the CAS properties of nonlinearity, path dependence, and emergent equilibria, while GST clarifies the structuring role

of subsystems. The framework therefore advances food loss scholarship by offering not only a taxonomy of interventions but also a roadmap for sequencing, aligning, and institutionalising them, setting the stage for the discussion that follows.

### 2.6.8 Discussion

This review set out to address a persistent fragmentation in food loss research: interventions have been catalogued extensively, but rarely rendered comparable, evaluable, or strategically alignable across contexts. By synthesising six domains of intervention into a systemic benchmarking framework and arranging them within an adaptive systems architecture, the study provides the first structured apparatus for evaluating how food loss strategies function both individually and in interaction.

The contribution lies in advancing a systemic benchmarking framework specific to food loss in agrifood supply chains. Prior studies have developed rich tools for comparing collaboration quality (Dania *et al.*, 2019), managing risks in dairy supply chains (Wang *et al.*, 2025), or assessing IoT adoption (Aamer *et al.*, 2021). Yet these treatments have tended to isolate single domains, metrics, or technologies. By contrast, the framework presented here moves from domain-specific benchmarking to systemic benchmarking, situating interventions within six interdependent domains, contracts, infrastructure, networks, data, behaviour, and governance, and tracing their interaction across enabling, execution, and adaptive layers.

This shift advances the canon in three respects. First, it redefines benchmarking for food loss not as the search for superior practices within one domain but as diagnostic comparison across domains, disclosing how strengths in one area may be offset by weaknesses elsewhere. Second, it situates food loss benchmarking within general systems theory (GST) and complex adaptive systems (CAS), allowing interventions to be evaluated as subsystems whose interdependencies condition systemic outcomes. Third, it operationalises this framework through a portable device (Table 11) that translates interventions into levers, metrics, and tools, making comparison actionable for scholars, practitioners, and policymakers alike.

The scenarios identified in the literature animate this contribution. Adaptive informality, data–governance integration, and transitional hybrid each crystallise as systemic configurations of interventions, which the framework renders evaluable through benchmarking metrics and diagnostic tools. This demonstrates not only the diversity of food loss trajectories but also the

methodological potential of systemic benchmarking to expose feedback loops, nonlinearities, and emergent equilibria that narrower benchmarking approaches cannot capture.

The appendices extend this contribution by demonstrating the dispersal of food loss research across journals, regions, and methods. While earlier reviews have struggled to integrate these heterogeneous literatures, the systemic benchmarking framework provides a shared evaluative grammar: disparate studies become comparable once mapped through levers, metrics, and tools. In this way, the framework both consolidates a fragmented evidence base and advances the methodological rigour of food loss research.

The implications are threefold. For practitioners, the framework enables diagnosis: farmers can identify whether losses stem from contractual inequities, infrastructural bottlenecks, or behavioural gaps; managers can align digital investments with training and governance; policymakers can deploy subsidies or regulations at leverage points where interventions reinforce one another rather than fragment. For scholars, the framework establishes an agenda for systemic benchmarking research: tracing complementarities and trade-offs across domains, comparing trajectories across contexts, and embedding fairness and inclusivity into evaluative criteria. For the benchmarking canon itself, the study demonstrates how systemic benchmarking can be extended to complex adaptive systems, moving the field beyond performance snapshots toward dynamic diagnosis.

Future research should pursue four directions. First, scenario-based benchmarking, where the framework is applied to trace food loss trajectories under varying shocks and policy environments. Second, longitudinal benchmarking, assessing how intervention configurations evolve over time and across scales. Third, mixed-methods benchmarking, integrating qualitative insights on networks and behaviours with quantitative system metrics to capture both depth and comparability. Fourth, equity-sensitive benchmarking, ensuring that systemic evaluations incorporate distributive outcomes alongside efficiency.

In sum, this study departs from earlier benchmarking treatments by introducing a systemic benchmarking framework for food loss reduction in agrifood supply chains. It provides both an analytical template and a practical roadmap, demonstrating that food loss interventions acquire significance not as isolated fixes but as interdependent configurations whose systemic properties can be benchmarked, compared, and strategically sequenced. This positions food loss research

within the benchmarking canon, while also extending that canon toward adaptive and systemic domains where future scholarship is urgently required. Taken together, the framework and indicators provide a benchmarking scaffold that is coherent with BIJ's recent contributions on food-chain traceability and measurement, capability-based performance comparison, digitalised contracting and CPS-enabled operations, reinforcing direct fit for readers who expect rigorous, comparable evidence to identify best practice and track improvement over time (Dash *et al.*, 2023; Gupta and Shankar, 2024; Orioli and Verissimo, 2024).

## 2.7 The Nigerian Tomato Supply Chain

### 2.7.1 Overview of The Nigerian Tomato Supply Chain

Nigeria is the highest tomato producer in sub-Saharan Africa and ranks fourteenth worldwide with an estimated annual yield of 4.1 million metric tonnes (PWC, 2018; Nwigwe *et al.*, 2020; Amurtiya and Adewuyi, 2020). Nigeria manages to produce vast amounts of raw tomatoes yet must import 1.3 metric tonnes of processed tomato paste yearly, demonstrating a disconnect between its production capabilities and value chain efficiency (Ugonna *et al.*, 2015). Conventional supply chain theory deems the sector's fragmentation inefficient because of its vast participant pool and limited direct coordination (Mena *et al.*, 2013; Kumar and Agrawal, 2023) as well as the involvement of multiple intermediaries (Collins, 2006), yet this view fails to recognise the decentralised systems' inherent adaptive resilience. Fig. 15 captures the production and sales dynamics within Nigeria's tomato supply chain, illustrating the various stages from farm-level activities to market distribution as documented through field research.







Fig. 15: Tomato Production and Sales in Nigeria (source research participants)

At the production phase smallholder dominance leads to productive fragmentation which defies traditional efficiency standards but supports advanced risk management with crop variety and labour distribution optimisation (Tan et al., 2008). This adaptive efficiency at the micro-level gives rise to a coordination paradox as while limited organisational structures and informal configurations enable individual resilience, they also constrain systemic modernisation and worsen infrastructural deficiencies and harvesting losses (Ugonna et al., 2015; Sibomana et al., 2018; Oke et al., 2019; Mazhar et al., 2022).

The tomato industry in Nigeria employs about 200,000 smallholder farmers while operating within a broad value chain network (World Bank, 2020; CALS, 2023). The value chain demonstrates serious structural inefficiencies, primarily due to structural constraints, resulting in post-harvest losses reaching 76%, exceeding the accepted global standards (World Bank, 2020). Agricultural land measuring 447,833 hectares becomes wasted through these losses, creating substantial greenhouse gas emissions at 3,078,608 tCO<sub>2</sub>e (CBI, 2021).



## PRODUCTION OF TOMATOES IN NIGERIA

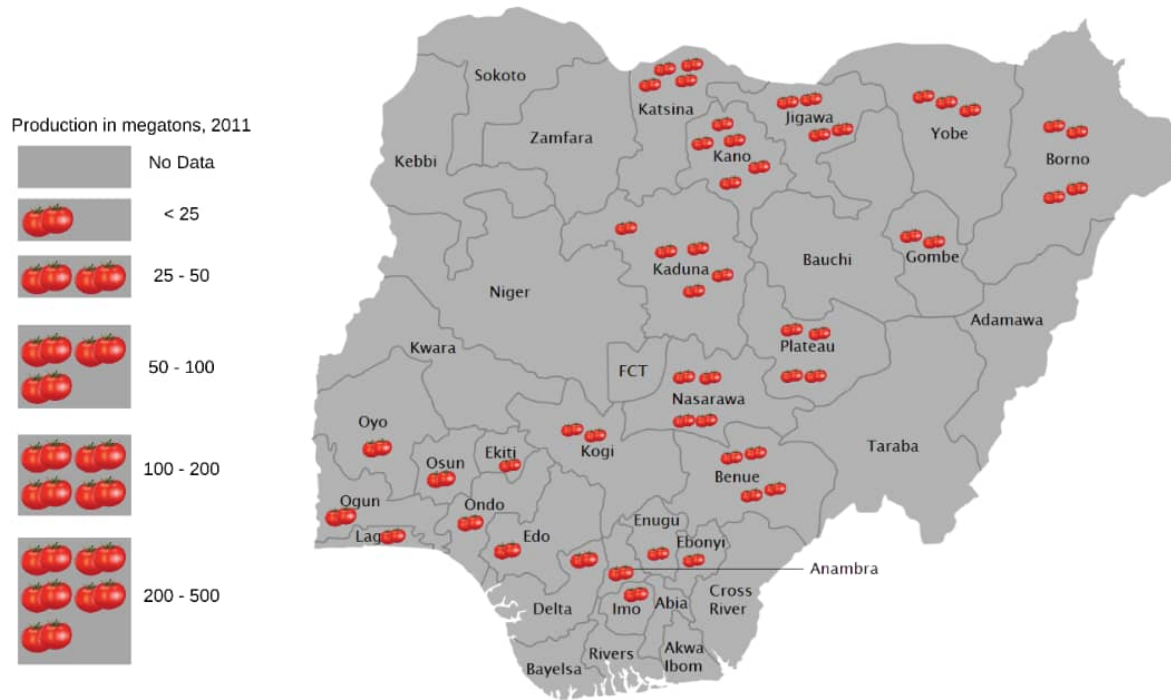


Fig. 16: Map of Nigeria Depicting Tomato Producing States and Production in Megatons (Adapted from World Bank, 2020)

The operational dynamics of this sector now include spatial distribution challenges between production zones and consumption areas. The southern areas' primary demand centres generate a geographical mismatch with northern production areas that traditional market mechanisms struggle to solve efficiently (Ugonna et al., 2015). Fig. 16 depicts the tomato producing states in Nigeria. The spatial production-consumption mismatch works alongside seasonal production trends to create supply shortages from March to July as local production nearly reaches a standstill (Fatobi et al., 2018). The mismatched timing and location (temporal and spatial misalignments) demonstrate that existing theories about agricultural market activities in developing countries have significant shortcomings (Ugonna et al., 2015).

According to the World Bank report (2020), tomato processing capacity in Nigeria experienced minimal growth from handling 10,000 metric tonnes annually in 2014 to facilities projected to manage over 1,361 tonnes daily by 2019. These changes have transformed farmers' interactions with markets while establishing fresh quality standards and pricing structures and introducing new technology systems throughout the entire value chain. Enterprises such as Tomato Jos

demonstrate a crucial shift in how value chain connections operate and market integration patterns have evolved (Maritz and Peters, 2022).

In Nigeria's tomato supply chain, the complex adaptive network model (Marchi et al., 2014) operates with informal intermediaries including local traders and collectors (aggregators), wholesalers and retailers (Ugonna et al., 2015) who serve institutional roles in addressing structural market gaps (Marchi et al., 2014). Traditional market efficiency theory considers intermediaries as a source of friction that raises transaction costs (Peng and York, 2001). Yet, their operations in Nigeria's tomato supply chain demonstrate sophisticated market-making activities that transcend supply-demand matching. These intermediaries function as knowledge brokers and risk arbitrageurs who generate multidimensional value by distributing information about processes, quality standards, and market demands (Cole and Aitken, 2020). Embedded learning through knowledge transfer demonstrates how market intelligence passes through informal yet systematic connections, creating social infrastructure that compensates for the absence of physical infrastructure (Hassan et al., 2021).

Through their activities of large-scale purchases and prepayments, intermediaries function as shadow banking institutions which establish a shadow banking system to offset capital market deficiencies in agricultural finance (Cole and Aitken, 2020; Hassan et al., 2021). Nonetheless, aggregating these vital market-making roles within intermediary networks engenders imbalances in structural power. By filling institutional gaps, intermediaries improve their market position, enabling rent-seeking practices that increase consumer prices and reduce farmer earnings (Glode et al., 2017; Ochoi et al., 2018; Zego et al., 2024). The existing market mechanisms create a structural lock-in which prevents the market from transitioning to more efficient arrangements (Ilu et al., 2021).

Nigerian tomato supply chain actors demonstrate frugal innovation resilience through locally adapted solutions that defy traditional assumptions about technological prerequisites for supply chain effectiveness (De Marchi et al., 2022; Oke and Nair, 2023). Plastic crates and shade during sorting, alongside improved handling tools, demonstrate bottom-up innovations that redefine supply chain modernisation discussions in developing economies (Tobe et al., 2023). Several studies suggest how gradual, specific solutions can produce substantial supply chain advancements that oppose the technological leapfrogging narrative in current supply chain discussions (Baryannis et al., 2019; Yap and Rasiah, 2017; Fawcett et al., 2018; Cricelli et al., 2022). For instance, Odeyemi et al. (2022) reusable plastic crates combined with zero-energy

cooling chambers (ZECCs) decreased losses from 30% to 10%, showing that resource-limited innovations can create efficiency improvements comparable to capital-intensive methods. Research outcomes establish foundations for developing new theories about suitable technology implementation in agricultural supply chains where effectiveness depends on sustainable use of available resources instead of absolute performance standards.

The promotion of climate-smart agriculture through multi-stakeholder interventions involving private enterprises alongside non-profit organisations and third parties exemplifies distributed innovation networks (Kühne et al., 2013) which foster technological advancement by sharing knowledge collectively instead of relying on centralised modernisation approaches (Abegunde et al., 2019). This research identifies persistent infrastructure constraints such as inadequate storage facilities and basic transportation methods (Shukla and Jharkharia, 2013) as factors leading to efficiency plateau points where further progress depends on system-wide changes instead of single action improvements. The 50% fresh tomato loss data presented by Onwude et al. (2023) demonstrates both quantitatively and qualitatively how step-by-step improvements fall short without comprehensive systemic change. This research expands knowledge on manual handling and low technology adoption in traditional supply chains (Zhong et al., 2017; Zego et al., 2024) by demonstrating localised innovation-driven efficiency pockets operating within systemic constraints.

The advancement of Nigeria's tomato supply chain demonstrates hybrid institutional emergence which features the simultaneous development and adaptation of formal and informal organisational systems (Mair et al., 2015). According to Zego et al. (2024), conventional models focus on institutional dichotomies. Studies demonstrate that partnership and cooperative formation in tomato production regions like Kaduna, Kano and Bauchi States showcases adaptive formalisation where informal networks embed formal structures and yet avoid complete transformation (Benabdellah et al., 2018). The described process shows how business collaborations improve profit margins by selective integration, as Oke (2019) described, enabling participants to access structured advantages while maintaining informal operational flexibility. The Nigeria Agribusiness Group and USAID programs alongside informal market dynamics show institutional layering through organised initiatives as described by Zego et al. (2024). These formal initiatives establish additional routes that enhance existing informal networks instead of replacing traditional practices.

Multiple institutional logics operate productively in Nigeria's tomato supply chain, challenging conventional modernisation theories (Takeshima et al., 2023; Adeniyi et al., 2024). For instance, informal markets thrive through adaptive pricing and flexible sourcing mechanisms, enabling a responsive informality that supports advanced risk management strategies in unpredictable environments, despite seeming inefficient (Mani et al., 2018; Oluwatayo, 2018). A significant theoretical advancement has arisen from investigating farmers' cultivation of crops during dry seasons in Kwara State and the northern regions. Farmers utilising irrigation technologies to seize seasonal market opportunities create value through temporal efficiency rather than spatial efficiency, constituting temporal arbitrage (Adenuga et al., 2013). The growth of dry-season farming, supported by government schemes and private investments, underscores technological hybridisation, which manifests as the selective integration of modern elements into traditional practices rather than a wholesale transformation (Olaleye et al., 2010).

However, the limited upstream integration among producers, processors, and logistics players reveals a structural persistence process, where entrenched operating systems endure despite incentives for change due to modernisation (Ugonna et al., 2015). The high seasonality and volatility that define the supply chain (Kitinoja et al., 2019) represent systemic informality, where apparent inefficiencies function as adaptive measures in conditions of limited institutional support.

## **2.7.2 Actors in Nigeria's Tomato Supply Chain**

### **2.7.2.1 Input Suppliers**

Input suppliers represent crucial stakeholders within the Nigerian tomato supply chain, as they furnish farmers with vital resources, including seeds, fertilisers, pesticides, and equipment. In addition, these suppliers extend advisory services and occasionally aid farmers in obtaining credit (Orji et al., 2020; Anglade et al., 2021). The provision of these inputs is essential for enhancing both the yield and quality of tomatoes, which in turn influences the entire supply chain (Wang and Xu, 2022).

The input suppliers in the Nigeria tomato supply chain adopt different approaches to reaching and serving the farmers. Essential strategies include setting up formal stores in rural communities to increase input accessibility (Anglade et al., 2021), adopting digital technologies to expand customer reach and sales channels (Schwering et al., 2022), and providing after-sales services and technical support to help create loyalty among farmers (Schaedler et al., 2022).

Input suppliers contribute to the tomato value chain by providing quality inputs, ensuring farmers access to high-yield seed varieties, effective fertilizers, and pest control solutions (Oso, 2020). Input suppliers also offer advisory services, such as educating farmers on best agricultural practices to maximize productivity (Hornum and Bolwig, 2021). In addition, they develop distribution networks that ensure the delivery of inputs to remote farming areas and sometimes through cooperatives (Ugonna et al., 2015).

Input suppliers implement various approaches, including local vendors and agro-dealers, extending value chains to the rural farmer level (Oso, 2020; Anglade et al., 2021). They work with cooperatives for effective input distribution mechanisms (Zego et al., 2024). Others use mobile technology, which provides digital platforms for ordering inputs and agricultural advice (Hornum and Bolwig, 2021). Fig. 17 depicts greenhouses offered for sale by local input suppliers, demonstrating the emerging infrastructure investments that support controlled-environment tomato production in Nigeria.



Fig. 17: Greenhouses for Sale by Local Input Supplier (source research participant)

However, the supply chain of tomatoes faces huge input transportation challenges in Nigeria. The country has very poor transport infrastructure and high logistics costs, which may cause bottlenecks in the supply and timely delivery of inputs to farmers (Asante et al., 2021). This may further result in late planting, reduced yields, and disruptions in the overall supply of tomatoes (Ugonna et al., 2015).

Recent innovations in the Nigerian tomato supply chain have focused on improving logistics and supply chain coordination to address these transportation challenges. For instance, the use of digital technologies, such as sensor-based greenhouse monitoring and supply chain management systems, could provide better visibility, coordination, and efficiency in the entire supply chain (Dou, 2022). Moreover, the implementation of revenue-sharing contracts between input suppliers and farmers can help align incentives to enhance coordination with suppliers in the supply chain (Shi and Wang, 2022).

Inefficiency at the input supply stage creates ripple effects through the value chain. Chikez et al. (2023) outline that the combined impact of poor-quality inputs and the existence of considerably improved varieties of seeds and adequate pest management practices results in yield gaps as high as 60% compared to international standards. These findings agree with the work of Norbert et al. (2023), which outlines high prices of inputs and limited access to extension services. Further, the GEMS4 (2015) report highlights these input constraints, which, coupled with poor handling practices, result in huge produce losses estimated at 40% due to poor sorting and packaging practices.

#### 2.7.2.2 Primary Producers

Recent empirical studies have delineated key elements and challenges that have determined the effectiveness and sustainability of the tomato value chain in Nigeria (Zego et al., 2024; Abdul et al., 2020; Chikez et al., 2023). The literature shows that the supply chain is primarily characterized by smallholder farmers operating on plots between 0.5–4 hectares (with an average farm size of 3.61 hectares), with production concentrated in the northern regions (Kaduna and Kano State as the highest producers) (Singh et al., 2015; Sahel Capital Partners, 2017). The small scale of production significantly affects the operational capacities and accessibility of resources for these agricultural producers; still, there is evidence that, at this small scale, tomato farming remains profitable in Nigeria (Akinola et al., 2023). Fig. 18 illustrates greenhouse-based primary production of tomatoes, showcasing the controlled cultivation environments employed by some producers to enhance yield quality and reduce exposure to climatic variability.





Fig. 18: Greenhouse Primary Production of Tomatoes (source research participant)

These farmers, which include smallholders and small-scale farmers, face critical challenges in accessing modern inputs, improved technologies, and irrigation systems. At the same time, their knowledge of climate adaptation strategies remains limited despite the recent targeted training programs (Adebisi-Adelani and Akeredolu, 2020). Besides, primary production is also further hindered by the cyclical nature inherent in tomato cultivation, which engenders great market instability and price fluctuations (Mani et al., 2018). They face significant challenges in technology adoption, leading to lower yields (an average of 4 MT/ha) compared to regional peers like Egypt (38.7 MT/ha) and South Africa (78.7 MT/ha) (Ugonna et al., 2015).

Some commercial producers have better access to resources in terms of irrigation and technology. Although they contribute significantly to production, it is limited by poor infrastructure (Ugonna et al., 2015). Most primary producers in Nigeria's tomato supply chain practice rain-fed agriculture that is subject to climate changes. The irrigation practice has grown in application with the development of simple and novel irrigation kits, which have fostered higher crop yields but require significant financial inputs (Adenuga et al., 2013).



To prevent post-harvest losses, novel technologies such as Zero Energy Cooling Chambers (ZECC) and Reusable Plastic Crates (RPC) have been invented. For example, ZECC showed a loss reduction of up to 75% in initial studies; nevertheless, adopting such practices remains low due to financial barriers (Odeyemi et al., 2021). The socio-economic characteristics of primary producers show that they are predominantly male and have low formal education, which reduces their ability to adopt modern agricultural practices and technologies (Amurtiya and Adewuyi, 2020; Ngbede et al., 2021). Women play a key role in tomato production and marketing, especially in southern Nigeria. However, gender disparities concerning access to resources like land and credit remain persistent (Iwuchukwu et al., 2017).

Tomato farming is practiced throughout Nigeria, although primary production is concentrated in the savannah agro-channel region, mainly in the Northern states. The reason for this dominance in tomato production by the Northern regions of Nigeria is the favorable agricultural conditions. However, there are significant losses during post-harvest handling and transportation due to inadequate facilities (Oso, 2020). The central producing states include Kano, which is the core production area, followed by Kaduna, Jigawa, Sokoto, Zamfara, Bauchi, Gombe, and Taraba; also, some of the southern states, like Kwara, Oyo, and Delta, contribute substantially to this (Akinola et al., 2023). This spatial distribution is primarily due to the reduced incidence of tomato-associated diseases and pests in these areas, making them more suitable for agricultural cultivation. Production in Southern Nigeria is low and often supplemented with extra backyard farming activities (Ugonna et al., 2015). Fig. 16 is adapted from Akinola et al. (2023) and captures Nigeria's tomato-producing states and the quantities of tomatoes produced.

Tomato farmers in Nigeria attain comparatively modest yields when evaluated against international standards. The typical yield is around 3.91 tonnes per hectare, a figure exceeding that of certain African nations, is markedly below global benchmarks (Akinola et al., 2023). The current yield per hectare is envisaged to be between 20 and 40 tons per year, which is far less than what is obtained in countries like the Netherlands, Belgium, and the United Kingdom, where production can reach over 400 tonnes per hectare (Akinola et al., 2023).

These producers face severe operational constraints. They mostly access low-yielding improved seeds, pesticides, and fungicides. Knowledge of markets is usually limited, with market fluctuation and crop shelf-life being very challenging for them. While most of the farmers have access to extension services, most have limited access to credit facilities and insurance (Akinola et al., 2023). Post-harvest losses are a big challenge for such producers, with estimates of 40 to 50%

yield being lost due to inadequate handling, processing, storage, and preservation techniques (Zego et al., 2024).

The high rate of loss, together with other biological and post-harvest challenges, such as the 2016 outbreak of the tomato leafminer (*Tuta Absoluta*) shows the vulnerability of these producers. This is very important, considering that Nigeria is among the leading tomato-producing countries in West Africa, with about 68.4% of the region's production coming from the country (Zego et al., 2024).

The government policies, ranging from import restrictions on tomato paste to financial subsidies on greenhouse technology, are focused on improving the supply chain. However, these policies have largely been compromised by corruption and weak policy implementation (Oso, 2020). Producers have depended on informal markets because of unstable policies that have so far barred the emergence of a strong domestic processing sector (Ugonna et al., 2015).

Primary producers in Nigeria's tomato supply chain are diverse in scale, geography, and socio-economic background. While smallholders dominate in terms of numbers, inefficiencies, vulnerability to climate change, and poor infrastructure dilute the effect. The chasm can be bridged by targeted investments such as those in technology, the strengthening of cooperatives, and infrastructure development. Taking a holistic approach will assure sustainable growth for Nigeria's tomato sector.

### 2.7.2.3 Intermediaries and Post-Harvest Actors

The role of intermediaries is a crucial but problematic part of the value chain, considering that, according to research by Plaisier et al. (2019), traditional intermediaries can add up to 150% markup over farm-gate prices. This causes significant price distortion for the end consumer and decreases farmers' profitability. Another big bottleneck is in the processing sector, which operates below 20% capacity, based on World Bank assessments of 2020. This underutilisation is mainly caused by raw material shortages and infrastructure constraints, as documented by Ugonna et al. (2015), who note that poor farmer-processor linkages are a core constraint to industrial growth in the sector.

Brokers, assemblers, storage providers, and transporters are intermediaries in the tomato supply chain (Atman et al., 2021; Suleiman et al., 2024). Brokers are intermediaries between producers and wholesalers, charging commissions (Atman et al., 2021). Brokers and assemblers can handle

the aggregation of produce and its distribution, thereby directly linking the farmgate and end consumer (linking businesses directly to the producers) (Atman et al., 2021).

Transporters are essential intermediaries in the Nigerian tomato supply chain; they facilitate the movement of tomatoes from rural agricultural production areas to urban centres, markets, and processing plants. While their contribution to reducing post-harvest losses through the speedy transportation of fresh produce is meaningful, inefficiencies abound (Idah et al., 2007). They collect produce from farms or aggregation centers and sell or supply to markets, wholesalers, or processing companies. Moreover, they facilitate the movement of agricultural products to urban markets where demand is highest (Idah et al., 2007). Adequate transportation systems ensure that harvested tomatoes maintain quality and market viability, reducing transportation waste (Oke et al., 2019). Fig. 19 shows tomatoes arriving at Mile 12 market in Lagos State, one of Nigeria's largest wholesale markets, illustrating the final stages of the transportation process from northern production zones to southern consumption centres.



Fig. 19: Tomatoes Arriving in Mile 12 market in Lagos State (source research participants)



Fig. 20: Modern Cooling Vans for Agri-fresh foods in Nigeria

Fig. 20 presents modern cooling vans designed for agri-fresh food transportation in Nigeria, representing emerging cold-chain innovations that aim to address the persistent challenge of temperature-related spoilage during transit. Tomatoes are frequently conveyed using open transportation methods, rendering them susceptible to environmental hazards including elevated temperatures, precipitation, and issues arising from physical handling (Zego et al., 2024). In rural regions, motorcycles and tricycles, referred to as “keke,” are typically employed for short-distance transport. Nevertheless, these modes of transportation may not be as effective for long-distance or bulk shipping (Atman et al., 2021).

Tomatoes are traditionally distributed in woven baskets; however, such a method leads to large-scale loss because of poor support and improper ventilation. Instead, reusable plastic crates are increasingly used (van Wagenberg et al., 2019). Postharvest loss is still a huge problem; for instance, studies have estimated that 40-50% of tomatoes harvested in Nigeria are lost due to poor handling and inefficient transport systems (Ugonna et al., 2015).

Inadequate road infrastructures markedly prolong transportation times and elevate the likelihood of spoilage, particularly in the rainy season (Sambo et al., 2016). The absence of cold chain facilities intensifies spoilage risks during transportation, notably for long-distance logistics (Zego et al., 2024). Escalating fuel costs and restricted access to financing impose a financial burden on transport operators and raise the overall expenses associated with tomato logistics (Adepoju, 2014).

At the value chain level, post-harvest handling has been identified among the major constraints that face this crop; various literature estimates losses to be within the range of 40-60% due to persistent losses (PwC, 2017; Odeyemi et al., 2022; Ojimi et al., 2021). This is further increased by continued reliance on conventional methods of handling and the use of raffia baskets, which is at almost all levels of harvesting activities. Considerable deficiency in infrastructure exacerbates this; for example, research work by Nwaizu et al. (2022) shows that rotting conditions and reputation of cold chain facilities contribute to a minimum of 45% of post-harvest losses. This gains considerable significance in the backdrop of geographical distances separating northern producing areas from central southern commercial markets (SureChain, 2021).

Processors transform raw tomatoes into value-added products such as paste or puree, which prolongs shelf life. By transforming tomatoes into processed varieties, processors improve these products' usability and market appeal (Ugonna et al., 2015). Cold-storage managers oversee

facilities that store fresh tomatoes, thereby minimising spoilage and enhancing market availability. Zego et al. (2024) state cold storage managers mitigate perishability, facilitating off-season sales and ensuring a stable supply. Fig. 21 depicts open market sales of fresh tomatoes alongside locally pureed tomatoes sold in public markets, illustrating the dual retail channels through which tomatoes reach final consumers in Nigeria.







Fig. 21: Open Market Sales of Tomatoes(top) and Locally Pureed Tomatoes(bottom) Sold in Public Markets (source research participants)

Packaging suppliers provide essential materials for transporting and handling tomatoes safely. Innovations such as reusable plastic crates (RPCs) have shown promise in reducing losses compared to traditional woven baskets (Babarinsa et al., 2018; Benson et al., 2020). Studies demonstrate that RPCs can reduce post-harvest transit losses and ensure safer handling (Benson et al., 2020). Market associations play a vital role in overseeing market activities, guaranteeing adherence to quality benchmarks, and establishing equitable pricing structures. They facilitate transactions and foster a more just marketplace for agricultural producers, merchants, and consumers (Sani et al., 2023). Fig. 22 contrasts reusable plastic crates with traditional woven baskets used for transporting tomatoes, visually demonstrating the packaging innovations that studies indicate can significantly reduce post-harvest transit losses.



Fig. 22: Plastic Crates(top) Innovation Versus Local Baskets (bottom) Used for Transporting Tomatoes (source research participants)

Intermediaries and post-harvest participants in Nigeria's tomato supply chain encounter numerous obstacles, particularly with infrastructure inadequacies. Insufficient road networks and a lack of appropriate cold storage facilities contribute to heightened post-harvest losses. Additionally, price instability stemming from seasonal production patterns and insufficient market



regulation results in erratic price variations. The prevalence of informal actors contributes to operational inefficiencies and a deficiency in standardisation. Furthermore, inadequate institutional support, characterised by restricted access to financing, training, and technology, impedes overall efficiency.

#### 2.7.2.4 Extension Services

Agricultural extension services play several vital but currently limited roles in Nigeria's tomato value chain. According to the reviewed studies, extension agents serve as a crucial link between research and technology and farmers' adoption of improved practices. Extension Officers are agricultural advisors who give post-harvest management training to farmers (Sani et al., 2023). Nevertheless, approximately 51% of tomato producers benefit from extension services (Akinola et al., 2023), signifying a notable disparity in coverage that impacts the overall efficiency of the sector.

Extension personnel predominantly facilitate technology dissemination and educators throughout the value chain. As articulated by Ugonna et al. (2015), they deliver essential information regarding Good Agricultural Practices (GAP), management strategies for diseases and pests, post-harvest handling techniques, and the selection and management of new cultivars. The knowledge transfer is indispensable for productivity improvement and for the reduction of the rampant post-harvest losses that characterise Nigeria's tomato sub-sector. Extension agents also serve as sources of information for markets, guiding the farmer to understand fluctuations in price levels, quality expectations, market opportunities and storage options critical for ensuring access to markets and profits accrual (Ugonna et al., 2015).

Extension agents also help to establish and support cooperatives. Danmaigoro et al. (2024) encourage farmers to develop cooperatives, provide technical support to cooperative members, and facilitate linkages between the cooperatives and other actors along the value chain. This organisational support is essential given the fragmented nature of tomato farming in Nigeria and the need for coordination to improve market access and build bargaining power.

However, several critical factors hamper the effectiveness of extension staff in the tomato value chain. These include inadequate access and coverage of extension services, insufficient funding and resources, poor transportation facilities, lack of knowledge of modern production techniques, and weak linkages with research institutions. These constraints have contributed to the

persistently high post-harvest losses (45-50%) and low yields (20-40 tons/ha) in Nigeria's tomato sector compared to global standards (Ugonna et al., 2015).

The literature reviewed presents a broader approach to strengthen extension services, including increased funding and resources, improved training of extension personnel, better coordination with research institutions, greater use of ICT and digital extension methods, and more focus on a whole-value-chain approach than just production. This metamorphosis is essential in enhancing the efficiency and productivity level of the tomato value chain in Nigeria.

#### 2.7.2.5 Regulatory Bodies

The supply chain for tomatoes in Nigeria is a complex structure that consists of different activities involved in production, distribution, and marketing, which are overseen by the diverse array of regulatory agencies. These include government ministries, parastatal organisations, and certifying bodies that are responsible for issues such as food safety and quality control, financial inclusion, and integrating new technologies. While important, the effectiveness of these regulatory institutions is mainly compromised by systemic inefficiencies, duplication of mandates, and enforcement gaps. This section critically reviews the main regulatory actors, their roles, and their contribution to the tomato value chain through a synthesis of the institutional framework, scholarly insights, and case studies.

The National Agency for Food and Drug Administration and Control (NAFDAC) is pivotal in ensuring food safety and compliance with agricultural product standards, particularly in regulating food additives and pesticide use (Eruaga, 2024; Amadi and Tsui, 2019). However, enforcement challenges and delays in approvals often undermine its impact, leaving gaps in monitoring pesticide residues on tomatoes, a critical concern for export markets. Similarly, the Standards Organisation of Nigeria (SON) enforces quality standards to enhance the market competitiveness of Nigerian tomatoes (Labaran and Hamma-Adama, 2021). Yet, its interventions often focus disproportionately on processed products, neglecting fresh tomato supply chains where informal trade dominates.

The Federal Ministry of Agriculture and Rural Development (FMARD) encourages farmer cooperatives and incentivizes domestic tomato production (Ugonna et al., 2015). Critics have, however, argued that FMARD's policies have generally been biased toward large-scale agribusinesses at the expense of smallholder farmers, who produce the bulk of tomatoes in Nigeria. Concurrently, the National Agricultural Seeds Council (NASC) is responsible for

safeguarding the quality of seeds that are supplied to agricultural producers (Olutuase et al., 2022); however, issues such as the prevalence of counterfeit seeds and restricted access to certified seeds continue to exist. These difficulties are further exacerbated by inadequate collaboration among NASC and additional organisations, including FMARD and NAFDAC, which obstructs establishing a unified regulatory framework for the tomato industry. The National Biosafety Management Agency (NBMA) extensively supervises and regulates GM crops, including GM tomatoes, developed to enhance shelf life and reduce postharvest losses (Yusuf et al., 2023).

The Central Bank of Nigeria plays a vital role in leading agricultural development through targeted finance programs and regulatory decisions that are most telling in effect on the tomato value chain. This will align with Nigeria's broader vision of ensuring food security, increasing local production, and reducing reliance on importation. The CBN has put in place different landmark initiatives to support smallholding farmers and enhance efficiency along the entire value chain of agriculture. The Anchor Borrowers' Programme (ABP) has contributed highly to ensure that farmers access various facilities at affordable costs for credit and other essential farm inputs like seeds and fertilisers to integrate them into formal value chains.

According to Olomu et al. (2020), the CBN encouraged local production by setting high import tariffs for tomato paste and introducing tax exemptions along with zero duty for importing greenhouse equipment. Implementing these measures aims to promote local cultivation and processing activities, thereby fostering a more self-sufficient tomato supply chain (Oso, 2020).

Despite these efforts, the outcomes of these measures are far from uniform. While the financial programs like ABP have managed to involve many smallholder farmers, significant disparities still occur in the distribution of resources, with larger agribusiness enterprises more often benefiting at the expense of smallholders. Secondly, reliance on tariff-based policies has been criticised for creating market distortions since local producers cannot meet the demand for quality processed tomato products.

Challenges related to market integration remain evident across the entire supply chain, as indicated by investigations conducted by the Tomato Sector Roadmap (2016) and NIRP (2016), which emphasise the disconnection between farmers and processors. This fragmentation contributes to supply chain inefficiencies and seasonal surpluses in production, culminating in considerable waste, estimated at 45% of total output. Furthermore, the predicament is intensified

by erratic governmental policies and restricted financial accessibility for both farmers and processors (Ringim, 2016). A recent study by Parfitt et al. (2010) broadens this investigation by assessing the global comparison of these challenges, highlighting that although developed markets grapple with waste at the consumer level, developing markets such as Nigeria encounter considerable difficulties upstream.

The available literature shows significant gaps in the current research scenario, particularly concerning quantitative modelling of post-harvest losses and optimisation of cold chain infrastructure. While research studies by GEMS4 (2015) and Tomato Feasibility Studies (2016) are relevant for industrywide insights, the strong analytical model is missing to assess the effectiveness of interventions. In addition, the studies by Amao et al. (2022) and Adepoju (2014) indicated that socioeconomic shocks significantly impact value chain development. However, there is an urgent need to go up the stairs concerning how these systems can actually build in resilience.

Works by Zego et al. (2024) and Abdul et al. (2020) have initiated filling these lacunae by providing holistic frameworks to analyse challenges along the value chain; their results have stopped at more descriptive than prescriptive analytics. Therefore, it will not be an insurmountable task for future research to develop such quantitative models able to optimise postharvest handling and analyse implications of digital technologies for supply chain integration. A study on the fluctuation of prices in local markets by Adeoye et al. (2022) established that there are appropriate market information systems combined with price stabilisation mechanisms. Table 19 provides an overview of the primary regulatory bodies and their roles.

Table 12: Food Regulatory Bodies in Nigeria and their Role Description

| <b>Regulatory Body</b>                                                | <b>Role</b>                                                                                  | <b>Key Challenges</b>                                | <b>Source</b>                      |
|-----------------------------------------------------------------------|----------------------------------------------------------------------------------------------|------------------------------------------------------|------------------------------------|
| National Agency for Food and Drug Administration and Control (NAFDAC) | Ensures food safety, regulates pesticides, and enforces agricultural product standards.      | Limited funding; insufficient digital infrastructure | Eruaga, 2024; Amadi and Tsui, 2019 |
| Standards Organisation of Nigeria (SON)                               | Develops and enforces quality standards for fresh and processed tomato products.             | Focus on processed tomatoes; neglect of fresh trade  | Labaran and Hamma-Adama, 2021      |
| Federal Ministry of Agriculture and Rural Development (FMARD)         | Implements agricultural policies, promotes farmer cooperatives, and incentivizes production. | Bias toward large agribusinesses                     | Ugonna et al., 2015                |
| National Agricultural Seeds Council (NASC)                            | Ensures quality control in seed production and distribution.                                 | Low rural reach; insufficient resources              | Olutuase et al., 2022              |

|                                             |                                                                                                                        |                                                 |                               |
|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|-------------------------------|
| National Biosafety Management Agency (NBMA) | Regulates genetically modified (GM) crops, ensuring biosafety, environmental sustainability, and ecological integrity. | Farmer resistance to GM seeds                   | Yusuf et al., 2023            |
| Central Bank of Nigeria (CBN)               | Supports financial inclusion through credit schemes and digital payment platforms, aiding smallholder farmers.         | Limited rural penetration of financial services | Labaran and Hamma-Adama, 2021 |

#### 2.7.2.6 Emerging Digital and Technology-Driven Agencies

The Nigerian tomato supply chain provides an illustrative example of digital transformation's potential and limitations in agrifood systems. Persistent challenges such as post-harvest losses, price volatility, and information asymmetry undermine supply chain efficiency (Ugonna et al., 2015). Mobile-based platforms, such as digital market information systems, have shown promise in mitigating these challenges. Ibrahim et al. (2023) found that farmers using these platforms received 15-20% higher prices for their produce. However, complete adoption has not been developed due to poor infrastructure and generally low levels of digital literacy in small-scale farmers.

Blockchain technology has been used in several pilot projects that enhance traceability and decrease fraudulent dealings in the Nigerian tomato value chain. According to Okonkwo et al. (2022), most of those projects face challenges like poor power supply, limited internet access, or lack of well-trained technical personnel, which are particularly serious in rural areas.

Digital transformation endeavours have led to the emergence of novel participants within the regulatory framework. For example, the National Information Technology Development Agency (NITDA) and the Nigerian Communications Commission (NCC) lead initiatives to digitise the agricultural sector. NITDA advocates for implementing blockchain technology and Internet of Things (IoT) applications to enhance traceability and mitigate postharvest losses (Kmiecik and Egbunu, 2022). However, such technology adoption by smallholder farmers needs further development due to deficits in infrastructure and gaps in digital literacy. On the contrary, NCC avails ICT infrastructure to mobile platforms connecting agricultural communities of the rural areas, Suleiman et al. (2024) add. The rural setting remains poorly fitted with digital infrastructure to limit the use of such technologies in changing the production and distribution of tomatoes.

Other initiatives involve the Digital Agriculture Development Initiative, the Nigeria Digital Agriculture Strategy, and many more that aim to improve productivity and market access through digital technologies. It is indicative that the leaders are conscious of the digital revolution. Critics, however, argue that the initiatives often do not rhyme with the needs of the small-scale farmers, the majority of whom are without reasonable access to affordable smartphones and digital sources of finance.

Table 13: Digital Regulatory Bodies and Their Roles

| Digital Tech Regulatory Body/Initiative                    | Role                                                                                     | Key Challenges             | Source                                                 |
|------------------------------------------------------------|------------------------------------------------------------------------------------------|----------------------------|--------------------------------------------------------|
| National Information Technology Development Agency (NITDA) | Facilitates blockchain and IoT solutions for agriculture.                                | Low implementation rate    | Kmiecik and Egbunu, 2022                               |
| Nigerian Communications Commission (NCC)                   | Provides ICT infrastructure for mobile platforms to enhance connectivity in agriculture. | Limited rural coverage     | Suleiman et al., 2024                                  |
| Digital Agriculture Development Initiative (DADI)          | Promotes digital solutions to reduce postharvest losses and improve market access.       | Moderate uptake            | Yusuf et al., 2023                                     |
| Nigeria Digital Agriculture Strategy (NDAS)                | Provides direction for adopting digital technologies in agriculture.                     | Early-stage implementation | Draft National Digital Agriculture Strategy, 2020–2030 |

#### 2.7.2.7 Certification Bodies and Quality Assurance

Table 14 summarises the principal certification bodies operating within Nigeria's agricultural sector and their roles in quality assurance. Certification bodies ensure that standards related to safety and quality are complied with along the value chain. The leading organisations concerned with setting standards for fresh and processed tomatoes are the Standards Organisation of Nigeria and the National Agency for Food and Drug Administration and Control. However, with the help of international certification bodies like Bureau Veritas Nigeria, offering ISO 22000 and HACCP certification significantly enhances the competitive positioning of Nigerian tomatoes in global markets. In fact, such accreditation is often key to accessing high-value export markets, but local producers' uptake has remained minimal due to their high costs and lack of awareness.

Table 14: Certification Bodies and Their Roles

| <b>Certification Body/Agency</b>                                      | <b>Role</b>                                                                                | <b>Key Challenges</b>                   | <b>Source</b>                |
|-----------------------------------------------------------------------|--------------------------------------------------------------------------------------------|-----------------------------------------|------------------------------|
| Standards Organisation of Nigeria (SON)                               | Develops and enforces safety and quality standards.                                        | Limited engagement with informal actors | Optimum Times, 2022          |
| National Agency for Food and Drug Administration and Control (NAFDAC) | Regulates food safety and quality compliance.                                              | Inadequate monitoring resources         | Nigerian Finder, 2023        |
| Bureau Veritas Nigeria                                                | Offers food safety certifications (ISO 22000, HACCP, etc.) for export-oriented businesses. | High compliance costs                   | Bureau Veritas Nigeria, 2021 |
| Nigerian Institute of Production Management (NIPM)                    | Provides certifications in production and supply chain management.                         | Limited outreach                        | NIPM Nigeria, 2022           |

The limited engagement of smallholder farmers with certification agencies remains a critical bottleneck. Addressing this gap requires targeted interventions such as subsidised certification fees, awareness campaigns, and enhanced collaboration between certification bodies and farmer cooperatives.

### 2.7.3 Innovations in Policies and Infrastructure

Recent policy developments include the National Agricultural Technology and Innovation Policy (NATIP) for 2022-2027 and the release of Genetically Modified (GM) tomatoes. The NBMA-regulated GM tomatoes have been developed to reduce losses due to the shelf-life extension. However, farmers' and environmental groups' resistance to GM crops remains a significant challenge (Yusuf et al., 2023).

In addition, cost-effective innovations such as Zero Energy Cooling Chambers (ZECC) and the use of returnable plastic crates have been experimented to reduce the spoilage rate from 40% to 5% in some regions (Plaisier et al., 2019). Scalable through innovation, this also relies on infrastructure challenges, systemic challenges related to inadequate cold storage facilities, and unreliable power supplies, contributing to postharvest losses of up to 50% annually (Suleiman et al., 2024).

## 2.8 Conclusion of Literature Review

This literature review systematically examines digital transformation in agri-food supply chains, with particular emphasis on upstream food-loss quantification methodologies, digital platform

governance, and the institutional and capability conditions that shape technology implementation in Sub-Saharan African contexts. Drawing on two systematic literature reviews and the critical analysis of Nigeria's tomato supply chain, the chapter identifies a set of interlocking research gaps that this thesis addresses.

### **Gap 1: Limited understanding of post-implementation operationalisation and realised digital performance**

Whilst existing literature extensively documents barriers to digital technology adoption in agri-food systems (Trendov, Varas, and Zeng, 2019; Birner et al., 2021), there remains insufficient explanation of why digital interventions frequently fail to deliver expected efficiency gains during implementation and in routine operation. Much of the evidence base remains disproportionately pre-adoption in orientation, emphasising connectivity constraints, digital literacy, and affordability, whilst offering limited insight into the operational frictions that arise when technologies are introduced into existing workflows (Fielke et al., 2020).

This chapter demonstrates that digitalisation can introduce or reproduce inefficiencies through weak interoperability, misaligned incentives that generate fragmented “digital islands”, inadequate workflow integration, and underutilisation that yields low returns on investment (Aker, 2011; Fabregas et al., 2019). These outcomes suggest that adoption should not be treated as a proxy for performance: implementation quality, governance fit, and coordination capacities shape whether digital tools become productive infrastructure or additional administrative burden. This thesis addresses the gap by examining implementation and post-implementation operational dynamics, analysing how and why efficiency gains are constrained despite technological availability.

### **Gap 2: Fragmented theorisation across technical capabilities, institutional voids, and platform governance mechanisms**

The literature on digital platforms in agri-food systems remains theoretically fragmented. Distinct streams examine capabilities and resources (Barney, 1991), institutional environments and governance quality (North, 1990; Williamson, 1985), and platform economics emphasising network effects and multi-sided market dynamics (Rochet and Tirole, 2003). However, these bodies of work are frequently mobilised in parallel rather than integrated into a unified



explanatory model for agrifood multi-sided platforms operating in resource-constrained and institutionally heterogeneous environments (Klerkx, Jakku, and Labarthe, 2019).

As this chapter shows, platform outcomes are co-produced by uneven user capabilities, institutional voids that weaken formal enforcement and dispute resolution, and platform-specific governance choices that structure participation, information access, and value capture. The thesis addresses this gap by developing an integrated framework that synthesises capability constraints, institutional governance conditions, and platform governance mechanisms, thereby enabling analysis of performance variation that cannot be explained by any single perspective alone.

### **Gap 3: Insufficient empirical and analytical attention to power asymmetries and governance failures in digital platforms**

Scholarship on digital agriculture platforms often foregrounds efficiency gains and expanded market access (Fabregas et al., 2019; Aker, 2011), whilst underexamining how platform architectures can reproduce or intensify asymmetries of power, information, and bargaining position between supply chain actors. Critical work indicates that platforms may concentrate control through data ownership, algorithmic opacity, and one-sided contractual terms that disadvantage smallholders and smaller intermediaries (Bronson and Knezevic, 2016; van der Burg, Bogaardt, and Wolfert, 2019; Rotz et al., 2019).

This chapter further indicates that effective agrifood platform governance requires explicit attention to data rights, transparency, accountability, and competition risks, particularly where enforcement capacity is weak and informal intermediation structures remain central. The thesis addresses this gap by empirically examining how platform governance and incomplete digital contracting shape distributional outcomes, focusing on how power is exercised through rules, standards, data control, and algorithmic decision-making

### **Gap 4: Methodological fragmentation and institutional embedding in upstream food loss quantification**

Despite sustained policy attention to food loss, upstream quantification remains characterised by definitional heterogeneity, method variation, and limited comparability across contexts and stages (Gustavsson et al., 2011; FAO, 2019). The chapter demonstrates that estimates differ materially depending on whether loss is captured through recall surveys, direct physical measurement,

mass balance approaches, or model-based coefficients, and on how boundaries are drawn between “loss”, “waste”, diversion to alternative uses, and quality degradation.

Crucially, the chapter shows that measurement is not merely a technical exercise: what is counted, who counts it, and what remains invisible are shaped by incentives, governance arrangements, and power relations, especially in informal markets where traceability and reporting infrastructures are weak. This thesis addresses the gap by treating quantification as a socio-technical practice, analysing how measurement choices interact with governance and incentives, and how these interactions shape both the evidence base and the apparent effectiveness of digital interventions. The objective is not to claim “perfect measurement”, but to produce more analytically defensible interpretations of loss figures and their governance consequences.

**Gap 5: Empirically uneven, commodity-specific evidence linking digital transformation, platform governance, and food loss dynamics in Sub-Saharan Africa**

Although Sub-Saharan Africa has received substantial scholarly attention in parts of the food loss literature, the evidence base remains unevenly distributed across countries, commodities, and supply chain forms, and is often thin where the interaction between digital platforms, governance arrangements, and upstream loss dynamics is most consequential. In particular, there is limited empirically grounded, commodity-specific work that connects platform governance and implementation conditions to both efficiency outcomes and distributional consequences within informal and hybrid market structures.

This thesis addresses the gap by providing a rich, contextualised analysis of Nigeria’s tomato supply chain, examining how digital initiatives operate within a landscape of infrastructural constraints, institutional fragmentation, and entrenched intermediation, and how these conditions shape both loss dynamics and the distribution of gains and burdens across actors.

**Gap 6: Inadequate theorisation of adoption without proportionate efficiency gains, alongside limited evaluation of environmental and distributional externalities**

A persistent puzzle across the literature is the coexistence of digital adoption with continuing inefficiency. Technology-centric perspectives, including diffusion of innovations (Rogers, 2003) and the Technology Acceptance Model (Davis, 1989), frequently imply that adoption should yield efficiency improvements once initial barriers are overcome. However, evidence indicates that

adoption does not reliably resolve transaction costs, market failures, or coordination breakdowns, particularly where institutional enforcement is weak and implementation conditions are constrained (Aker, 2011; Fabregas et al., 2019; Fielke et al., 2020). This paradox remains undertheorised.

In addition, the chapter identifies a related sustainability problem: the environmental footprint of digital infrastructures, including energy demand, electronic waste, water use in cooling systems, and extraction impacts, is often excluded from evaluations that treat digitalisation as inherently “green” (Aschemann-Witzel and Stangherlin, 2021). These omissions risk overstating net benefits and obscuring who bears environmental and economic costs.

The thesis addresses this combined gap by developing Constrained Efficiency as a core explanatory concept, theorising how institutional voids, contractual incompleteness, and capability constraints jointly limit realised efficiency gains (Hart and Moore, 1990; Grossman and Hart, 1986; North, 1990; Williamson, 1985). Environmental and distributional externalities are incorporated as evaluative and governance-relevant dimensions of efficiency, rather than as a full life-cycle accounting exercise, thereby avoiding scope claims that cannot be empirically supported within the thesis design.

### **2.8.1 Integration with the theoretical framework and research design**

The gaps identified in this chapter motivate a mechanism-focused theoretical synthesis in Chapter Three. Theoretical perspectives used here, including Complex Adaptive Systems and Institutional Theory for upstream measurement and governance diagnosis, and the platform governance triad emphasising network effects, institutional voids, and platform governance, establish the empirical and conceptual patterns requiring explanation. Chapter Three builds on, rather than discards, these insights by introducing a complementary analytical strategy that foregrounds causal mechanisms.

Accordingly, Chapter Three integrates Incomplete Contract Theory (Grossman and Hart, 1986; Hart and Moore, 1990), New Institutional Economics (North, 1990; Williamson, 1985), and the Resource-Based View (Barney, 1991). In combination, these perspectives enable analysis of how contractual incompleteness and renegotiation shape implementation outcomes, how institutional enforcement gaps constrain coordination and performance, and how capability and resource asymmetries condition the feasibility and value of digital tools. Within this synthesis, Constrained Efficiency functions as the central explanatory construct, whilst the thesis’s wider conceptual

model, referred to as the Digital Constraint Paradox Framework, specifies how these mechanisms interact in empirically observable ways across contrasting governance configurations.

These gaps also inform the research design and methodological strategy developed in subsequent chapters. A multi-case study approach enables comparison of how different governance forms, including informal or state-influenced arrangements and private platform-driven models, interact with resource constraints to shape digital outcomes. An abductive logic supports iterative movement between empirical evidence and theoretical refinement, strengthening explanatory validity by ensuring that conceptual development remains anchored to observed organisational and institutional realities.

Overall, this chapter establishes the foundations for a thesis contribution that moves beyond adoption-centred explanations and single-lens accounts: it advances an integrated approach to digital transformation in resource-constrained agri-food systems that takes seriously operational implementation, institutional enforcement, platform governance, power and distribution, measurement politics, and environmental trade-offs within a single, coherent explanatory framework.

### 3 Chapter Three: Theoretical Framework

#### 3.1 Introduction

Chapter Two demonstrated that upstream agri-food supply chains are characterised by fragmented data, methodological inconsistency, weak governance, and uneven digitalisation, particularly in low and middle-income settings such as Nigeria (Sheahan and Barrett, 2017; Abiad and Meho, 2018; Hoehn et al., 2023; Gustavsson et al., 2011). It highlighted that food loss quantification remains dominated by linear, reductionist methods (Boiteau and Pingali, 2023) that overlook complex adaptive dynamics and institutional power relations; that interventions at production, processing, and logistics nodes are treated in isolation rather than as part of a coordinated system; and that digital transformation and platformisation are frequently framed in techno-optimistic terms that obscure structural constraints, power asymmetries and ecological costs (Bronson and Knezevic, 2016; Rotz et al., 2019; Rijswijk et al., 2021). It also revealed that the Nigerian tomato sector combines high levels of informality, frugal innovation and institutional hybridity with persistent post-harvest loss and incomplete integration of digital tools and formal contracts (Plaisier et al., 2019; Abdulrahman et al., 2025).

The findings from Chapter Two identify six interlocking research gaps that motivate this chapter. Gap 1 concerns the limited understanding of post-implementation operationalisation and realised digital performance, highlighting why digital interventions may fail to deliver expected efficiency gains during implementation and routine operation. Gap 2 concerns fragmented theorisation across technical capabilities, institutional voids and platform governance mechanisms, which are frequently mobilised in parallel rather than integrated. Gap 3 concerns insufficient empirical and analytical attention to power asymmetries and governance failures in digital platforms, including the distributional consequences of data control, algorithmic opacity and one-sided contractual terms. Gap 4 concerns methodological fragmentation and the institutional embedding of upstream food loss quantification, where measurement choices and visibility are shaped by incentives, governance arrangements and power relations as well as by method. Gap 5 concerns empirically uneven, commodity-specific evidence linking digital transformation, platform governance and food loss dynamics in Sub-Saharan Africa, particularly within informal and hybrid market structures. Gap 6 concerns inadequate theorisation of adoption without proportionate efficiency gains, alongside limited evaluation of environmental and distributional externalities, motivating the Constrained Efficiency construct and the Digital Constraint Paradox framework.

This chapter addresses these gaps by developing a multi-theory framework that integrates Incomplete Contract Theory (ICT), New Institutional Economics (NIE), and the Resource-Based View (RBV). ICT foregrounds residual control rights, renegotiation and power asymmetries in incomplete contracts (Grossman and Hart, 1986; Hart and Moore, 1990), and is particularly useful for analysing how digital tools and platforms reconfigure contractual power, surveillance and risk allocation along the chain. NIE emphasises how formal rules, informal norms, enforcement capacities and institutional voids shape transaction costs and feasible governance structures (Coase, 1937; Williamson, 1985; North, 1990), which is crucial for understanding Nigeria's hybrid formal-informal tomato markets. RBV and related capability perspectives focus on how firms and networks mobilise tangible and intangible resources, including digital infrastructure and human capital, to create and sustain advantage under constraint (Penrose, 1959; Barney, 1991).

Table 15 provides an explicit mapping between the thesis research question foci and the theoretical lenses mobilised in this chapter. The research question foci below follow the six gaps articulated in Chapter Two and should be read alongside the formal research questions in Chapter One.

Table 15: Mapping between thesis gaps derived foci and theoretical lenses

| <b>Research question focus (gap-derived)</b>                                                                           | <b>Relevant gap(s)</b> | <b>Primary theoretical lens</b>       | <b>Mechanisms foregrounded in Chapter Three</b>                                                                            |
|------------------------------------------------------------------------------------------------------------------------|------------------------|---------------------------------------|----------------------------------------------------------------------------------------------------------------------------|
| Post-implementation operationalisation and realised digital performance in upstream agri-food chains                   | Gap 1; Gap 6           | NIE; RBV; ICT; Constrained Efficiency | Workflow integration, interoperability, incentive alignment, enforcement capacity and renegotiation shaping realised gains |
| Integrated explanation of digital platform outcomes under uneven capabilities and institutional voids                  | Gap 2                  | NIE; RBV; ICT (integrated in DCP)     | Joint conditioning of platform governance by institutional support and capability distributions                            |
| Power asymmetries and governance failures in digital platforms, including data control and algorithmic decision-making | Gap 3                  | ICT; NIE                              | Residual control rights, hold-up, rule-setting, algorithmic opacity and limited contestation under weak enforcement        |
| Upstream food loss quantification as an institutionally embedded socio-technical practice                              | Gap 4                  | NIE; RBV; DCP                         | Incentives, visibility, reporting infrastructures and method choice shaped                                                 |

|                                                                                                                                     |       |                                            |                                                                                                                                          |
|-------------------------------------------------------------------------------------------------------------------------------------|-------|--------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                     |       |                                            | by governance and capability constraints                                                                                                 |
| Commodity-specific explanation of how platform governance and digital implementation shape food loss dynamics in Sub-Saharan Africa | Gap 5 | DCP Framework (ICT+NIE+RBV)                | Contextualised tracing of mechanisms across hybrid market structures in Nigeria's tomato supply chain                                    |
| Adoption without proportionate efficiency gains and the role of environmental and distributional externalities in evaluative claims | Gap 6 | Constrained Efficiency; DCP; ICT; NIE; RBV | Interacting contractual, institutional and capability constraints; externalities treated as governance-relevant dimensions of efficiency |

The core argument is that no single theory is sufficient to explain the digital transformation paradox identified in Chapter Two: extensive investment in measurement, digital tools and platform solutions co-existing with persistent food loss, weak inclusion and constrained system performance. Instead, the chapter develops a Constrained Efficiency perspective that shows how contractual, institutional and resource logics interact to limit the realised benefits of digital technologies. This is formalised through the Digital Constraint Paradox (DCP) Framework, this thesis's original theoretical contribution, which categorises digital transformation trajectories by levels of institutional support and resource capability in the Nigerian tomato supply chain.

The chapter proceeds as follows. Section 3.2 provides a concise theoretical foundation from classical contract theory to contemporary institutional and resource perspectives, signalling the move towards Constrained Efficiency. Section 3.3 develops the ICT lens and extends it to digital platform governance in agri-food systems. Section 3.4 introduces NIE and RBV as complementary perspectives on institutional environments and resource constraints in digital transformation. Section 3.5 integrates these strands in the Constrained Efficiency and DCP Framework, linking them explicitly to the six gaps identified above. Section 3.6 concludes by summarising the theoretical contribution and establishing the bridge to the methodology in Chapter Four.

### 3.2 Theoretical Foundations: From Contract Theory to Constrained Efficiency

This section provides the essential theoretical context for the study. A more extensive historical discussion of contract theory's development from Cournot and Walras through Coase, Williamson

and North is not reproduced in full here, as the chapter focuses on the mechanisms required for the research design.

### **3.2.1 Classical Contract Theory and Its Limitations**

Classical economic models, from Cournot's (1838) strategic interaction framework to Walras' (1874) general equilibrium theory, conceptualised markets as self-correcting systems in which contracts function as efficient coordination mechanisms. Within these models, contracts are largely invisible institutional devices embedded in price systems and competitive equilibria; they are assumed to form and adjust smoothly as agents respond to price signals. These formulations rely on strong assumptions of rational behaviour, complete information, and relatively costless adjustment, treating deviations from equilibrium as temporary.

In agri-food supply chains, especially in developing contexts, these assumptions rapidly break down. Coordination between multiple heterogeneous actors, pervasive uncertainty about quality and demand, and the perishability of produce generate high transaction costs and complex risk profiles (Williamson, 2008; Di Marcantonio and Seccia, 2020) that classical models do not capture. As Coase (1937) demonstrated, when negotiation, monitoring and enforcement are costly, firms will internalise transactions or design governance structures that depart from the frictionless market ideal. Contracts in such environments are no longer neutral background devices; they become central instruments for allocating risk, controlling assets and structuring long-term relationships (Ménard and Valceschini, 2005; Sykuta and Parcell, 2003).

### **3.2.2 The Turn to Institutional and Incomplete Contract Theory**

Recognition of these limitations led to two critical theoretical developments that underpin this thesis. First, New Institutional Economics reframed contracts as governance structures embedded in wider institutional environments. Williamson (1985, 1996) argued that transaction attributes such as asset specificity, uncertainty and frequency shape the comparative costs of alternative governance forms, including spot markets, long-term contracts and vertical integration. North (1990) added a historical and political dimension, emphasising that institutional change is path-dependent and often locked in by past power configurations. In agri-food systems, this directs attention to institutional voids, path dependence and hybrid arrangements that characterise many African supply chains (Khanna and Palepu, 2010; Doh et al., 2017; Liedong et al., 2020).



Second, Incomplete Contract Theory formalised the insight that contracts cannot specify all relevant contingencies *ex ante*. Grossman and Hart (1986) and Hart and Moore (1990) showed that bounded rationality and non-verifiable states mean parties must allocate residual control rights over assets and decision-making in unforeseen circumstances. This allocation shapes *ex ante* investment incentives, bargaining power and *ex post* surplus division. ICT shifts focus from idealised complete contracts towards the distribution of control and the governance of renegotiation when circumstances deviate from expectations. In agri-food chains, where weather shocks, policy changes and price volatility are endemic, this *ex post* dimension is systematically important.

### **3.2.3 Integrating Resource-Based Perspectives**

Whilst ICT and NIE illuminate governance failures and institutional constraints, they do not directly address the distribution of resources and capabilities required to realise potential efficiency gains. The Resource-Based View fills this gap by arguing that firm performance depends on the configuration of valuable, rare, inimitable and non-substitutable resources (Barney, 1991; Penrose, 1959). Subsequent work on dynamic capabilities has emphasised the ability to reconfigure resource bases in response to environmental change (Teece, 2007; Teece, 2014; Eisenhardt and Martin, 2000; Teece et al., 1997). In agri-food systems, this directs attention to technological infrastructure, organisational routines, human capital, financial liquidity and data capabilities that condition whether digital tools and sophisticated contracts can function in practice. As Chapter Two showed, Nigerian tomato actors operate under severe constraints of storage, transport, cold chain and digital connectivity, combined with highly uneven access to finance and extension services (Arah, 2015; Ugonna et al., 2015; Olayemi et al., 2010; Adenuga et al., 2024). Under these conditions, governance reforms and digital innovations can easily produce thin digitalisation: formal systems without the material and organisational capabilities required to use them effectively.

### **3.2.4 Paradox Theory and the Co-presence of Efficiency and Constraint**

The thesis frames digital transformation outcomes in upstream agri-food supply chains as paradoxical, in the sense that efficiency improvements and new constraints can be generated through the same governance arrangements and can persist simultaneously over time. Paradox theory provides an established organising lens for analysing such persistent, interdependent tensions, distinguishing them from dilemmas that can be resolved through sequential either–or choices. Within this tradition, paradox dynamics are treated as structural features of organising

and governance rather than as transitional frictions that disappear with time, learning, or adoption maturity (Smith and Lewis, 2011; Schad et al., 2016). This perspective is analytically relevant to the empirical puzzle identified in Chapter Two: digital tools can reduce some transaction frictions whilst intensifying others, including exclusionary enforcement, information asymmetries, and value capture imbalances, particularly in hybrid markets where institutional support and capabilities are uneven.

In this thesis, paradox theory is not introduced as a parallel explanatory stream. It is used to specify the outcome logic that the subsequent theoretical integration must be able to explain: why contractual, institutional, and capability arrangements can jointly produce efficiency gains and constraint reproduction rather than linear improvement. The Constrained Efficiency construct and the Digital Constraint Paradox (DCP) framework operationalise this insight by treating efficiency and constraint as co-produced governance effects whose configuration depends on institutional support and resource capability conditions.

The concept of Constrained Efficiency emerges at the intersection of these perspectives. It denotes situations in which contractual and institutional arrangements are designed to promote efficiency, often through digital tools and platforms, but where limited resources and capabilities, coupled with power asymmetries and weak enforcement, prevent these arrangements from delivering their promised benefits. The remainder of this chapter develops this logic and operationalises it in the Digital Constraint Paradox Framework, linking it to the empirical puzzles and research gaps identified in Chapter Two.

### **3.3 Incomplete Contract Theory and Digital Platform Governance**

#### **3.3.1 Foundations of Incomplete Contract Theory**

Incomplete Contract Theory starts from the premise that many relevant contingencies cannot be specified, verified or enforced at reasonable cost (Grossman and Hart, 1986; Hart and Moore, 1990). Grossman and Hart (1986) and Hart and Moore (1990) show that, under these conditions, ownership and residual control rights become central for incentivising relationship-specific investment. When parties cannot foresee or write down all future states of the world, they allocate formal control over key assets so that, ex post, the owner can decide how to use the asset in unforeseen situations.

This perspective is particularly relevant for agri-food supply chains, where contracts routinely omit contingencies around weather extremes, transport breakdowns, regulatory shocks and

technological failures. The original ICT models focus on bilateral relationships between firms, but their core mechanisms generalise to more complex networks in which multiple buyers, intermediaries and processors interact with smallholders (Swinnen and Maertens, 2007; Bellemare and Bloem, 2018; Baker, Gibbons and Murphy, 2002). Key analytic elements include: residual control rights and ownership (who has authority to decide on diversion, rejection, regrading or rescheduling when unforeseen events occur); ex ante investment incentives (how the allocation of control and surplus affects incentives to invest in quality, technology, traceability or relationship-specific assets); and renegotiation and hold-up (how parties use bargaining power to adjust contractual terms ex post, including the risk that one side exploits sunk investments by the other).

Empirical research in agricultural contracting demonstrates that these mechanisms are not merely theoretical (Bellemare, 2012; Barrett et al., 2012). Bellemare (2012) documents high exit rates from contract farming schemes where farmers bear substantial downside risk without commensurate control over prices, grading or timing. Barrett et al. (2012) show that ambiguities in quality and delivery clauses often allow buyers to shift risk to smallholders by rejecting produce or unilaterally modifying terms. In such settings, contractual incompleteness is not a benign technical problem; it is a locus of strategic power.

### **3.3.2 Power Asymmetries and Hold-Up in Agri-Food Contracts**

In many fresh produce chains, including tomatoes, smallholders make specific investments in seed selection, fertiliser regimes, harvesting schedules, and post-harvest handling technologies tailored to particular buyers or processors. When these investments are relationship-specific and not easily redeployed, farmers become vulnerable to hold-up: downstream actors can threaten to cancel, delay, or regrade deliveries to extract more favourable terms once the investments are sunk.

ICT predicts that such risks will distort investment incentives, leading to underinvestment in quality, technology and efficient logistics (Williamson, 1985; Saenger et al., 2013). Evidence from European fruit and vegetable supply chains indicates that strict cosmetic standards and delivery penalties imposed by large retailers lead to overproduction and anticipatory rejection, which in turn cause upstream food loss (Canali et al., 2017; Gustavsson et al., 2011). Chapter Two highlighted similar dynamics in food loss quantification, where upstream actors face strong

incentives to misreport or hide losses when contractual and regulatory frameworks place disproportionate burdens on them.

In the Nigerian tomato supply chain, power asymmetries take a distinctive form. Intermediaries perform vital market-making and financing functions, but also exercise considerable discretion over grading, price formation, and market access. Contracts, where they exist, are typically informal, verbal, and incomplete, leaving farmers with limited recourse when agreements are not honoured (Baker, Gibbons, and Murphy, 2002). From an ICT perspective, this configuration combines high asset specificity, high uncertainty and weak formal enforcement, creating fertile conditions for opportunistic recontracting and hold-up (Di Marcantonio and Seccia, 2020).

A further implication concerns intermediation. ICT and NIE imply that intermediaries persist where they supply functions that contracts and formal enforcement cannot reliably provide under uncertainty and weak institutional support, including liquidity bridging, dispute mediation, and adaptive renegotiation in response to shocks. In digitally mediated agri-food markets, these brokerage functions are frequently reconfigured rather than eliminated: digital platforms can shift intermediaries' roles towards compliance coordination, data handling, and rule translation, while leaving their underlying governance function intact. This mechanism is essential for the thesis because it links contractual incompleteness and institutional fragility to the empirical persistence of intermediaries, including in settings where price information and matching tools are available (Fafchamps, 2004; Barrett et al., 2022).

### **3.3.3 Digital Platforms, Contracts and Surveillance**

Digital platforms have been promoted as mechanisms to reduce transaction costs, improve transparency and discipline opportunism (Zhao et al., 2019; Cole, Stevenson and Aitken, 2019). In principle, real-time data, digital traceability and automated payments can limit scope for ex post opportunism and improve contractual performance (Cai et al., 2018). Blockchain-based traceability is often presented as a way of ensuring that quality standards are objectively verifiable, which could theoretically reduce disputes between buyers and suppliers.

ICT suggests, however, that digital platforms do not remove incompleteness; they relocate it (Kumar, Liu and Shan, 2020; Cole, Stevenson and Aitken, 2019). Relocation is not limited to enforcement rules and contingency specifications. Digitally mediated exchange also generates forms of value that are not easily specified and allocated at the point of contracting, including data-derived insights, learning effects, and ecosystem-level coordination benefits. These residual

benefits can be systematically captured by actors controlling the digital infrastructure and data access conditions, even when upstream actors bear the compliance burdens and operational risks of participation. This shifts attention from residual control rights alone towards the distribution of digital value creation across an ecosystem, clarifying why efficiency gains in transaction processing can coexist with constrained inclusion and asymmetric value capture (Jacobides, Cennamo and Gawer, 2018; Cutolo and Kenney, 2021). Smart contracts and platform rules encode certain contingencies and enforcement protocols, but they cannot anticipate all relevant states of the world, particularly in volatile agri-food environments with climatic and infrastructural shocks. Recent studies of blockchain traceability in food supply chains show that automated rejection of consignments failing pre-specified parameters can actually increase food loss when minor deviations, which could be accommodated under relational governance, are treated as binding breaches (Henderson et al., 2024; Feng et al., 2020; Casino et al., 2020).

Moreover, platforms often amplify existing power asymmetries (Sarku and Ayamga, 2025). Dominant buyers or platform owners typically control the design of smart contracts, data access rights and algorithms that rank, match and reward suppliers. When powerful actors specify contractual conditions in code, the opacity of algorithmic enforcement can further weaken the bargaining position of smallholders who lack the expertise or institutional support to contest outcomes (Barrett et al., 2012; Dora et al., 2021; Kitchin, 2017; Gillespie, 2014).

From an ICT standpoint, digital platforms reshape residual control rights in two main ways (Ruder, 2025). First, they shift control from dispersed human managers to centralised technical architectures controlled by platform owners or lead firms. Second, they change the information set available in ex post bargaining, since detailed digital records can be selectively mobilised to justify particular interpretations of incomplete clauses. The net effect may be more precise enforcement of some terms and greater discretionary power over others, rather than a simple reduction in transaction costs.

### **3.3.4 Algorithmic Governance, Platform Power, and the Reconfiguration of Market Coordination**

The relocation of contractual incompleteness through digital platforms is closely linked to algorithmic governance: the embedding of coordination and control within computational systems that structure decision rights, participation conditions, and enforcement practices. Within organisations and markets, algorithmic systems can reshape control by converting data into classifications, rankings, and automated actions that appear procedural yet remain contestable

in their design assumptions and parameter choices (Kellogg, Valentine and Christin, 2020). In platform settings, this dynamic is amplified because the platform operator defines the rules of interaction, the informational architecture, and the mechanisms through which participants are matched, evaluated, and rewarded, thereby exercising governance through infrastructural design rather than through direct managerial intervention (McIntyre and Srinivasan, 2017; Cutolo and Kenney, 2021).

For the purposes of this thesis, algorithmic governance matters because it generates a specific set of power-relevant mechanisms that are later traced empirically in Chapter Six. One mechanism concerns algorithmic price-setting and parameterised “objective” pricing that can narrow bargaining space and legitimise asymmetric price adjustments under opacity. A further mechanism concerns predictive optimisation and ranking, in which access to preferred market channels and contractual opportunities is conditioned on algorithmic assessments that can privilege actors with stronger digital footprints and compliance capacity. A third mechanism concerns data-driven scoring systems that stratify access to complementary resources such as credit, insurance, logistics priority, or premium market segments, thereby translating informational advantage into capability advantage. These mechanisms provide a platform-specific specification of how digital efficiency in transaction processing can coexist with intensified constraints on autonomy, participation, and value capture.

### **3.3.5 ICT Under Resource Scarcity and Institutional Weakness**

Standard ICT models assume that parties have access to legal enforcement and can anticipate the distributional implications of different ownership structures (Macchiavello, 2022). In contexts such as Nigeria’s tomato chain, these assumptions are weak (World Bank, 2020). Formal contract enforcement is costly and slow, informal norms and reputation often substitute for litigation, and many actors lack access to legal advice or financial buffers (Fafchamps, 2004; Macchiavello, 2022). At the same time, resource constraints mean that actors cannot always respond optimally to contractual risks through diversification, insurance or investment in better monitoring (Dercon, 2002; Belissa et al., 2019).

Under such conditions, contractual incompleteness interacts with resource and institutional constraints to produce what this study terms Constrained Efficiency. Agents may design contracts that are theoretically efficiency-enhancing, such as quality-linked pricing or performance-based logistics agreements, but find that weak enforcement, limited information and liquidity constraints

prevent these contracts from achieving their intended effects.( Karakostas et al., 2025; Belissa et al., 2019).

### **3.3.6 Link to Gap 3: Contracts, Platforms and Digital Transformation**

Chapter Two identified a gap in the insufficient empirical and analytical attention devoted to power asymmetries and governance failures in digital platforms, including the distributional consequences of data control, algorithmic opacity and one-sided contractual terms(Kitchin, 2017; Gillespie, 2014). ICT addresses Gap 3 by specifying how residual control rights, renegotiation and hold-up risks are reconfigured by platform rules, data architectures and digital enforcement (Sarku and Ayamga, 2025). In the Nigerian tomato case, this provides analytical leverage for examining how rules, standards, data access and algorithmic decision-making structure bargaining positions, distribute risks and shape both food loss outcomes and inclusion. It also clarifies why digital tools can intensify, rather than resolve, governance failures when underlying enforcement capacity and bargaining power remain asymmetrical.

## **3.4 Institutional and Resource Perspectives**

### **3.4.1 New Institutional Economics: Institutional Voids and Path Dependence**

NIE broadens the analysis from bilateral contracts to the institutional environments in which they operate. Coase (1937) introduced the idea that firms arise to economise on transaction costs that markets cannot handle efficiently. Williamson (1985, 1996) developed this into a comparative governance framework where asset specificity, uncertainty and frequency determine when firms rely on markets, hybrids or hierarchies. North (1990) added a historical and political dimension, emphasising that institutional change is path-dependent and often locked in by past power configurations.

In the Nigerian tomato system, Chapter Two showed that formal institutions, including seed regulation, quality standards, credit programmes and extension services, coexist with dense informal arrangements based on personal ties, rotating savings, market associations and religious or ethnic networks. Institutional voids emerge where formal mechanisms for supporting market transactions, such as quality certification, collateral registries or reliable dispute resolution, are absent or inaccessible to smallholders (Khanna and Palepu, 1997; Mair and Marti, 2009; Barnard and Luiz, 2018; Umar, Rahman and Zanello, 2025). Intermediaries fill these voids by

providing finance, information and market access, but they also generate new forms of dependency and rent extraction.

NIE helps to explain why digital interventions and sophisticated contracts do not automatically displace these hybrid arrangements. Formal digital platforms must compete with, and often depend upon, entrenched informal institutions that already structure trust, information flows and risk sharing. Where formal rules are inconsistent or weakly enforced, actors may rationally prefer informal enforcement through social sanctions or local dispute-resolution mechanisms, even if these appear inefficient from a narrow transaction-cost perspective (Fafchamps, 2004; Landa, 2016).

### **3.4.2 Institutions, Digital Transformation and Food Loss**

Chapter Two's analysis of digital transformation in agri-food systems highlighted how infrastructural gaps, regulatory fragmentation and weak coordination produce a two-speed digital economy, where large firms benefit from sophisticated tools while smallholders remain effectively offline. From an NIE perspective, this reflects misalignment between the institutional architecture of digital agriculture policies, the incentives of platform providers, and the informal logics of smallholder production and trade (Addom et al., 2019; Ehui and Tsigas, 2009; Minten, Reardon and Chen, 2017).

Institutional theory also helps to interpret the persistent focus on downstream food waste in many regulatory frameworks, and the neglect of upstream loss documented in Chapter Two. Measurement regimes and policy priorities are shaped by powerful actors in retail and waste management sectors, whose interests do not necessarily lie in exposing upstream loss patterns or renegotiating procurement contracts.

A further mechanism concerns institutional rigidity expressed through what becomes visible and governable within policy and organisational attention structures. The attention-based view of the firm emphasises that action follows from how rules, resources, and routines channel decision-makers' attention towards some issues and away from others, thereby shaping which performance problems are treated as salient and which remain peripheral (Ocasio, 1997). Applied to food system governance, this implies that long-standing institutional commitments to yield, food safety, and market access can crowd out sustained attention to upstream loss reduction, even when loss is materially significant. Digitalisation does not automatically correct this prioritisation. Digital monitoring and reporting systems frequently intensify attention to existing metrics by



improving their measurability and auditability, but they often under-measure upstream loss if it is not incorporated into core accountability and performance frameworks. In this sense, institutional rigidity is not only a matter of weak enforcement or missing institutions; it can also arise where governance systems reinforce established priorities and thereby stabilise metric selection over time, producing path-dependent visibility and intervention patterns (Sydow, Schreyögg and Koch, 2009).

### **3.4.3 Resource-Based View: Capabilities, Complementarities and Thin Digitalisation**

RBV complements NIE by shifting attention from rules to capacities. At its core, RBV argues that performance differentials arise from heterogeneous access to and deployment of resources, including physical assets, human skills, organisational routines and relational networks (Barney, 1991). In the context of digital transformation, this extends to data infrastructure, analytics capabilities and the ability to integrate new technologies into established practices.

Chapter Two showed that Nigerian tomato actors face multiple resource constraints: inadequate storage and cold chain, poor road infrastructure, limited access to affordable credit, and uneven digital connectivity and skills. These constraints mean that even when digital tools are formally present, such as mobile price information or simple logistics applications, they may not significantly alter behaviour or outcomes. The result is thin digitalisation: digital artefacts exist but remain marginal to core decision-making.

RBV further emphasises complementarities. Digital traceability, for instance, only reduces loss if it is combined with sufficient storage capacity, responsive logistics, and contractual incentives that reward quality differentiation. In the absence of these complementary resources, digital measurement may simply document loss more precisely without enabling actors to act upon it.

### **3.4.4 Institutional and Resource Mechanisms for the Thesis Gaps**

NIE addresses Gap 1 by explaining why post-implementation operationalisation and realised digital performance depend on the institutional environment, particularly transaction costs, enforcement capacity and hybrid formal-informal governance. It also contributes to Gap 2 by theorising institutional voids and governance quality as conditions shaping how platform governance mechanisms operate, and to Gap 4 by showing that upstream food loss quantification and reporting practices are institutionally embedded and incentive-shaped rather than merely technical.

RBV addresses Gap 2 by foregrounding heterogeneous resources, capabilities and complementarities that condition participation in and value capture from digital platforms. It also speaks to Gap 1 and Gap 6 by explaining why adoption may not translate into proportionate efficiency gains when digital tools are not integrated into workflows, when complementary assets such as logistics and cold chain are absent, or when capability distributions are highly uneven, producing thin digitalisation and low returns on investment.

Together with ICT, these perspectives underpin the thesis response to Gap 3 by situating power asymmetries within institutional weakness and capability inequality, and they provide the basis for addressing Gap 5 through a commodity-specific, empirically grounded analysis of Nigeria's tomato supply chain. Section 3.5 integrates ICT, NIE and RBV into the Constrained Efficiency construct and the Digital Constraint Paradox framework, providing a single explanatory model aligned with the six gaps identified in Chapter Two.

Both perspectives need to be connected to the contractual dynamics developed in Section 3.3 to understand why particular combinations of institutions and resources give rise to specific digital transformation paths and food loss outcomes. This integration is developed in Section 3.5.

### **3.5 Integrating Theories: The Constrained Efficiency and DCP Framework**

#### **3.5.1 The Limits of Contract and Resource Logics in Isolation**

Sections 3.3 and 3.4 suggest that both contract-centred and resource-centred perspectives capture important but partial aspects of digital transformation and food loss. Contract theory highlights how ownership, control rights and enforcement rules shape incentives and risk distribution but tends to treat technology and capabilities as exogenous. RBV and related capability frameworks stress the importance of technological and organisational resources, but often assume that governance structures are neutral or easily optimised.

Chapter Two showed that in practice these logics interact in more complex ways. Digital tools introduced into misaligned contractual environments may be used to intensify surveillance and risk-shifting rather than to support mutual efficiency gains. Conversely, promising contractual reforms may remain on paper if actors lack the infrastructure, skills or liquidity to comply. The empirical literature reviewed in Chapter Two documented many instances where sophisticated measurement systems, circular economy tools and digital platforms coexist with high levels of loss, particularly upstream.

This motivates a shift from asking whether contracts or resources are designed 'efficiently' in isolation, towards analysing how they jointly constrain or enable the realisation of potential gains. The Constrained Efficiency perspective developed here focuses on the execution phase: how contractual, institutional and resource arrangements interact when actors attempt to implement digital solutions and loss reduction strategies in real time.

### **3.5.2 Constrained Efficiency as an Integrative Concept**

Constrained Efficiency can be defined as a configuration in which actors adopt contractual and digital arrangements that are ostensibly efficiency-enhancing, yet the combination of institutional weaknesses and resource scarcity prevents these arrangements from delivering their intended benefits. Efficiency is not absent; it is bounded by interacting constraints and can entail distributional and environmental externalities that are obscured by narrow efficiency assessments.

From ICT, the framework takes the importance of residual control rights, renegotiation and hold-up risk. From NIE, it incorporates institutional voids, path dependence and hybrid formal-informal governance. From RBV, it integrates resource scarcity, capability limitations and complementarities. In a Constrained Efficiency setting: contracts formalise responsibilities, quality standards and digital reporting requirements, but weak enforcement and information asymmetries allow powerful actors to externalise risks and costs; institutions provide partial support for digital agriculture and loss reduction, yet fragmented policies, limited regulatory capacity and informal norms undercut implementation; and resources such as cold storage, transport, connectivity and skills are insufficient or unevenly distributed, so that digital tools cannot be used to their full potential.

Under these conditions, actors may rationally adopt practices that appear inefficient from outside, such as overproduction, early distress sales or reliance on informal intermediaries, because they offer robustness against uncertainty and weak support. Constrained Efficiency is therefore not simple failure; it is a locally rational adaptation to structural constraints.

### 3.5.3 The Digital Constraint Paradox (DCP) Framework

The Digital Constraint Paradox (DCP) Framework, this thesis's original theoretical contribution, operationalises Constrained Efficiency in a 2×2 matrix that maps digital transformation trajectories according to two core dimensions derived from NIE and RBV:

1. Horizontal axis-Institutional Support: ranging from low (fragmented rules, weak enforcement, pervasive institutional voids) to high (coherent policies, credible enforcement, supportive meso-level organisations such as cooperatives and extension systems).
2. Vertical axis-Resource Capability: ranging from low (limited physical infrastructure, finance, human capital and digital skills) to high (robust storage and logistics, access to affordable technology, strong analytical and organisational capacities).

Crossing these axes yields four ideal-typical quadrants representing distinct digital transformation trajectories:

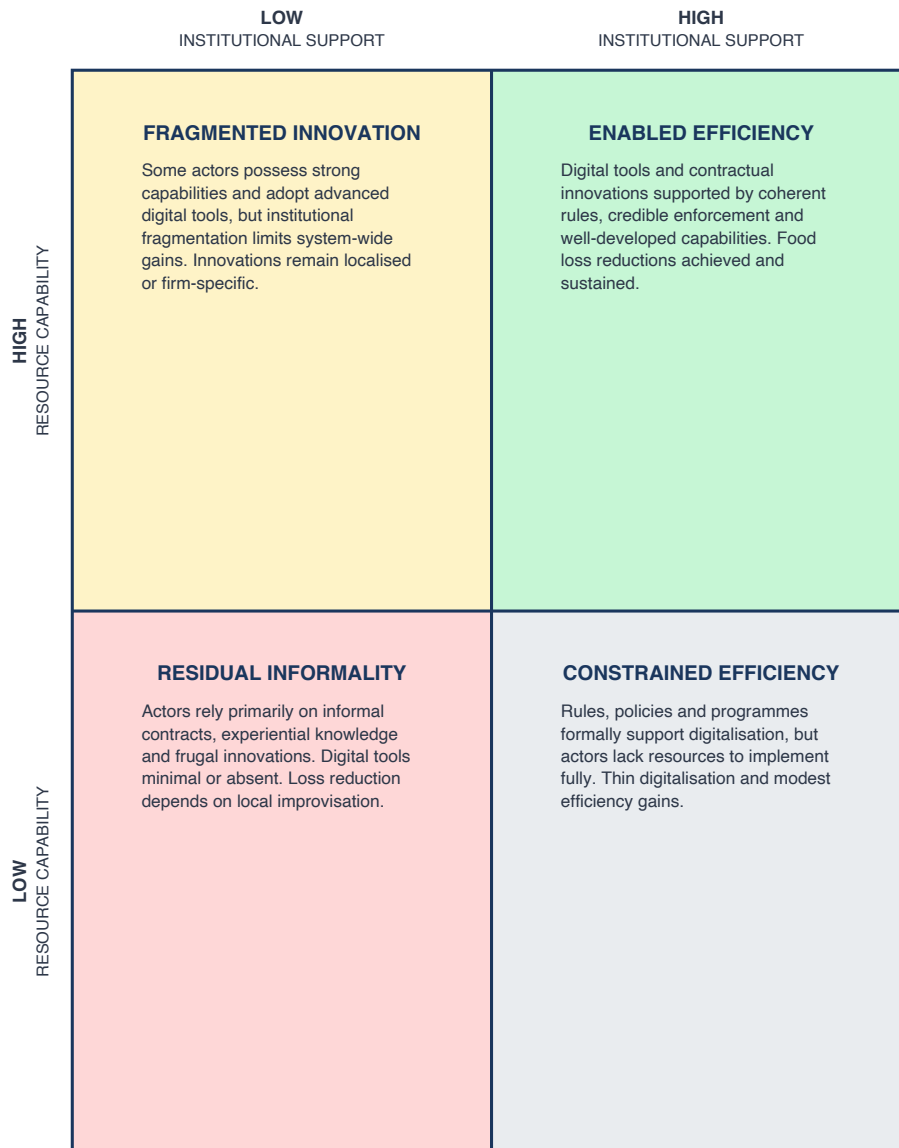


Fig. 23: The Digital Constraint Paradox (DCP) Theoretical Framework

The quadrant labels in Figure 3.1 describe governance configurations implied by the two axes. In Chapter Six, the same underlying quadrant positions are relabelled to foreground their empirically observed outcome patterns: Residual Informality corresponds to the Stagnation Trap, Fragmented Innovation corresponds to the Illusion of Efficiency, Constrained Efficiency corresponds to Institutionalised Rigidity, and Enabled Efficiency corresponds to the Zone of

Digital Synergy. The axes and the conceptual content of each quadrant remain unchanged; the shift in labels reflects the move from theoretical specification to empirically grounded interpretation.

In the Nigerian tomato chain, Chapter Two suggested that many upstream actors currently occupy the Residual Informality quadrant, with pockets of Fragmented Innovation around better-resourced processors, traders or platform pilots. Some donor-led programmes and policies attempt to move the system towards Constrained Efficiency by introducing formal quality standards, reporting frameworks and digital tools, but without commensurate investment in storage, logistics and training.

### **3.5.4 DCP and the Thesis Research Gaps**

The DCP Framework provides a conceptual map for interpreting empirical material on the Nigerian tomato chain. It is not a static typology but a way of tracing shifts over time and across actors. For example, an aggregator may move from Residual Informality to Fragmented Innovation after adopting a smartphone-based logistics application, whilst a cooperative might shift from Constrained Efficiency to Enabled Efficiency if sustained investment in storage and transport is combined with credible cooperative governance and supportive regulation.

Crucially, the DCP Framework integrates the six gaps from Chapter Two:

1. Gap 1 (limited understanding of post-implementation operationalisation and realised digital performance): Constrained Efficiency shifts analysis from adoption to execution, showing how post-adoption performance depends on the interaction between institutional support, contractual governance and resource capability, and why digital tools can yield thin digitalisation and low returns when interoperability, incentives and workflow integration are weak.
2. Gap 2 (fragmented theorisation across technical capabilities, institutional voids and platform governance mechanisms): The DCP Framework integrates ICT, NIE and RBV within a single explanatory model, treating institutional support and resource capability as joint conditions for platform governance, coordination and value creation rather than as parallel explanatory streams.
3. Gap 3 (insufficient attention to power asymmetries and governance failures in digital platforms): The DCP Framework, combined with ICT, foregrounds how residual control rights, data access and algorithmic enforcement shape bargaining power and

distributional outcomes, and how weak institutional support can allow platform governance to intensify exclusion and risk shifting.

4. Gap 4 (methodological fragmentation and institutional embedding in upstream food loss quantification): The lower-capability and low-support configurations clarify why upstream loss remains difficult to measure and compare. They highlight that quantification is a socio-technical practice shaped by incentives, governance arrangements and infrastructural capacity, not solely by method selection (Boiteau and Pingali, 2023).
5. Gap 5 (empirically uneven, commodity-specific evidence in Sub-Saharan Africa): The DCP Framework provides an explicit analytical lens for commodity- and context-specific explanation, guiding the empirical analysis of Nigeria's tomato supply chain and enabling comparison across contrasting governance configurations within informal and hybrid market structures.
6. Gap 6 (adoption without proportionate efficiency gains, alongside environmental and distributional externalities): The Digital Constraint Paradox explicitly theorises the coexistence of digital adoption and persistent inefficiency as an outcome of interacting institutional, contractual and capability constraints. It also treats distributional and environmental externalities as governance-relevant dimensions of efficiency rather than as peripheral concerns.

### 3.5.5 Operationalisation and Implications for Case Design

The Constrained Efficiency and DCP Framework has direct methodological implications. It suggests that the case study design should purposively sample actors occupying different quadrants and transition paths to observe how institutional, contractual, and resource configurations interact. Table 16 presents the operationalisation schema linking framework constructs to observable indicators and data sources.

Table 16: Operationalisation of DCP Framework Constructs

| Construct                         | Observable Indicators                                                                                                                                   | Data Sources                                                                         |
|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| <b>Contractual Incompleteness</b> | Ambiguous terms; renegotiation frequency; disputes over interpretation; unilateral modifications; asymmetric enforcement; informal vs formal agreements | Contract documents; stakeholder interviews; dispute records; transaction observation |

| <b>Construct</b>                      | <b>Observable Indicators</b>                                                                                                                                                            | <b>Data Sources</b>                                                                                           |
|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| <b>Institutional Support</b>          | Legal enforcement effectiveness; regulatory coherence; meso-level organisations (cooperatives, associations); standardisation; dispute resolution mechanisms; formal-informal hybridity | Policy documents; regulatory analysis; stakeholder interviews; observation of governance practices            |
| <b>Resource Capability</b>            | Financial capital access; technical skills; infrastructure (storage, cold chain, transport, connectivity); organisational capacity; complementary resources for digital adoption        | Stakeholder interviews; financial records; skills assessments; infrastructure audits; organisational analysis |
| <b>Digital Transformation Outcome</b> | Food loss rates; coordination efficiency; transaction costs; platform adoption/utilisation; thin vs thick digitalisation indicators                                                     | Production and loss data; platform analytics; stakeholder interviews; supply chain observation                |

The framework implies that interview guides and coding schemes should attend explicitly to: how actors experience and negotiate contractual incompleteness in digital and non-digital settings; how institutional support and voids shape their access to and use of digital tools; and how resource constraints and frugal innovations condition their capacity to respond to contractual and institutional demands.

In this sense, the framework does not only interpret empirical material *ex post*; it structures the questions, comparisons and triangulation strategies used in the analysis. Chapter Four operationalises these implications in detail, specifying case selection criteria based on variation across framework dimensions, data collection procedures aligned with construct indicators, and analytical techniques for tracing how configurations of contractual, institutional and resource conditions produce observed outcomes.

This chapter is explicitly structured to address the two research questions articulated in Chapter One. Rather than introducing additional or parallel questions, the chapter treats the research questions as mechanism-focused problem statements that are operationalised through theory. Each theoretical lens is mobilised to explain distinct, but interrelated, dimensions of the six research gaps identified in Chapter Two.



1. Research Question 1 (RQ1): How do digital interventions in Nigeria's tomato supply chain generate paradoxes of efficiency and constraint, and what governance mechanisms shape these outcomes?

RQ1 is addressed through Gaps 1, 3, and 6. Incomplete Contract Theory explains why digital interventions can underperform once deployed, despite technological availability. Contractual incompleteness, weak interoperability, misaligned incentives, and limited renegotiation capacity generate operational frictions that constrain realised efficiency. New Institutional Economics complements this analysis by explaining how institutional voids, weak enforcement, and hybrid governance structures condition implementation outcomes. Power asymmetries embedded in platform governance, including data ownership, algorithmic opacity, and one-sided rules, further shape distributional outcomes. These mechanisms are synthesised through Constrained Efficiency, which theorises the coexistence of digital adoption and persistent inefficiency, whilst treating environmental and distributional externalities as governance-relevant dimensions of efficiency.

2. Research Question 2 (RQ2): How can these paradoxes be systematically characterised, and what governance frameworks enable digital interventions to reduce constraints and improve food waste reduction outcomes?

RQ2 is addressed through Gaps 2, 4, and 5. The Digital Constraint Paradox Framework integrates New Institutional Economics and the Resource-Based View to provide a systematic characterisation of how institutional support and resource capability jointly condition digital performance. The framework treats upstream food loss quantification as a socio-technical practice shaped by incentives, governance arrangements, and infrastructural capacity, addressing methodological fragmentation in the literature. The empirical focus on Nigeria's tomato supply chain provides commodity-specific, governance-sensitive evidence that enables comparison across contrasting platform and coordination models within informal and hybrid market structures.

This alignment ensures that this chapter translates the thesis research questions into a coherent theoretical architecture. RQ1 explains the emergence of efficiency–constraint paradoxes through contractual, institutional, and power-based mechanisms, whilst RQ2 systematises these dynamics within an integrated governance framework that informs the research design and the empirical analysis that follow.

### 3.6 Conclusion

This chapter has developed a theoretical framework for analysing the digital transformation of Nigeria's tomato supply chain and its implications for food loss. It began by revisiting the six gaps identified in Chapter Two, which collectively pointed to the need for a multi-theory approach that could integrate contractual, institutional and resource perspectives.

Incomplete Contract Theory provided a lens for examining how residual control rights, renegotiation and hold-up shape contractual relationships in agri-food systems and how digital platforms and smart contracts reconfigure these dynamics. New Institutional Economics highlighted the importance of institutional voids, hybrid governance and path dependence in shaping both contract enforcement and digitalisation trajectories. The Resource-Based View focused attention on resource scarcity, capability limitations and complementarities that condition whether digital tools and contractual innovations can be implemented and sustained under constraint.

Building on these strands, the chapter introduced the Constrained Efficiency concept and formalised it through the Digital Constraint Paradox Framework. The DCP matrix maps how varying levels of institutional support and resource capability produce different digital transformation outcomes, from Residual Informality and Fragmented Innovation to Constrained Efficiency and Enabled Efficiency. It shows how contractual, institutional, and resource logics jointly constrain or enable the realisation of potential efficiency gains and reductions in losses, particularly in upstream segments of the Nigerian tomato chain.

The chapter also clarified how this integrated framework directly addresses the gaps identified in Chapter Two: it shifts analysis from adoption to post-implementation operationalisation and realised digital performance; it integrates capability constraints, institutional voids and platform governance mechanisms within a single explanatory model; it foregrounds power asymmetries and governance failures in digital platforms through incomplete contracting, data control and algorithmic decision-making; it treats upstream food loss quantification as an institutionally embedded socio-technical practice; it provides a commodity-specific lens for analysing Nigeria's tomato supply chain within informal and hybrid market structures; and it theorises the coexistence of adoption and constrained efficiency whilst incorporating environmental and distributional externalities as governance-relevant dimensions of evaluative claims.

Finally, the chapter has established a transparent bridge to the methodological design in Chapter Four. The DCP Framework and the Constrained Efficiency perspective inform case selection, sampling and the analytic strategy, ensuring that empirical work systematically explores variation across institutional and resource contexts and attends to the lived experience of contracts and digital tools. In doing so, the thesis moves from abstract theory to a contextually grounded analysis of how digital transformation shapes and is shaped by Constrained Efficiency in Nigeria's tomato supply chain. Fig. 23 reproduces the DCP Framework as a single-page summary of the theoretical framework at the end of the chapter.

## 4 Chapter Four: Methodology

### 4.1 Introduction

This chapter presents the methodological approach used to investigate paradoxes of digital transformation in Nigeria's tomato supply chains. Grounded in a critical realist philosophy and employing an abductive research design, the study adopts a multiple-case study strategy to examine how institutional factors, contractual structures, and resource constraints shape the implementation of digital technologies and post-adoption performance. The chapter is organised to make the chain of reasoning between the theoretical framework, the research questions, and the empirical strategy transparent. Critical realism provides the ontological and epistemological basis for distinguishing between observable events and the generative mechanisms that produce them, whilst abductive reasoning supports iterative movement between empirical material and theory refinement. The multiple-case design enables within-case explanation and cross-case comparison across contrasting governance configurations, allowing the analysis to specify how efficiency gains can coexist with persistent constraints.

The research questions that guide the study are presented below to foreground the methodology's explanatory task and clarify how the research design is structured to address them.

**Research Question 1 (RQ1):** How do digital interventions in Nigeria's tomato supply chain generate paradoxes of efficiency and constraint, and what governance mechanisms shape these outcomes?

**Research Question 2 (RQ2):** How can these paradoxes be systematically characterised, and what governance frameworks enable digital interventions to reduce constraints and improve food waste reduction outcomes?

In addition to the research questions, the study is guided by four objectives that specify the analytical and practical tasks required to generate credible answers to RQ1 and RQ2:

- i. To identify and explain the mechanisms through which digital interventions in Nigeria's tomato supply chain generate paradoxical outcomes of efficiency and constraint.
- ii. To examine the governance mechanisms, including contractual terms, platform rules, data control and enforcement practices, that shape these outcomes across different actor groups.

- iii. To develop a systematic characterisation of efficiency–constraint paradoxes, operationalised through the Digital Constraint Paradox framework, and to specify how these patterns vary across contrasting governance configurations.
- iv. To identify and assess governance frameworks and practical intervention levers that can reduce constraints and improve food loss reduction outcomes, with explicit attention to distributional consequences.

To provide explicit alignment between the study objectives, research questions and methodological choices, Table 17 maps each study objective to the relevant research question(s) and the methodological components used to generate evidence. This mapping clarifies why a critical realist, multiple-case study design, supported by phased semi-structured interviews, focus groups and documentary analysis, was appropriate for the thesis problem framing.

Table 17: Mapping of study objectives and research questions to phases of research

| <b>Study objective</b> | <b>Linked RQ(s)</b> | <b>Research phase(s)</b> | <b>Primary method/data</b>                                                                          | <b>Analytical contribution</b>                                                                     |
|------------------------|---------------------|--------------------------|-----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| Objective 1            | RQ1                 | Phases 1–2               | Semi-structured interviews; focus groups; archival data                                             | Mechanism identification through retroduction and abductive theorisation                           |
| Objective 2            | RQ1                 | Phases 1–2               | Interviews across actor categories; governance document review                                      | Governance mechanism tracing: contracts, rules, data control and enforcement                       |
| Objective 3            | RQ2                 | Phases 2–3               | Cross-case comparison; thematic coding; framework refinement                                        | Systematic characterisation via DCP framework and comparative logic                                |
| Objective 4            | RQ2                 | Phases 3–4               | Synthesis of mechanisms and governance configurations; triangulation with policy/industry documents | Identification of governance levers and conditions for constraint reduction and food loss outcomes |

## 4.2 Research Phases and Linkage to the Research Questions

The study proceeded through a phased research strategy designed to support abductive movement between emerging empirical patterns and theory refinement. Each phase is explicitly linked to the research questions, ensuring that data collection and analysis choices are traceable to the explanatory tasks of the thesis.

### **Phase 0: Systematic literature reviews and problem specification (links to RQ1 and RQ2)**

Two systematic literature reviews were conducted to map: (i) theoretical framings of food loss and digital transformation and (ii) upstream food loss quantification approaches. This phase refined the mechanism-focused problem framing, informed the initial interview protocol, and supported the case selection logic by clarifying where explanatory and empirical gaps were most salient.

### **Phase 1: Exploratory fieldwork and broad mechanism mapping (primary link to RQ1)**

Exploratory semi-structured interviews and early document review were used to identify how digital interventions are implemented in practice, the operational frictions encountered during implementation and routine use, and the initial contours of efficiency–constraint paradoxes across actor groups.

### **Phase 2: Focused governance and contractual mechanism probing (links to RQ1 and RQ2)**

Follow-up and targeted interviews, alongside focus group discussions and focused document analysis, were used to probe contractual terms, platform rules, data control practices and enforcement dynamics. This phase strengthened the identification of governance mechanisms and supported early cross-case comparison to refine the categories of the Digital Constraint Paradox framework.

### **Phase 3: Coding, cross-case comparison and theory refinement (primary link to RQ2)**

Iterative coding and cross-case comparison were used to stabilise first- and second-order themes, test competing explanations, and formalise the Digital Constraint Paradox framework as an explanatory model. Abductive engagement with theory ensured that the framework remained anchored in empirical material whilst specifying the mechanisms that generated observed patterns.

### **Phase 4: Synthesis and governance implications (primary link to RQ2)**

Mechanisms and configurations were synthesised to identify governance frameworks and practical intervention levers for reducing constraints and improving food loss reduction outcomes, with explicit attention to distributional consequences.

Research Philosophy

At the outset, the research positioned itself within the dominant theoretical paradigms that framed this issue. On one side were efficiency-based perspectives, mainly derived from transaction cost economics (TCE) and resource-based views, which suggested that digital technologies should, in theory, reduce inefficiencies by lowering information asymmetries, transaction costs, and market frictions (Williamson, 1985; Barney, 1991). On the other side were institutional perspectives, which emphasised how regulatory barriers, infrastructural deficiencies, and socio-political constraints inhibited the effectiveness of these digital tools in practice (North, 1990; Scott, 2014).

Thus, the initial research framing was structured as an institutional efficiency problem: digital technologies were introduced to improve efficiency, but institutional constraints were preventing their intended impact. This theoretical orientation aligns with prior studies on digital adoption in emerging markets, which focus on overcoming barriers such as infrastructure gaps, digital literacy, and regulatory misalignment (Berman, 2012; Aker and Fafchamps, 2015). The methodology was therefore designed to engage with actors across Nigeria's tomato supply chain to interpret their perspectives on food waste and digital adoption, an approach rooted in interpretivism.

#### **4.3 The Evolution of Research Inquiry**

The first year of research involved an extensive systematic literature review in two distinct phases. The first phase focused on theoretical frameworks of food waste, analysing the dominant conceptual approaches that structured food waste research. Most studies approached food waste through four primary lenses: supply chain inefficiencies, consumer behaviour, policy and governance structures, and digital interventions. The second phase examined quantification approaches to food waste, particularly the role of digital tracking, predictive analytics, and data-driven optimisation in monitoring food loss across supply chains.

A striking observation from the literature was that the effectiveness of digital technologies in reducing food waste was heavily dependent on the contractual conditions under which they were introduced. Studies that reported significant reductions in food waste often derived their data from pilot projects, research-driven interventions, or highly structured commercial environments. In contrast, studies examining government-led programs or broader market-wide implementations reported inconsistent outcomes, suggesting that food waste reduction was not merely a function

of technology access or institutional constraints but a reflection of digital interventions' contractual design.

This realisation was further reinforced by preliminary fieldwork in Nigeria's tomato sector, which highlighted how the contractual mechanism underpinning digital adoption fundamentally shaped its implementation and impact.

#### **4.4 Critical Realism as an Ontological and Epistemological Foundation**

##### **4.4.1 Ontological Positioning**

The study adopted critical realism as its ontological foundation to navigate this evolving theoretical orientation (Bhaskar, 1978, 2008). Critical realism was particularly suited to this research because it distinguishes between observable events and underlying causal mechanisms, offering a structured way to analyse why digital technologies fail to deliver their intended efficiencies in food waste reduction.

According to Bhaskar (2008), reality is stratified into three interconnected layers:

1. The Real: The underlying institutional, contractual, and structural mechanisms shaping digital adoption.
2. The Actual: The observed digital adoption patterns, supply chain inefficiencies, and contractual structures influencing food waste.
3. The Empirical: The lived experiences and perceptions of actors within the supply chain.

By adopting this stratified ontology, the study moves beyond a surface-level analysis of digital adoption metrics. Instead, it interrogates how contractual structures mediate the relationship between digital interventions and supply chain efficiencies. For example, a digital logistics platform may appear to improve efficiency, but a critical realist approach allows us to investigate how its contractual conditions, such as payment structures, data ownership, and enforcement mechanisms, determine its success or failure in reducing food waste.

##### **4.4.2 Epistemological Positioning**

The study's epistemological orientation aligns with critical realist epistemology, recognising that knowledge is historically contingent, contextually situated, and refined through iterative engagement with data (Sayer, 2000; Danermark et al., 2002). This required the use of retrodution and abduction as key methodological strategies.

- Retrodution involves identifying the underlying causal mechanisms that explain observed phenomena. This study meant moving beyond the apparent inefficiencies of digital



adoption (e.g., low farmer uptake, logistical failures) to uncover the contractual and governance structures shaping these inefficiencies.

- Abduction allows for an iterative interplay between empirical observations and theoretical refinement (Timmermans and Tavory, 2012). For instance, initial fieldwork suggested that digital platforms were failing due to infrastructure gaps, but abductive analysis revealed that infrastructure constraints were structured by contractual and financial misalignments.

These epistemological tools were embedded in the research design and data collection. Interview questions were not just descriptive but structured to probe causal mechanisms, for example:

- Instead of asking, “Why do farmers not adopt digital platforms?” the study asked, “What conditions shape how farmers engage with digital platforms, and how do contractual terms affect their decision-making?”.
- Instead of merely documenting digital inefficiencies, interviews explored how supply chain actors negotiated contractual constraints and power asymmetries in digital adoption.

By integrating retroduction and abduction, the research methodology moved beyond surface-level explanations. It facilitated the construction of the Digital Constraint Paradox (DCP). This framework captures the paradoxical ways digitalisation efforts are constrained by the very contractual and institutional mechanisms intended to facilitate them.

#### **4.5 Theorizing Digital Constraints Through a Contractual Lens**

The evolution of the research philosophy reflects the iterative and reflexive nature of theorising in complex, multi-actor environments. What began as an inquiry into institutional constraints transformed into a multi-layered investigation of contractual governance, revealing the paradoxical ways in which digital interventions are simultaneously structured for efficiency yet constrained by the governance models that oversee them.

This theoretical pivot has profound implications for both research and policy:

1. For research, it extends the literature on digital transformation by integrating contract theory with critical realism, providing a structurally embedded perspective on digital inefficiencies.
2. For policy and practice, it highlights that addressing digital inefficiencies requires more than just better infrastructure or institutional reform, it necessitates a fundamental reconsideration of how digital contracts are designed, negotiated, and enforced.

By unveiling the Digital Constraint Paradox, this study reshapes the discourse on digital governance in agri-food supply chains, offering a new theoretical lens to understand why digital efficiencies fail to materialise in practice, and how they might be restructured to overcome systemic constraints.

#### **4.6 Research Design and the Structuring of the Multiple-Case Study**

Following the ontological and epistemological commitments outlined earlier, this study adopted a multiple-case study design deliberately selected to unravel the contextual complexities of digital adoption in Nigeria's tomato supply chain and its impact on food waste reduction. Given the study's critical realist stance, which emphasises uncovering the hidden causal mechanisms that shape observed phenomena (Bhaskar, 2008; Sayer, 2000), a single-case approach would have been inadequate in capturing the heterogeneous ways in which contractual structures mediate digitalisation outcomes in different institutional and market settings. A multiple-case design allowed for a comparative interrogation of digital interventions under distinct contractual and institutional arrangements, providing a robust analytical lens through which to theorise the Digital Constraint Paradox.

##### **4.6.1 Justifying the Multiple-Case Study Approach**

The choice of a multiple-case study design was shaped by three primary considerations. First, the research problem necessitated exploring how digital interventions unfold in different contractual and institutional settings. As the initial literature review and preliminary data collection revealed, the adoption of digital technologies in agri-food supply chains is not a uniform process; rather, its outcomes are mediated by the governance models and contractual conditions under which these technologies are introduced (Hart and Moore, 1990; North, 1990). A single case would have limited the study's generalisation of insights across different contractual environments.

Second, a comparative design was essential to unpacking the layered constraints of digital adoption. A growing body of research in agri-food digitalisation highlights that institutional barrier, such as infrastructure deficits, policy inconsistencies, and market asymmetries, differ significantly across different governance models (Aker and Fafchamps, 2015; Reardon et al., 2019). By selecting multiple cases across diverse digitalisation pathways, this study was able to examine

variations in how different institutional structures and contractual frameworks shape digital transformation efforts.

Third, the study sought to generate theoretical propositions applicable beyond Nigeria's tomato sector. The theoretical ambition of this research extended beyond a descriptive account of Nigeria's digital supply chain inefficiencies; rather, it aimed to develop a structured framework for understanding digital constraints in emerging economies more broadly. This goal necessitated a replication logic, where insights from different cases could be synthesised to construct a generalisable framework for digitalisation governance in fragmented agri-food markets (Eisenhardt, 1989; Yin, 2018).

#### **4.6.2 Mapping the Cases: Contractual Configurations and Selection Criteria**

The case selection process was theoretically driven. Given the centrality of contractual framing in shaping digital adoption and food waste reduction outcomes, cases were selected based on the predominant contractual mechanisms that governed digital intervention within the supply chains under study. The study identified two primary cases through a rigorous purposive sampling strategy, each comprising distinct sub-cases that reflected different digitalisation pathways.

##### **4.6.2.1 Case One: Primary and Emerging Tomato Production Hubs**

The first case focused on traditional tomato production zones in northern Nigeria, where digital adoption was shaped by historical agricultural production structures and state-led interventions. This case was further subdivided into two sub-cases:

1. **Primary Production Hubs:** These were historically established tomato farming regions, such as Kano, Katsina, and Kaduna, where digital interventions had been introduced incrementally through local cooperatives and informal market arrangements. The adoption of digital tools in these hubs was primarily shaped by traditional knowledge systems, localised contract structures, and informal trading networks. The role of digital technology in these contexts was constrained by the absence of formal contractual governance, leading to highly fragmented and inconsistent uptake of digital innovations.
2. **State-Led Digital Interventions:** In contrast, the second sub-case examined government-driven digitalisation efforts in select regions within the same states, where state programs had introduced structured digital interventions through agricultural extension projects and food security policies. These initiatives sought to modernise traditional farming through digital platforms, input subsidies, and financial inclusion programs. However, as interviews

revealed, state-led interventions often encountered bureaucratic inertia, weak enforcement mechanisms, and difficulties in aligning digital governance with informal agricultural markets.

The comparison between these two sub-cases enabled an examination of how digitalisation unfolds under informal, market-driven contract structures versus structured, state-led initiatives. It allowed for an analysis of how contractual governance influences adoption dynamics, power asymmetries, and digital access across Nigeria's primary tomato production zones.

#### 4.6.2.2 Case Two: Commercial and Innovation-Driven Tomato Hubs

The second case focused on commercial and innovation-led hubs, where digital transformation efforts were driven by private sector investment and entrepreneurial ecosystems. These hubs, concentrated around Lagos, Ogun, and Plateau States, represented distinct market-led models of digital adoption. Again, two sub-cases were identified:

1. **Private-Sector Digitalisation Models:** This sub-case examined corporate-driven agri-tech solutions where digital technologies were integrated into the tomato supply chain through commercial contracts, fintech solutions, and private sector-led investments. These models emphasised efficiency-driven innovations, such as precision farming, IoT-based logistics, and algorithmic price forecasting. However, as findings demonstrated, these contractual arrangements often excluded smaller producers, prioritised commercial scalability over equitable access, and reinforced digital monopolisation.
2. **Hybrid NGO-Private Sector Digitalisation Models:** The second sub-case focused on agribusiness startups and NGO-led digital innovation programs. These initiatives blended donor funding, social enterprise models, and startup incubation strategies to drive digital adoption in fresh food supply chains. Unlike purely private-sector models, these initiatives were often short-term pilot projects that required external funding and faced sustainability challenges once donor support ended.

This comparative approach allowed the study to juxtapose state-led, market-driven, and hybrid contractual models of digital transformation, revealing the diverse ways in which contractual governance and institutional arrangements shape the adoption, efficiency, and sustainability of digital solutions in Nigeria's tomato sector.

#### 4.7 Actor Selection and the Logic of Snowball Sampling

A multi-actor interview strategy was employed to capture the diversity of perspectives within the selected cases, ensuring that insights were gathered from all key stakeholders within the tomato supply chain. Interview participants were selected through purposive and snowball sampling, emphasising strategic actors with direct experience with digital transformation efforts.

The researcher's background and embeddedness in Nigerian agrifood networks played a crucial role in gaining access to relevant participants. Having worked extensively in agricultural extension programs, market access research, and grassroots digitalization efforts, the researcher was well-positioned to leverage existing contacts within ministries, agri-tech startups, cooperatives, and international development organisations. Early access was facilitated through engagements with:

- i. The Federal Ministry of Agriculture provided insights into state-driven digitalisation programs.
- ii. Agri-tech startups operating within commercial tomato hubs, offering perspectives on private-sector governance models.
- iii. Cooperatives and producer networks representing smallholder perspectives on digital exclusion and informal governance.

A snowball sampling strategy was employed from these initial contacts, where key informants provided referrals to additional stakeholders. This ensured that both formal and informal digitalisation actors were included, capturing a holistic view of digital transformation's contractual, institutional, and socio-economic dynamics.

##### Structuring the Data Collection

A total of 79 semi-structured interviews were conducted across the two cases, ensuring a representative cross-section of supply chain actors. The 79 represent unique participants across the full fieldwork corpus: 15 participated in the pilot, 38 were interviewed in Phase 1, and 26 were interviewed in Phase 2; the six focus groups introduced no additional participants, as all discussants were drawn from the same pool and were used primarily for triangulation, hypothesis testing, and surfacing collective negotiation logics. Participants included are outlined in Appendix 8.

The diversity of participants allowed for triangulation of perspectives, ensuring that findings were not biased towards a single governance model. Interviews were structured to probe beyond surface-level adoption narratives, capturing hidden constraints, strategic non-adoption

behaviours, and contractual ambiguities that shape digital efficiencies. By structuring the study through a multiple-case comparative framework, this research was able to interrogate the paradoxes of digital adoption in agri-food supply chains through a contractual governance lens. The selection of contractually distinct hubs provided the necessary analytical depth to theorise digital constraints as an emergent phenomenon, not simply a function of technological access or institutional support, but of the underlying governance structures that define digital engagement. Full interview guides, focus group schedules, consent materials and the detailed fieldwork protocol are provided in Appendix 6.1.

#### **4.8 Instrumentation and Data Collection**

The design and execution of the study's data collection process followed a structured but adaptable methodological approach that allowed for an in-depth engagement with the paradoxes of digital transformation in Nigeria's tomato supply chains. Digital adoption in agri-food supply chains is not a straightforward process of technological diffusion but one that is deeply embedded within contractual, institutional, and market structures. The research instrumentation had to be designed to capture these interdependencies while remaining flexible enough to incorporate emerging empirical insights that surfaced throughout the research process.

At the heart of this study was the recognition that the standard efficiency-institutional dichotomy in digital transformation literature was insufficient for explaining the constraints and frictions that emerged within these supply chains. By employing a combination of semi-structured interviews and focus group discussions, the study was able to probe both individual rationales for technology adoption and collective negotiation processes related to contractual governance, algorithmic governance, and residual benefits in digital transformation. This approach made it possible to capture the mechanisms by which technological innovations were introduced, managed, contested, and sometimes abandoned, not simply as a function of institutional inefficiencies or infrastructural gaps but as deeply rooted contractual governance challenges.

A core realization that emerged early in the research process was that digital transformation constraints were not merely infrastructural or institutional but were also embedded within the governance mechanisms that structure digital participation. This required an iterative process of refining the research instrumentation, ensuring that questions were not only contextually appropriate but also theoretically generative. The study's data collection evolved over multiple phases, each building on the insights gathered from the previous phase, to sharpen the focus on

how digital transformation was shaped by the nature of contractual arrangements in Nigeria's tomato supply chains.

The theoretical foundations of the research instrumentation were grounded in critical realism, which provided the necessary methodological foundation to interrogate both observable and latent causal mechanisms shaping digital adoption. Unlike positivist approaches that focus primarily on measuring adoption rates or efficiency gains, or interpretivist approaches that emphasize actor perceptions, critical realism enabled a deeper inquiry into the structural mechanisms, both seen and unseen, that influence technological engagement. Bhaskar's (2008) three-domain model of reality was central to this research, allowing for an analytical distinction between empirical experiences, actual causal mechanisms, and underlying structural conditions. The empirical domain captured the lived experiences of supply chain actors in their engagements with digital technologies, while the actual domain identified institutional and regulatory constraints that shaped these engagements. The real domain, the deepest layer of analysis, focused on governance structures, contractual asymmetries, and power dynamics that determined how digital transformation unfolded across different contractual models.

The use of semi-structured interviews was particularly suited to this methodological approach, as it provided both theoretical depth and empirical openness. Unlike structured interviews, which impose rigid frameworks, or unstructured interviews, which risk incoherence across respondents, semi-structured interviews offer the flexibility to probe emerging themes while maintaining comparability across cases (Brinkmann, 2014; Kallio et al., 2016). This flexibility was essential in capturing not just the expected efficiencies of digital transformation but also the governance constraints that shaped those transformations in unanticipated ways. The semi-structured approach allowed the study to navigate the complexities of digital adoption within fragmented supply chains, where diverse actors, including government agencies, private agritech firms, smallholder farmers, cooperatives, intermediaries, and logistics providers, each engaged with digital transformation under different governance arrangements.

The study employed an abductive theorisation approach, as outlined by Gioia et al. (2013), recognising that theoretical refinement must be a continuous process informed by empirical insights. The first iteration of interview questions was designed to capture constraints in digital adoption broadly, reflecting dominant theoretical frames in the literature at the time. However, as the research progressed, it became clear that contractual governance was central to

understanding digital transformation outcomes. This realisation necessitated revising the research instrumentation to focus more on the contractual logics and governance structures shaping digital technology adoption.

One of the methodological strategies employed in this study was scenario-based elicitation, which allowed respondents to articulate decision-making processes within dynamic, real-world contexts. Instead of simply asking about past experiences, participants were presented with hypothetical but plausible scenarios to probe their reactions to governance challenges, contractual disputes, or algorithmic decision-making processes. This approach ensured that the study did not simply document existing realities but also captured how supply chain actors navigated decision-making under constraints.

The research instrumentation developed iteratively, unfolding over two distinct phases. The first data collection phase was an exploratory inquiry involving a broad set of interview questions designed to map the key constraints and paradoxes shaping digital transformation. These initial questions focused on actors' perceptions of digital efficiencies, the barriers to adopting technology, and the institutional constraints influencing digital engagement. This phase was informed by a systematic literature review on food waste, digital transformation, and institutional constraints (Rejeb et al., 2022). The research questions aimed to establish whether technology adoption in Nigeria's tomato supply chains was hindered primarily by infrastructural deficiencies or whether more profound governance challenges were at play.

However, as data from the first phase was analysed, it became evident that actors were not simply identifying technology-related constraints but were consistently framing their experiences in terms of contractual structures that governed digital adoption. This observation led to a fundamental shift in focus, requiring the research instrumentation to be adapted to interrogate contractual and governance dynamics explicitly. The study's second phase thus incorporated new questions to uncover how contractual arrangements, governance logics, and algorithmic decision-making shaped digital transformation outcomes. Additional interviews were conducted with selected respondents from the first phase to probe these themes further.

Given respondents' geographical and demographic diversity, multilingual data collection strategies were critical to ensuring accessibility and depth in data gathering. Interviews were conducted in English, Hausa, Yoruba, and Pidgin English, reflecting the linguistic composition of



Nigeria's tomato supply chain actors. Where necessary, trained interpreters facilitated discussions, particularly in cases where participants were more comfortable expressing complex ideas in indigenous languages. The researcher's fluency in Hausa and Yoruba allowed for direct engagement with many participants, enabling deeper interactions and reducing potential biases introduced through translation. All translated transcripts underwent a cross-verification process to maintain analytical rigour, ensuring that key governance-related concepts, such as algorithmic pricing, data ownership, and contractual asymmetries, were accurately preserved across linguistic adaptations (Temple and Young, 2004).

In addition to individual interviews, focus group discussions were employed to facilitate collective negotiation logics and test emerging findings. While individual interviews provided deep insights into personal decision-making and strategic actions, focus groups offered a comparative perspective by allowing participants to respond to and debate governance issues collectively. This methodological juxtaposition revealed critical discrepancies between private and public articulations of digital transformation challenges. For instance, while many interview participants initially framed cost barriers as the main obstacle to digital adoption, focus group discussions frequently uncovered governance misalignments and contractual uncertainties as more fundamental deterrents. This underscored the importance of incorporating both individual and collective perspectives into the research design.

The study's instrumentation strategy was designed to be iterative, reflexive, and theoretically grounded. Rather than treating research instruments as static tools for data extraction, the study employed them as evolving mechanisms for theory-building. The combination of semi-structured interviews, multilingual engagement, and scenario-based elicitation ensured that the study moved beyond surface-level documentation of constraints to uncover the deeper governance structures shaping digital adoption. By structuring the study through a phased abductive framework, this research ensured that the Digital Constraint Paradox framework is empirically grounded and theoretically robust. The study's methodological contributions highlight the importance of contractual governance in shaping digital transformation trajectories, offering a comprehensive and analytically rigorous foundation for understanding technology adoption in agri-food supply chains.

#### **4.8.1 Pilot Study**

A pilot study was conducted prior to full-scale fieldwork to test the feasibility, clarity, and theoretical sensitivity of the research instruments. The pilot had four purposes: assessing whether

interview prompts elicited mechanism-relevant accounts rather than purely descriptive responses; validating the sequencing and pacing of questions across actor types; testing the accessibility of terminology relating to platform governance, contractual terms, and data practices; and refining the consent, briefing, and multilingual translation procedures.

Participants were recruited purposively from the broader population of supply chain actors represented in the study, with selection focused on individuals who had direct experience of digital interventions and contractual arrangements in the tomato chain. Pilot interviews followed the initial semi-structured protocol and were recorded, transcribed, and reviewed using the same procedures applied in the main study. Where multilingual engagement was required, the translation workflow was trialled to verify that key governance constructs were retained consistently across languages.

The pilot produced four material refinements that strengthened instrument quality and analytical fit. Questions were reworded to reduce normative framing and to encourage respondents to describe specific episodes of implementation and decision-making, thereby supporting later retroductive inference. Targeted probes were added to explicitly capture contractual and platform governance mechanisms, including data access, payment terms, dispute resolution, and enforcement practices. The protocol was modularised into actor-specific versions to preserve cross-actor comparability whilst avoiding irrelevant prompts and reducing the risk of leading questions. Consent and briefing scripts were simplified and standardised across languages, and additional prompts were introduced to minimise social desirability bias when discussing sensitive issues such as price formation, exclusion, and informal payments.

Overall, the pilot enhanced construct validity by improving question clarity, strengthening alignment with the research questions, and ensuring that the protocol could consistently elicit accounts of underlying mechanisms. The final interview guides, focus group protocols, and a summary of refinements introduced following the pilot are provided in Appendix 6.1. as captured in Appendix 6.1, 15 participants were involved in the pilot study.

#### **4.8.2 Phase One**

The first data collection phase involved exploratory semi-structured interviews with a diverse set of supply chain actors, designed to map the key constraints and paradoxes shaping digital transformation. This phase was informed by existing literature on food waste, digital efficiencies, and institutional constraints (Makov et al., 2020; Rejeb et al., 2022), and questions were designed

to probe respondents' experiences with digital technologies, efficiency expectations, and the barriers they faced.

The initial interview protocol focused on three broad thematic areas, with the following types of questions:

Table 18: Sample Interview Questions and Themes Covered

| Theme     | Digital Technology Adoption and Efficiency Perceptions                                                                                                                                                                                                                                                                                                                                                                                                       |
|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Questions | <ul style="list-style-type: none"> <li>• "What digital tools or technologies have you integrated into your operations?"</li> <li>• "How have these technologies affected efficiency, costs, and waste management in your business?"</li> <li>• "Have the promised benefits of these digital tools been realized in practice?"</li> </ul>                                                                                                                     |
| Theme     | Institutional and Market Constraints                                                                                                                                                                                                                                                                                                                                                                                                                         |
| Questions | <ul style="list-style-type: none"> <li>• "What are the main barriers to adopting and using digital technologies in your work?"</li> <li>• "Do government regulations, policy incentives, or institutional support play a role in shaping your engagement with digital tools?"</li> <li>• "How do market conditions, such as pricing, contracts, and buyer expectations, affect your ability to adopt and sustain digital transformation efforts?"</li> </ul> |
| Theme     | Supply Chain and Food Loss Dynamics                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Questions | <ul style="list-style-type: none"> <li>• "To what extent does digital technology help in reducing food loss and waste in your operations?"</li> <li>• "What other factors, beyond technology, contribute to food waste in your supply chain?"</li> <li>• "What strategies have been most effective in reducing food waste in your context?"</li> </ul>                                                                                                       |

This first phase involved 38 semi-structured interviews, conducted across both primary/emerging production hubs and commercial innovation hubs.

#### 4.8.3 Phase Two

As data from the first phase were analysed, it became clear that contractual governance structures played a central role in shaping digital transformation trajectories. The second phase of interviews was therefore designed to interrogate contractual logics and governance constraints explicitly. This phase included follow-up interviews with selected respondents from Phase One, ensuring continuity and deeper exploration of emerging themes.

In this phase, additional questions were introduced, as outlined in Table 18, capturing new insights from the initial data analysis.

Table 19: Governance Themes Captured in Interview Questions

|                 |                                                                                                                                |
|-----------------|--------------------------------------------------------------------------------------------------------------------------------|
| <b>Theme</b>    | Governance Structures and Contractual Arrangements                                                                             |
| <b>Question</b> | “How do the contractual structures that govern your operations affect your ability to adopt and sustain digital technologies?” |
| <b>Theme</b>    | Algorithmic Governance and Decision-Making                                                                                     |
| <b>Question</b> | “Have digital platforms or automated decision-making systems altered power dynamics in the supply chain? In what ways?”        |
| <b>Theme</b>    | Residual Benefits and Digital Constraints                                                                                      |
| <b>Question</b> | “Beyond the direct efficiencies of digital tools, have there been unanticipated benefits or constraints that have emerged?”    |

This second phase involved an additional 26 interviews, with a more targeted selection of actors who had direct experience with contractual governance mechanisms.

#### 4.8.3.1 Multilingual Data Collection and Contextual Adaptation

The study’s multilingual data collection strategy was critical to ensuring inclusivity and depth, given the linguistic diversity of Nigeria’s tomato supply chain actors. Interviews were conducted in English, Hausa, Yoruba, and Pidgin English, ensuring that language barriers did not constrain data richness.

The researcher’s fluency in Hausa enabled direct engagement with a broad range of participants, while trained interpreters facilitated interviews in cases where other languages were required. A rigorous translation and transcription process was employed to ensure that conceptual meanings were accurately preserved across languages, with cross-verification by bilingual experts.

#### 4.8.4 Focus Group Discussions

Alongside individual interviews, six focus group discussions were conducted involving stakeholders across different governance structures. These focus groups included:

1. Local Government Agricultural Extension Officers (8 participants)
2. Smallholder Farmer Cooperatives (12 participants across two focus groups)
3. Digital Agritech Entrepreneurs and Startups (9 participants)
4. Private Sector Logistics and Supply Chain Managers (7 participants)
5. Policy and Regulatory Experts from Government Agencies (6 participants)

Focus group discussions were a crucial mechanism for validating individual interview findings, allowing the researcher to compare and contrast divergent perspectives and test emerging hypotheses (Krueger and Casey, 2014). Notably, while individual interviews often highlighted

individual strategic decisions and constraints, focus groups revealed broader structural patterns, particularly in how actors navigated contractual uncertainties and digital governance challenges.

#### A Reflexive and Iterative Approach to Instrumentation

The instrumentation strategy in this study was not static but evolved through continuous empirical engagement. By structuring data collection in two distinct phases, the research could adapt its theoretical lens in response to emerging empirical insights, ensuring a high level of analytical rigour and depth.

Through its multilingual, iterative, and theoretically informed approach, the study ensured that findings were descriptive and analytically robust, providing a nuanced understanding of how contractual governance structures shape digital adoption outcomes in Nigeria's tomato supply chains. The integration of semi-structured interviews and focus group discussions allowed the study to capture individual decision-making rationales and collective governance mechanisms, offering a comprehensive framework for analysing digital constraints in agri-food supply chains.

#### **4.9 Archival Data Collection**

Understanding the structural and institutional dynamics that shape digital transformation in Nigeria's fresh produce sector requires meticulously examining archival data. This study systematically engaged with federal, state, and local policies, legislative acts, strategic frameworks, and regulatory documents that impact the deployment of digital technologies, food loss management, and agricultural modernization. These policies were sourced from various ministries, agencies, and parastatals, as well as private-sector initiatives and state-led agricultural programs, ensuring a holistic understanding of how governance structures mediate technology adoption in Nigeria's tomato supply chains.

Digital transformation governance and food waste reduction in Nigeria's fresh produce sector spans multiple governmental institutions, reflecting a complex policy landscape that intersects agriculture, technology, trade, and environmental sustainability. The key institutions whose policies were examined and a complete table listing all analysed policy documents, legislative acts, and regulatory frameworks, including their issuing authorities, publication dates, and relevance to digital transformation and food loss and waste reductions provided in Appendix 5.

#### **4.10 Ethical Considerations**

Ethics guided the conception, fieldwork, and communication of this research. Following Aston University's ethics policy and the researcher's ethics, the study adhered to the core values of beneficence, nonmaleficence, autonomy, informed consent, anonymity, and equity (Beauchamp and Childress, 2019). Ethics approval was obtained from Aston University's College Research Ethics Committee in June 2024, permitting data collection between July and September 2024.

The study tended to prioritise participant protection in multiple ways. For the 79 participants, who represented local actors, processing companies, regulatory authorities, and small processors, informed consent was obtained in multilingual forms (English, Pidgin English, Hausa). They had the right to withdraw 14 days after the interview or before the focus group discussions began. Briefings and convenience for pre-interview preparation removed any psychological hurdles (Israel, 2014). Power differentials, especially in rural areas where local leaders might sway participation, were overcome by recruitment from within and by educating participants that participation is voluntary (Karnieli-Miller et al., 2009).

Cultural understanding was a critical aspect. The study respected local traditions and hierarchies, aiming to overcome potential obstacles, including gender roles and technological illiteracy. The consent forms were translated into a language they could easily understand and a civil tone was maintained throughout interviews and focus groups to create inclusion and trust (Liamputtong, 2008). Data protection procedures were consistent with GDPR and the UK Data Protection Act 2018. Electronic data was stored safely in Aston Box, accessible only to the researcher and collaborators. Recordings were quickly transcribed and anonymised, and pseudonymisation with alphanumeric locator and organisation codes was used (Warren et al., 2021). According to Aston University's policy, this research relied on the 3-2-1 backup rule to ensure robust data governance, with data stored for 6 years.

Results were shared via scholarly papers, stakeholder reports and policy briefings, with participants regularly updated throughout the research. Written lay summaries addressed to different stakeholder audiences helped to make results easily digestible and takeable (Crow et al., 2020). The study considered the ethical question of achieving participant anonymity while maintaining contextual richness, transparency, and respect during the study.

In keeping with the reflexive method of approaching ethical issues and devising culturally relevant approaches, this research produced ethically valid, contextually relevant and impactful results that catalysed academic and practical understanding of digital transformation in Nigerian AFSCs. To maintain transparency whilst keeping the main chapter focused, the detailed coding modes, codebook development process, double-coding procedure, and worked examples of first- and

second-order coding have been moved to Appendix 6.2. Appendix 6.2 also documents the reliability checks and the approach used to manage disagreement and code drift.

The study used an iterative thematic analysis approach to move from empirically grounded first-order codes to theoretically informed second-order themes. Initial coding remained close to participant language to preserve empirical fidelity, before patterns were consolidated through constant comparison and abductive engagement with the theoretical framework. Cross-case comparison was used to test whether emergent themes were configuration-specific or recurrent across governance arrangements.

#### **4.11 Development of First- and Second-Order Themes**

##### **4.11.1 Addressing Trustworthiness in this Study**

Using established frameworks from operations management and qualitative research, the study ensured trustworthiness through a clearly defined and well-documented qualitative methodology (Voss et al., 2002; Miles et al., 2014; Eisenhardt and Graebner, 2007). To meet the trustworthiness requirements, we used the technique of prolonged engagement, data triangulation, repeated coding and an open audit trail. As agricultural supply chains were complex and involved multiple stakeholders, these strategies played a significant role in achieving sustainability (Mena et al., 2013; Wilhelm et al., 2016). Trustworthiness was assessed based on a combined framework of traditional criteria (Lincoln and Guba, 1985) and their adaptations for operations research (Ketokivi and Choi, 2014) that spanned the dimensions of credibility, transferability, dependability, confirmability, saturation, and integrity. Refer to Appendix 6.2 (Table 19) for an overview of how each criterion was fulfilled and the specific methodology undertaken to ensure the findings are robust and relevant. Table 20 outlines the criteria employed to establish the trustworthiness of this study, mapping each criterion to the specific strategies implemented during data collection and analysis.

Table 20: Criteria for trustworthiness of study and findings

| Trustworthiness Criteria                                                                                                                                              | Approach to Addressing Trustworthiness in this Study                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Credibility:</b> The extent to which findings are authentic and believable representations of the phenomenon under study (Barratt et al., 2010; Voss et al., 2002) | <p>Conducted 79 semi-structured interviews across 10 Nigerian states, ensuring broad geographic and actor representation. Triangulated interview data with government reports, policy documents, and existing studies. Employed reflexivity through researcher journals documenting assumptions and decision-making processes. Iterative refinement of interview protocols through pilot testing. Cross-verification of findings across different actor groups and regions.</p> <p><b>Result:</b> Revised theoretical framing, addressing systemic barriers and actor roles, informed by stakeholder feedback.</p>                                                                                                                                                                                                                                                                                                                                                                                                                      |
| <b>Transferability:</b> Degree to which findings can be applied to other contexts while maintaining their inferences (Stuart et al., 2002)                            | <p>A purposive sampling strategy ensured the inclusion of diverse participants (farmers, processors, retailers, regulators) across multiple scales of operations. Theoretical sampling aligned with systemic conditions in the Nigerian tomato supply chain. Strategic selection of diverse regions representing different production environments and supply chain contexts. Inclusion of multiple actor categories (13 distinct groups) with detailed sampling rationale. Detailed description of regional contexts and actor characteristics. Purposive sampling across different scales of operations and technological adoption levels. Detailed documentation of selection criteria for each actor group in line with Lincoln and Guba (1985 p. 316) requirement to provide the data base that “makes transferability judgements possible on the part of potential appliers.” in different AFSC contexts.</p> <p><b>Result:</b> theoretical model validated for broader applicability across different supply chain contexts.</p> |
| <b>Saturation:</b> The point where further data collection does not add new insight to the theory development (Guest et al., 2006).                                   | <p>Data collection continued through interviews and workshops until no new themes emerged. Triangulation was performed using observations, archival data, and literature reviews. Coding and thematic analysis were iteratively refined among three researchers to ensure saturation.</p> <p><b>Result:</b> Generated sufficient examples and quotes for rich and clear distinctions of relevant themes.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| <b>Dependability:</b> Consistency and reliability of the research process and findings (Miles et al., 2014; Yin, 2018)                                                | <p>This research followed a structured protocol and maintained detailed documentation of the methodology, ensuring a clear audit trail. Consistency in methods and data analysis was supported by adherence to the study protocol throughout. Detailed documentation of sampling framework and participant selection criteria. Consistent application of semi-structured interview protocol. Extensive interviewer training to ensure consistent data collection. Clear</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |



|                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                 | <p>documentation of theoretical alignment with CEF dimensions. Systematic approach to addressing actor heterogeneity. Regular cross-checking of coding and analysis procedures</p> <p><b>Result:</b> Interpretation of themes remained consistent across all data sources.</p>                                                                                                                                                                                     |
| <p><b>Confirmability:</b> Extent to which findings reflect participants' perspectives rather than researcher bias (Creswell and Poth, 2016)</p> | <p>Use of reflexivity journals throughout the research process. Explicit acknowledgment and documentation of researcher assumptions. Cross-verification of interpretations across research team members. Direct quotations and evidence from participants used to support findings. Triangulation with multiple data sources to verify interpretations</p> <p><b>Result:</b> Phrasing of codes and themes refined to reflect consensus around interpretations.</p> |
| <p><b>Integrity:</b> Quality and honesty of the research process and findings (Miles et al., 2014)</p>                                          | <p>Rigorous interviewer training and protocol development. Careful attention to ethical considerations in data collection. Transparent documentation of research decisions and processes. Clear alignment between theoretical framework and methodology. Systematic approach to addressing potential biases</p> <p><b>Result:</b> No evidence of bias or misinformation was identified, enabling deeper analysis of key issues.</p>                                |
| <p><b>Fit:</b> Alignment between research findings and the substantive area under investigation (Voss et al., 2002) .</p>                       | <p>Clear theoretical alignment with CEF framework dimensions. Purposive sampling strategy reflecting research objectives. Systematic coverage of all relevant actor groups and contexts. Regular verification of findings against theoretical constructs. Comprehensive documentation of context and actor characteristics</p> <p><b>Result:</b> Concepts related to the supply chain were richly described and extended through the CEF lens.</p>                 |
| <p><b>Understanding:</b> Degree to which findings resonate with participants' experiences (Barratt et al., 2010)</p>                            | <p>Use of semi-structured format allowing participant voice. Inclusion of diverse perspectives across actor groups. Rich description of contextual factors and challenges. Attention to regional and actor-specific variations. Regular verification of interpretations during interviews</p> <p><b>Result:</b> Findings were well received by stakeholders, affirming relevance and accuracy.</p>                                                                 |
| <p><b>Generality:</b> Comprehensiveness of findings in capturing multiple aspects of the phenomenon (Eisenhardt, 1989</p>                       | <p>Broad geographic coverage across 10 Nigerian states. Inclusion of 13 distinct actor categories. Attention to heterogeneity within actor groups. Systematic documentation of variations in context and practice. Comprehensive sampling across supply chain roles</p> <p>Addressed through methods used for credibility.</p> <p><b>Result:</b> Multiple aspects of actor dynamics and systemic constraints were effectively captured.</p>                        |

|                                                                                                                  |                                                                                                                                                                                                                                                                                                                                                                                                                              |
|------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Control:</b> Extent to which organizational factors influence the theoretical framework (Stuart et al., 2002) | Explicit consideration of power dynamics and resource access. Documentation of institutional and systemic constraints. Analysis of actor-specific barriers and enablers. Attention to formal and informal institutional structures. Recognition of varying influence levels across actor groups<br><b>Result:</b> Each actor influenced key aspects of the framework, revealing power asymmetries and adaptation strategies. |
|------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

#### **4.12 Summary**

The development of first- and second-order themes in this study was not a static, one-time exercise but rather a dynamic and iterative process that evolved in response to ongoing empirical engagement and theoretical refinement. By structuring the thematic development process through empirical granularity (first-order codes) and theoretical abstraction (second-order themes), this study was able to move beyond descriptive findings and towards deep structural insights into digital transformation constraints.

The careful interplay between inductive coding, theoretical synthesis, and cross-case validation ensured that the final themes were robust, theoretically grounded, and methodologically rigorous. This reflexive, iterative approach to thematic analysis provided a methodologically rigorous foundation for structuring the study's findings and discussion, ensuring that emerging insights were both empirically valid and theoretically generative.

## 5 Chapter Five: Results

### 5.1 Overview

This chapter presents the study's empirical results, organised in a two-case design that differentiates governance configurations shaping digital intervention outcomes in Nigeria's tomato supply chain. The results are reported primarily from semi-structured interviews across actor groups and are triangulated with policy and strategy documents where these illuminate the design intent and stated implementation mechanisms.

Case One examines primary and emerging tomato production hubs where digitalisation unfolds within mixed governance conditions. It contrasts historically established production zones characterised by informal coordination and fragmented contracting with state-led digitalisation efforts implemented through agricultural programmes and extension structures. Case Two examines commercial and innovation-driven hubs in which digital transformation is driven by private sector investment and entrepreneurial ecosystems, including corporate-led agri-tech solutions and hybrid NGO-private sector initiatives.

To improve analytical clarity and comparability, each case is reported using a consistent set of conceptual categories that capture infrastructure and absorption conditions, knowledge and access dynamics, market coordination and regulatory enforcement, data and algorithmic control, and institutional adaptation. Each case concludes with a structured synthesis that links the findings directly to the study objectives and research questions, and each case is summarised in a consolidated table to support rapid interpretation and cross-case comparison.

### 5.2 Case One: Primary and Emerging Tomato Production Hubs

The first case focused on traditional tomato production zones in northern Nigeria, where historical agricultural production structures and state-led interventions shaped digital adoption. This case was further subdivided into two sub-cases:

1. **Primary Production Hubs:** These were historically established tomato farming regions, such as Kano, Katsina, and Kaduna, where digital interventions had been introduced incrementally through local cooperatives and informal market arrangements. Traditional knowledge systems, localised contract structures, and informal trading networks primarily shaped the adoption of digital tools in these hubs. The role of digital technology in these contexts was constrained by the absence of formal contractual governance, leading to highly fragmented and inconsistent uptake of digital innovations.
2. **State-Led Digital Interventions:** In contrast, the second sub-case examined government-driven digitalisation efforts in select regions within the same states, where state programs

had introduced structured digital interventions through agricultural extension projects and food security policies. The states in this category are Niger, Plateau, Sokoto, and Kwara States. These initiatives sought to modernise traditional farming through digital platforms, input subsidies, and financial inclusion programs. However, as interviews revealed, state-led interventions often encountered bureaucratic inertia, weak enforcement mechanisms, and difficulties in aligning digital governance with informal agricultural markets.

The comparison between these two sub-cases enabled an examination of how digitalisation unfolds under informal, market-driven contract structures versus structured, state-led initiatives. It allowed for an analysis of how contractual governance influences adoption dynamics, power asymmetries, and digital access across Nigeria's primary tomato production zones.

The discussion is structured along five key conceptual categories, drawing on policy document analyses and stakeholder interviews to highlight the tensions between policy rhetoric and implementation realities. Appendix 9 captures a detailed table of the thematic coding.

### **5.2.1 Technological Absorption and Infrastructure Constraints**

This category examines the physical and technical foundations necessary for digital agriculture and how their presence or absence shapes adoption patterns across different production hubs. Despite ambitious government plans for agricultural technological transformation, this thesis reveals significant gaps between policy aspirations and on-ground infrastructure realities in Kano and Kaduna. These traditional tomato-growing regions demonstrate considerable adaptive capacity but face substantial barriers to formal digital adoption.

The Rural Access and Agricultural Marketing Project (RAAMP) strategy (2018) ambitiously promises:

*"The activities in Component 1 will focus on rehabilitation of rural access roads and construction of river crossings in selected participating States to provide all-weather access to connect rural communities to local agricultural markets." (RAAMP, p.3).*

However, actors from the primary production hubs where RAAMP has been operational for over five years still grapple with rural access roads challenges that limit their local market access. As one of the farmers in Kaduna stated:

*"We face significant transportation challenges that discourage tomato farmers as many of us struggle to move our produce from farms to markets, whether locally or to Lagos. The*

*poor condition of roads makes it hard to transport our tomatoes without damage, especially during rainy seasons when these roads become terrible". (FRM05)*

Another farmer from Kano State presents other challenges associated with infrastructure that exacerbate food loss in the primary production hubs:

*"We have nearby markets, but there are times when the market crashes due to a lack of transportation options. Many farmers struggle to transport their produce from Kano to other cities, and some even have difficulty moving their goods locally. Some farmers rely on basic transportation like bikes and keke [tricycles], which limits how much we can transport at once. When transportation costs rise, they sometimes exceed what we earn from selling our tomatoes." (FRM03)*

The National Agricultural Technology and Innovation Policy (NATIP) 2022–2027 emphasises using digital tools for pest control, soil monitoring, and precision agriculture.

*"Encouraging the development of on-farm and off-farm use and adoption of digital technology and innovation platforms." (NATIP, 2022, p.55).*

However, key informant interviews from Kano and Kaduna revealed critical infrastructure deficits undermining these policy ambitions. Farmers consistently reported limited access to basic utilities such as electricity, reliable internet connectivity, and water for irrigation, let alone advanced technological tools. A processor in Kano articulated this disconnect:

*"Internet connectivity is also a problem. For example, connecting to this meeting took me a long time. So, connectivity issues are common. Additionally, there are concerns about data management and security." (PRC01).*

The infrastructure gap extends to digital tools and connectivity. The National Broadband Plan 2020–2025 explicitly targets rural agricultural communities:

*"70% of eligible individuals with broadband penetration by 2025, ensuring connectivity across rural and underserved areas." (NBP, 2020, p.39).*

Participants from Kaduna's rural districts revealed persistent network failures, with farmers reporting no access and minimal connectivity for only 3 to 5 hours per day in some locations. This unreliability makes mobile-based extension services impractical for time-sensitive agricultural activities. An agriculture extension worker articulated the challenges farmers face and the frustrations in stark terms:

*"Many tomato farmers across Kano State struggle with unreliable rural connectivity, making it impossible to access real-time market prices or weather forecasts. The high cost*

*of smartphones and limited last-mile internet infrastructure leave them isolated from digital agricultural platforms that could help improve harvesting and reduce post-harvest losses.” (EXT05)*

Beyond digital connectivity, the research identified significant gaps in the physical logistics infrastructure for perishable crop value chains. While policy documents such as the National Agricultural Technology and Innovation Policy (NATIP) 2022–2027 outline ambitious targets:

*“Reduce production and post-harvest losses by 50% in food and cash crops by 2027.” (NATIP, p. 73).*

The reality for farmers and other actors in the Nigerian tomato supply chain remains challenging. Without adequate cold storage facilities and processing technologies, tomato producers, processors, and logistics actors face significant post-harvest losses, estimated by respondents at 30-45% during peak harvest periods. As two farmers from the primary production hubs suggest:

*“These tomatoes spoil too fast after we harvest. When we get too many at once, we are forced to sell them cheap quickly or watch them rot away completely. It's painful to see our hard work wasted like that.” (FRM13)*

*“We have no proper storage here. Sometimes we try to dry our tomatoes in the sun, but honestly, it doesn't work well. The rains come, insects attack, and we lose most of what we grew. That's our biggest problem.” (FRM05)*

Despite these constraints, the research observed innovative adaptations among farmers in the emerging production hubs, including using basic mobile phones for voice-based market price checking and WhatsApp groups for sharing farming techniques, representing a form of “frugal digitalisation” that works within infrastructure limitations. As one farmer suggests:

*“I have learned from other farmers who have successfully implemented these technologies and continue to share their insights. I also participate in online farmer groups, such as those on platforms like Huge Garden, where we exchange knowledge and support each other in our agricultural endeavours.” (FRM14)*

In contrast to the adaptive approach in traditional hubs, government-driven digitalisation efforts in Niger, Plateau, Sokoto, and Kwara benefit from more formalised policy frameworks and dedicated funding for digital agriculture initiatives. However, these programs face significant implementation challenges from bureaucratic processes and institutional fragmentation.

The National Agricultural Technology and Innovation Policy (NATIP) presents an ambitious vision:

*"Facilitate the deployment and utilisation of digital technologies and innovations, such as remote-sensing, yield mapping, GPS guidance systems, food Blockchain, artificial intelligence (AI), etc." (NATIP, 2022, p. 56).*

Similarly, the National Data Strategy (2022) envisions comprehensive technological integration:

*"IoT-enabled precision agriculture to optimise water usage, reduce input costs, and maximise yields through data-driven farming techniques."(NDS, 2022, p.34)*

Key informants from the emerging production hubs revealed that while pilot projects exist in all four states, they remain largely confined to demonstration farms and research stations, with limited diffusion to ordinary farmers. Administrative delays in fund disbursement create significant implementation gaps. While farmers in these emerging hubs attest to using mobile applications as captured by a Farmer from Sokoto State, as an extension officer in Kwara explained how challenging the applications of digital tools can be :

*"We use some applications on the internet on our phones to detect diseases from the plants. We use some applications that can dictate and give us solutions to the disease and what we can and the possible solution, you know, to cure or to maintain the disease on the farm." (FRM09).*

*"Mobile app-controlled irrigation sounds great and works well on demo sites, but the funding gets stuck in government approval chains. By the time programs roll out, we are already in a new farming season. Last year, smart irrigation equipment arrived two months after planting season and was not as effective on the field as large farms that adopted had issues with internet connectivity." (EXT06)*

This timing mismatch between agricultural seasons and bureaucratic processes represents a significant barrier to technology adoption. Document analysis revealed that budget approval processes for agricultural technology projects typically take 4-6 months, meaning that the optimal window for technology deployment has often passed by the time resources are available.

This observation points to a key finding that digital initiatives in state-led contexts benefit those already possessing technological advantages, creating a "digital stratification" effect rather than broadly inclusive transformation. While mobile-based extension platforms are available through the Kaduna State Policy on Agriculture (2022), virtual interviews confirmed that primarily larger commercial farmers benefited due to higher digital literacy, better network access, and more significant financial resources to implement recommended technologies.



### 5.2.2 Digital Access and Knowledge Fragmentation

This category explores how digital knowledge and skills are distributed across different stakeholder groups and how uneven access shapes technological adoption and information flows within tomato supply chains.

In Kano and Kaduna, research revealed complex information-sharing patterns that blend traditional knowledge networks with selective digital tool adoption. The National Digital Economy Policy and Strategy (NDEPS) 2020–2030 articulates an inclusive vision:

*“The Service Infrastructure pillar will address the provision of robust digital platforms to drive the digital economy. These platforms enable transactions and interactions online. They also have the added advantage of enabling a supply of data from which both government and the private sector can gain useful insights with which to develop the digital economy.” (NDEPS, 2020, p. 41).*

However, interviews consistently revealed that smallholder farmers prefer and prioritise informal, trust-based networks over formal digital platforms. These preferences reflect both pragmatic adaptations to connectivity constraints and deeper trust issues in institutional systems. An agronomist in Kaduna observed:

*“Most of these substance farmers are in rural areas where, in Nigeria, there are no mobile networks. And some of these technologies require that you have some access to a mobile service provider... because some of these technologies require internet to work. So they don't have access to them, number one. Some don't even have one because they don't have access to the internet; there is no need for them to have an Android phone. So those are the two basic things that need to be dealt with first. Access to knowledge and provision of the internet service for them.” (AGR02)*

This observation highlights how negative experiences with formal digital systems can reinforce reliance on traditional practices. The research found that trust in digital platforms is particularly fragile in agricultural communities with limited recourse to technical support or complaint resolution mechanisms.

Despite scepticism toward formal platforms, farmers in these regions significantly adopted accessible consumer technologies for agricultural purposes. Farmers increasingly turn to WhatsApp groups and peer learning networks to share market insights and farming techniques. A cooperative leader in Kano emphasised:

*“We communicate primarily through phone calls, but we also use WhatsApp to snap pictures of any challenges and send them to each other. This allows us to discuss the*

*issues effectively. So, both phone calls and WhatsApp serve as important communication tools for us.” (ORG02)*

This finding reveals how farmers selectively incorporate accessible digital tools into existing social structures, creating hybrid knowledge-sharing systems that operate largely outside formal agricultural extension frameworks. In Kano, researchers observed active WhatsApp groups with 50-120 members sharing daily updates on market prices, weather conditions, and pest management techniques.

However, knowledge distribution across these informal networks remains uneven and fragmented. The NATIP formally promotes:

*“AI-driven farming analytics to provide personalized crop management recommendations based on soil conditions, climate data, and market forecasts.” (NATIP, 2021, p.9)*

Yet interviews revealed that such advanced analytical tools remain inaccessible to most smallholders who lack the technical skills to interpret complex digital outputs. A greenhouse specialist in Ogun stated:

*“Current agricultural policies promote the adoption of technologies, but do not address the critical knowledge gap among farmers. Many producers find themselves equipped with sophisticated technological solutions without the necessary training to leverage them effectively.”(AGR06)*

This observation highlights how technological sophistication can inadvertently exacerbate knowledge gaps without appropriate capacity building. The semi-structured interviews identified significant disparities in digital literacy even within the same farming communities, with younger, more educated farmers typically serving as digital intermediaries for older or less literate community members.

Government-driven digitalisation initiatives in Niger, Plateau, Sokoto, and Kwara feature more structured digital training programs, but participants interviewed revealed significant disparities between formal program designs and implementation realities. The National Digital Economy Policy and Strategy (2020) outlines an ambitious approach:

*“Establish a National Digital Literacy programme for rural communities. Government will work with stakeholders and partners to setup and run digital literacy programs in rural areas throughout the country. Stakeholders will play a major role in equipping the rural populace with digital skills.” (NDEPS, 2020, p. 21).*

However, interviews with extension staff and farmers revealed that these programs often fail to reach their intended beneficiaries or address their specific needs. Three key barriers emerged: geographical accessibility, curriculum relevance, and technological prerequisites.

The National Financial Inclusion Strategy (2020) explicitly supports:

*"To drive adoption of digitised G2P/P2G payments, the following strategies shall apply: Ensuring that government achieves 70% digitisation of G2P/P2G payments at all levels. Currently, only 60% of federal government flows have been digitised. This rate is lower at the state government levels and lowest at the level of local government. Local governments have the strongest interface with the financially unserved and underserved. If they lead in the adoption of digital payment, the potential for a trickle-down effect is high."* (CBN, 2020, p. 26)

Yet the semi-structured interviews confirmed that training sessions typically occur in centralised locations, requiring significant travel time and expense for remote farmers. Moreover, when farmers do access these programs, they often encounter challenges in applying the knowledge to their specific contexts. A farmer from Sokoto described his experience:

*"Most of the technologies that are supposed to be technological are no longer working. They're not properly maintained. As to adopting new technology, it's not been easy because farmers need to be trained. The technical aspects are challenging for most farmers who often lack the skills to operate them. It's a process that requires proper education...if your technology solution is too complex for small-scale farmers to use, it defeats the purpose of whatever you are designing."*(AGR06)

This quote highlights how digital literacy programs often focus narrowly on operational skills rather than troubleshooting capabilities or systemic understanding, leaving farmers vulnerable when systems don't function as expected. Document analysis of training curricula from three state programs confirmed this finding, with 75-80% of content focused on basic operations and only 5-10% addressing problem resolution or consumer rights.

Regional disparities in digital literacy training were also documented. The Niger State Policy On Agriculture (2020) outlines:

*"Phased digital transformation targeting youth farmers through smartphone-based advisory services and market linkage platforms."* (NSPA, 2020, p.14)

However, an agribusiness specialist observed:

*"Most farmers don't have access to the training they need. The challenge is transportation from my area to their area, rural farmers are in the interior parts and cannot easily come*

*to town. When we have workshops, those who attend are often not the ones who need it most. The network is not available in these communities, so even when farmers come to town to get knowledge, they cannot make use of it back in their own villages.” (EXT02)*

This observation highlights how state-led digital inclusion efforts can paradoxically reinforce existing digital divides by focusing resources where implementation is easiest rather than where needs are greatest. The semi-structured interviews documented that in all four states, training centres were predominantly located within 25km of state capitals or major towns, despite most agricultural production occurring in more remote areas.

### **5.2.3 Regulatory Control and Market Coordination Failures**

This category examines how formal and informal rules govern digital interactions in agricultural supply chains and how regulatory frameworks impact market coordination through digital means.

The research revealed significant disjunctures between formal regulatory frameworks and market realities in Kano and Kaduna's tomato supply chains. The Nigeria Digital Agriculture Strategy (2020) mandates maximising the quality and traceability of agricultural produce.

Yet the semi-structured interviews involving markets in both states confirmed that enforcement remains weak or non-existent in informal tomato markets, accounting for an estimated 70-85% of total trade volume. These markets operate through established relationships and traditional quality assessment methods rather than digital verification. A tomato aggregator in Kano articulated this disconnect:

*"You see, the government has these fancy policies about digital agriculture and traceability systems for our tomatoes, but on the ground here in Kano markets, it's a different story. Nobody is enforcing these standards. The reality is our market works on trust and relationships, not apps and digital records. Those digital systems cost money that small traders like us cannot afford, and honestly, our buyers don't even ask for that information."(AGR09)*

This observation highlights how digital regulatory frameworks often fail to account for the practical realities of traditional market systems. Document analysis revealed that regulatory implementation strategies typically assume digital infrastructure and literacy levels that exceed current realities, creating de facto exclusion of smaller market participants.

The Agricultural Produce Quality Control Act similarly emphasises formal digital mechanisms:

*"Digital certification and verification protocols for all agricultural produce entering formal market channels." (APQCA, 2019, p.18)*

However, market observations and interviews revealed the limited practical reach of these requirements. A market leader in Kaduna stated:

*"When agencies or donors introduce new policies, they could implement them effectively through Agricultural Development Programs (ADPs)... However, challenges arise during implementation. Sometimes, influential individuals, such as politicians, interfere with these programs, manipulating or redirecting the policies for personal or political gain...on paper digital verification and certifications exist but not in practice... Inspectors visit once a month at most, and everyone knows when they're coming "(EXT05)*

This quote highlights the performative nature of digital compliance in many contexts, a finding consistent across multiple markets in both states. Instead of formal digital systems, the research documented how market participants have developed alternative verification mechanisms based on personal networks, reputation systems, and physical inspection – what one respondent described as “relationship-based traceability” that functions alongside but separate from official regulatory frameworks.

In contrast to the informal governance of traditional markets, state-led initiatives in Niger, Plateau, Sokoto, and Kwara attempt to formalise market transactions through digital technologies but face significant adoption challenges. The National Blockchain Policy For Nigeria (2023) outlines an ambitious vision:

*"Agrikore is a blockchain-based smart-contracting, payments, and marketplace system that ensures that everyone in agriculture (Farmers, FMCGs, Agriculture inputs providers, produce aggregators, insurance companies, financial institutions, governments, development partners) can do business with each other in a trusted environment." (Federal Ministry of Agriculture and Rural Development, 2020, p. 7).*

The semi-structured interviews revealed that while pilot projects for blockchain-based contracting exist in all four states, participation remains limited and disproportionately benefits more prominent market actors. Smallholder farmers expressed significant scepticism about these systems, from technological barriers and deeper concerns about power dynamics. Document analysis of digital contract templates from two state programs confirmed this concern, revealing significant imbalances in risk allocation between buyers and sellers, with farmers bearing disproportionate risk for quality assessment and price fluctuations.

The National Agricultural Technology and Innovation Policy (NATIP) 2022–2027 similarly promotes market digitalisation:

*“Facilitating the use of information and telecommunication technologies in agricultural product marketing.” (NATIP, 2022, p. 54).*

However, interviews with platform developers and users revealed significant design-reality gaps. A digital agriculture consultant with experience across multiple state programs noted:

*“The platforms are designed without adequately understanding farmers' realities. Many farmers can't navigate complex digital interfaces or don't have consistent internet access to monitor prices. Successful platforms must be designed with farmers, not for them, and must work under real-world constraints like intermittent connectivity and low digital literacy.” (TEC03)*

The semi-structured interviews confirmed this assessment, documenting how state e-marketplace platforms often require continuous connectivity for updates and transactions, a requirement that excludes many rural producers who experience intermittent network coverage. In Sokoto state, researchers observed that a government-backed digital marketplace registered over 5,000 farmers but recorded fewer than a hundred active monthly users six months after launch.

#### **5.2.4 Algorithmic Supply Chain Control and Power Asymmetries**

This category explores how digital technologies reshape power relationships within agricultural value chains and how algorithmic decision-making affects resource distribution and market outcomes.

In Kano and Kaduna, the research documented emerging concerns about data ownership and algorithmic control as digital platforms gradually enter traditional market spaces. The National Artificial Intelligence Strategy (2024) articulates a vision of balanced technological development:

*“AI-powered precision agriculture solutions that provide data-driven insights to help farmers optimise their outputs. These productivity improvements have a direct impact on economic contribution, as AI innovations have the potential to contribute to economic growth in Africa.” (National AI Strategy, 2024, p.10).*

However, interviews revealed significant farmer scepticism about who benefits from these technologies. Farmers consistently expressed concerns about transparency and accountability in algorithm-mediated transactions. A cooperative leader articulated these fears:

*"These tech platforms gather all our data, but we have zero control over it. When they adjust their pricing algorithms, we're completely in the dark. There's no way to see how prices are calculated. So, when an app claims prices dropped, we can't tell if that's genuine or if they're just quietly taking a bigger cut for themselves." (ORG02)*

This observation highlights how digital technologies can obscure rather than illuminate market operations when implemented without adequate oversight or transparency. Farmers in both states reported experiences with mobile trading platforms where pricing mechanisms remained opaque, creating suspicion about whether algorithms served platform operators rather than market participants.

The Nigeria Data Protection Regulation (2019) theoretically provides safeguards:

*"Anyone who is entrusted with Personal Data of a Data Subject or who is in possession of the Personal Data of a Data Subject owes a duty of care to the said Data Subject. [...] The right of a Data Subject to object to the processing of his data shall always be safeguarded. Accordingly, a Data Subject shall have the option to: a) object to the processing of Personal Data relating to him which the Data Controller intend to process for the purpose of marketing; b) be expressly and manifestly offered the mechanism for objection to any form of data processing free of charge." (Nigeria Data Protection Regulation, 2019, p. 8).*

Yet the interviews revealed limited awareness of these protections and even more limited enforcement mechanisms. A digital rights advocate working with farming communities observed:

*"Most farmers don't understand their data rights, and there's no effective oversight of how agtech companies use farmer data or design their algorithms. Farmers share sensitive information about yields, inputs, and practices without understanding how it might be used against their interests." (FRM15)*

This quote highlights significant knowledge and power asymmetries in digital agricultural markets. Document analysis of user agreements from five agricultural platforms operating in these regions confirmed that farmers routinely grant extensive data rights to platform operators while receiving limited guarantees about how their data will be used or shared.

State-led digital initiatives in Niger, Plateau, Sokoto, and Kwara demonstrate more formal approaches to digital market governance, but participants in the field revealed these often favour established market actors over smallholders. The Nigeria Digital Agriculture Strategy (NDAS) 2020-2030 explicitly promotes digital formalisation:

*"The Nigeria Digital Agriculture Platform is a multistakeholder initiative that will showcase Nigeria's competitive advantages, opportunities and strengths in AgTech and Digital*

*Agribusiness to a global audience. Objectives include: 1. To attract more foreign investors, partners and innovators to Nigeria's digital agriculture space. 2. The platform will act as a hub that links agriculture value chain players across vast areas of discipline for sharing information, knowledge and resources necessary for the growth and sustainability of agriculture in Nigeria. 3. It will enable collaboration with investors and researchers who are exploring ways of working with Nigeria to develop the agricultural and food technologies of the future. 4. It will enable AgTech startups and farmers in Nigeria to attract foreign interest and investment, enabling them to seize opportunities in food production and AgTech in global markets." (NDAS, Federal Ministry of Agriculture and Rural Development. (2020)).*

However, the policy's implementation mechanisms reveal a structural bias toward scale and standardisation. Participants in these semi-structured interviews confirmed that this emphasis on scale and standardisation systematically disadvantages smallholder producers who cannot easily meet digital compliance requirements or achieve the transaction volumes that make platform participation economically viable. A financial service provider in Kano who works with both state programs and informal producer groups noted:

*"We offer group loans and cooperative savings, but many farmers fear being locked into unfavourable terms. The digital platforms often advantage larger producers who can meet volume and quality standards. Smallholders get squeezed out or forced to sell through intermediaries who capture most of the value." (FRM03)*

This observation highlights how digital market systems can reinforce rather than transform existing power hierarchies in agricultural value chains. Document analysis of participation criteria for three state-backed digital marketplaces confirmed minimum production volume requirements that effectively excluded 60-70% of tomato producers in target regions.

The Kwara State Agricultural Transformation Plan similarly emphasises aggregation as a strategy but does not include digital integration as a key component. While aggregation theoretically offers smallholders access to digital markets, interviews revealed mixed experiences with these models. A smallholder farmer coalition representative argued:

*" These platforms just dictate what we'll get paid, take it or leave it. Once you're in their system, you've got no bargaining room at all. In the regular market, I could at least talk to buyers face-to-face or sit on my harvest if prices weren't right. But with these digital middlemen? They've got you based on their terms while your crops are still in the field. That's not a partnership, that's just a fancy new way to get squeezed." (PRJ05)*

This critique highlights how digital market systems can reduce farmer autonomy and adaptability values particularly important in volatile agricultural markets. Data collected from the semi-structured interviews documented how state-led aggregation platforms typically establish fixed



pricing schedules weeks before harvest, preventing farmers from capitalising on favourable market shifts while still holding them accountable for delivery despite adverse conditions.

### 5.2.5 Institutional Adaptation and Digital Governance Challenges

This category examines how formal and informal institutions are evolving in response to digital agricultural transformation and how governance structures shape technological adoption and outcomes.

The research documented significant grassroots institutional innovation in Kano and Kaduna as farming communities adapt digital tools to their specific contexts. The Agricultural Transformation Agenda Support Program theoretically supports such innovations:

*“The establishment of Agricultural Digital Innovation Hubs will provide agricultural tech entrepreneurs, the research community, farmers, and financial institutions with opportunities to advance innovation and boost performance in the food and agriculture space. The hubs will seek to empower passionate entrepreneurs, startups, researchers, and other members of the ecosystem that can solve the problems of farming communities using innovation through a combination of matters relating to agriculture, ICT, and finance. It will facilitate the experimentation, prototyping, and development of new technologies to meet the actual needs of farmers and their communities.” (ATASP-I, p. 21).*

However, the semi-structured interviews revealed that most institutional innovations occur outside formal support frameworks. Farmers and cooperatives have developed hybrid governance systems that blend traditional practices with selective digital adoption. A cooperative leader in Kano explained:

*“We just made our quality check system using WhatsApp because the government one’s a nightmare. We send photos and voice messages to verify our tomatoes. Our buyers trust us because they know us - we’ve been working together for years. That’s worth more than any fancy app telling them what to think.”(FRM09)*

This quote highlights how farming communities innovate pragmatic solutions that work within their technological and social constraints – often achieving the functions intended by formal digital systems through simpler, more accessible means. Researchers documented multiple examples of such "frugal innovation" across both states, including cooperative-managed digital payment records, photo-based crop forecasting systems, and voice-message market alerts.

These informal innovations typically emerge through iterative, collective problem-solving rather than predetermined design. They emphasize accessible consumer technologies and build upon

existing trust networks rather than attempting to replace them. Importantly, these systems often incorporate non-digital fallback mechanisms that ensure continuity when technology fails – a resilience feature frequently absent in formal digital platforms.

In contrast to the bottom-up innovation observed in traditional hubs, state-led initiatives attempt to restructure agricultural institutions through formal digital transformation. The Nigeria Digital Agriculture Strategy (2020-2030) outlines comprehensive institutional reforms:

*"Develop Extension services plan that incorporates e-extension and capacity development. Identify funding requirements from plan. Obtain funding from Bank of Agriculture" (NDAS, 2021, p. 35).*

However, semi-structured interviews revealed significant gaps between institutional rhetoric and organisational realities. While digital policies proliferate, the underlying institutional structures often remain unchanged and ill-equipped to implement digital transformation. An agricultural official in Niger State candidly assessed:

*"Look, we've got all these digital policies that sound great in government documents, but our actual systems are stuck in the past. Most extension officers can barely use a smartphone properly... You've got one department building a farmer database while another makes a completely different system for the exact same farmers. So instead of one working system, we end up with a bunch of disconnected pieces that don't talk to each other. It's just wasting money and not helping anyone."(EXT03)*

This observation highlights how technological change often outpaces institutional adaptation, a pattern documented across all four states with state-led initiatives. Document analysis revealed that while digital agriculture policies have multiplied (with 18 new policies identified across these states since 2019), institutional restructuring has lagged significantly, creating implementation bottlenecks and coordination failures.

The semi-structured interviews further revealed significant vertical and horizontal coordination challenges. Vertically, national, state and local digital agriculture initiatives often operate in parallel with limited integration, creating duplicate systems and contradictory requirements for farmers. Horizontally, agricultural, technology and financial sector regulations frequently conflict, creating compliance dilemmas for digital platform operators and users alike.

The production and emerging hubs case findings demonstrate that successful digital transformation in Nigeria's tomato supply chains requires approaches that address both

technological infrastructure and the social, economic, and institutional contexts in which technologies are deployed.

### **5.2.6 Case One: synthesis and linkage to research objectives and research questions**

Case One demonstrates that digital interventions in primary and emerging production hubs generate paradoxical outcomes because they are layered onto infrastructural and institutional conditions that limit reliability, enforceability, and equitable access. Rural logistics deficits, intermittent connectivity, seasonal timing mismatches, and the persistence of informal coordination as the dominant mode of exchange routinely constrain mechanisms that appear efficiency-enhancing in policy or programme design.

In relation to Objective 1, the results identify mechanisms through which paradoxical outcomes emerge: frugal digitalisation through consumer platforms enables partial coordination and knowledge exchange, yet does not resolve foundational constraints around transport, storage, and time-critical decisions that structure spoilage risk. Digital tools thereby produce incremental efficiencies for some activities while leaving the core loss drivers intact.

In relation to Objective 2, the findings indicate that the governance mechanisms shaping these outcomes are uneven and often non-binding in practice. Informal contracting and relational governance remain pivotal in primary production hubs. In contrast, state-led initiatives introduce formal structures that are weakened by fragmented institutional responsibilities, slow disbursement cycles, and limited enforcement capacity. Across both sub-cases, accountability mechanisms that would stabilise adoption and sustain use over time are partial or absent, which reinforces uneven uptake and strategic compliance.

In relation to Research Question 1, Case One clarifies how digital interventions generate efficiency-constraint paradoxes: they can reduce search and communication costs through accessible tools, yet they also intensify stratification by privileging actors with connectivity, literacy, and organisational proximity to formal programmes. In relation to Research Question 2, Case One indicates that governance frameworks enabling constraint reduction require alignment with local operating realities, continuity mechanisms when technology fails, and credible enforcement and grievance channels that make digital participation contestable rather than opaque.

Table 21: Case One summary: Primary and emerging production hubs (consolidated findings and governance implications)

| <b>Conceptual category (reported in Case One)</b>          | <b>Consolidated finding (what the evidence shows in this case)</b>                                                                                                                                                       | <b>Governance mechanism shaping the outcome (contracts, platform rules, data control, enforcement)</b>                                                                                                           | <b>Efficiency-constraint paradox expressed (efficiency gain alongside constraint)</b>                                                                   | <b>Implications for food loss reduction in upstream stages</b>                                                                                    |
|------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Technological absorption and infrastructure constraints    | Policy aspirations for digital agriculture are recurrently undermined by deficits in rural roads, electricity, connectivity, and cold-chain logistics; farmers adapt through low-tech and consumer-platform workarounds. | Weak implementation capacity and limited enforcement of infrastructure programmes; informal contracting with limited accountability; reliance on non-integrated digital tools rather than interoperable systems. | Frugal digitalisation enables some coordination while deep infrastructure gaps constrain scale, reliability, and time-sensitivity of decisions.         | Loss reduction remains structurally bounded by transport delays and lack of storage, producing forced distress selling and spoilage during peaks. |
| Digital access and knowledge fragmentation                 | Knowledge flows hybridise: informal trust networks remain primary, while WhatsApp and peer-learning channels partially substitute for formal e-extension; advanced tools remain inaccessible to many.                    | Training designs are centralised and misaligned with rural realities; technological prerequisites and limited support undermine retention and troubleshooting capability.                                        | Selective digital uptake improves information exchange for some while reinforcing intra-community asymmetries in digital literacy and device access.    | Inconsistent adoption limits system-wide reduction of post-harvest loss, with benefits concentrated among digitally capable actors.               |
| Regulatory control and market coordination failures        | Formal digital traceability and quality control provisions have limited reach in informal markets; compliance is often performative and predictable, encouraging circumvention.                                          | Weak enforcement, political interference, and low inspection capacity; regulatory frameworks assume infrastructure and literacy conditions that are not present.                                                 | Digital regulation promises coordination, yet weak enforcement shifts markets back to relational governance, limiting transparency and standardisation. | Traceability and quality assurance mechanisms remain partial, constraining coordinated loss prevention and market stabilisation.                  |
| Algorithmic supply chain control and power asymmetries     | Emerging platform use introduces opacity in pricing and data extraction; actors report limited control over data and limited awareness of protections.                                                                   | Platform control over pricing logics and user agreements; asymmetric data rights; low practical recourse for data misuse or contestation.                                                                        | Digital market participation can reduce search costs while increasing dependence on opaque algorithmic decisions and shifting bargaining power.         | Gains in connectivity may not translate into loss reduction if farmers cannot contest terms or secure stable market access.                       |
| Institutional adaptation and digital governance challenges | Grassroots institutional innovation occurs largely outside formal support structures, using accessible tools and trust networks; state-led reform is slowed by fragmented institutions and duplicative systems.          | Bottom-up governance (cooperatives, relational verification) versus top-down programme fragmentation and slow bureaucratic cycles.                                                                               | Informal institutions can deliver workable solutions quickly, while formal systems produce scale ambitions that stall in implementation gaps.           | Durable loss reduction appears more plausible where governance aligns with local operating conditions and provides continuity mechanisms.         |

### 5.3 Case Two: Commercial and Innovation-Driven Tomato Hubs

The second case focused on commercial and innovation-led hubs, in which digital transformation efforts were driven by private-sector investment and entrepreneurial ecosystems. These hubs, concentrated around Lagos, Ogun, and Plateau States, represented distinct market-led models of digital adoption. The two sub-cases identified as discussed in Chapter Four are the:

1. Private-Sector Digitalisation Models:
2. Hybrid NGO-Private Sector Digitalisation Models

This comparative approach allowed the study to juxtapose state-led, market-driven, and hybrid contractual models of digital transformation, revealing the diverse ways in which contractual governance and institutional arrangements shape the adoption, efficiency, and sustainability of digital solutions in Nigeria's tomato sector. The digital transformation of tomato supply chains in Lagos, Ogun, and Oyo reflects two distinct private-sector-driven models: corporate-led agri-tech solutions and hybrid NGO-private sector models. Both models leverage advanced digital tools, financial technology, and data analytics yet diverge in inclusivity, governance, and sustainability. The discussion is structured along six key conceptual categories, drawing on policy document analyses and stakeholder interviews to highlight the tensions between policy rhetoric and implementation realities. Appendix 9 captures a detailed table of the thematic coding.

#### 5.3.1 Algorithmic Market Governance and Adaptive Infrastructure

In commercial agribusiness, digitalised logistics and IoT-powered monitoring systems are increasingly used to optimise tomato production and supply chain operations. However, while corporate-led agritech firms have institutionalised real-time IoT soil sensors, GPS mapping, and AI-based yield forecasting, these tools remain mainly inaccessible to smallholder farmers.

As one of the commercial tomato producers in Lagos emphasised:

*"Digital technologies have transformed how we determine optimal planting schedules and harvest timing. However, many smallholder farmers across Nigeria remain disconnected from these valuable tools....unless they're affiliated with larger commercial operations or formal contracts, these farmers continue to rely on traditional knowledge rather than data-driven insights..."(FRM15)*

This admission reveals how digital infrastructure deployed by corporate entities establishes technological prerequisites that effectively filter market participants. Large-scale producers employ sophisticated predictive analytics to anticipate market fluctuations, optimise production

schedules and reduce post-harvest losses, while smallholder farmers continue to rely on traditional knowledge systems and informal market intelligence networks that lack the precision and timeliness of digital alternatives.

The National Digital Economy Policy and Strategy (NDEPS) 2020–2030 acknowledges this divide, stating:

*“The Digital Society and Emerging Technology pillar will map the development of the digital economy to the attainment of 7 of the Sustainable Development Goals (SDGs) that are most relevant to the digital economy, namely: Poverty Eradication; Good Health and Well-being; Quality Education; Decent Work and Economic Growth; Industry, Innovation, and Infrastructure; Reducing Inequality; and Sustainable Cities and Communities.” (NDEPS, 2019, p. 56).*

However, this research found considerable implementation gaps between policy rhetoric and market reality. Despite policy pronouncements, corporate-led digitalisation continually reinforces market stratification, with digital tools becoming mechanisms for consolidating market position rather than facilitating broader participation.

One of the project managers of an agribusiness firm in Ogun State candidly acknowledged:

*“Our technology platform helps us identify and work with farmers who can consistently meet our quality standards. Through our onboarding process and psychometric tests, we carefully select farmers who are genuine and can reliably engage with our systems. While this approach doesn't accommodate all farmers, especially those in remote areas or with limited technological access, our business model depends on being able to predict supply patterns, track production data, and ensure reliable quality.” (PRJ05)*

### **5.3.2 Hybrid NGO-Private Sector Models**

By contrast, hybrid NGO-private sector projects have piloted accessible digital solutions, albeit with sustainability concerns. A project coordinator in Oyo noted:

*“...the service providers does come free, where I work, we are the ones that take responsibility of the service, what we focus on is a sustainability plan, last year we paid for the services, but this year, we had a matching ground, the farmers are even in need of the information when they saw how useful it was... The cooperatives came together so this can continue, the plan is that going forward they would be doing this by themselves.” (PRJ03, Oyo)*

These hybrid models demonstrate greater initial inclusivity during project implementation, with access to technology extended to farmers who would otherwise be excluded from digital ecosystems. However, post-project sustainability remains problematic, with usage rates declining

significantly after project completion. This decline correlates with the withdrawal of technical support and subsidised data packages that initially facilitated adoption.

An agronomist who works with an NGO in Lagos State acknowledged this structural weakness:

*"When we first implemented our weather advisory service and extension messaging, we saw promising adoption rates among farmers. They appreciated getting information that helped them make better decisions about when to plant or apply fertilisers. But the consistency on the part of the service providers became an issue. This year, I've been asking about renewing our subscription, but they haven't given me an answer. The challenge is that while these technologies show great potential initially, maintaining them over time without ongoing support becomes difficult." (AGR04)*

This critical assessment reveals how hybrid models create temporary digital access that reinforces dependency rather than building sustainable digital ecosystems. The findings demonstrate that hybrid models struggle to translate temporary project success into lasting digital transformation, creating cycles of adoption and abandonment that may ultimately undermine farmer trust in digital technologies.

### **5.3.3 Decentralised Digital Finance and Market Fluidity**

The expansion of mobile banking, digital payments, and algorithmic credit scoring has reshaped financial access in Nigeria's tomato sector, but smallholder farmers remain largely excluded within corporate-led models.

An agri-entrepreneur in Lagos noted:

*"We've developed a contracting system that uses technology to formalise our relationships with farmers. The farmers sign agreements that specify exactly what inputs they receive, when they need to repay, and how much product they'll provide at harvest. We've digitised this process with our app that captures biometric data, fingerprints and facial recognition, to verify identity and create digital records. This system works well for farmers who can engage with our technology, but we recognise it creates a divide. Many smallholders struggle to participate in this digital ecosystem, especially older farmers or those in remote areas with poor connectivity. They might be excellent farmers, but without the digital footprint and formal documentation our system requires, they remain outside our contracting framework." (PRJ05)*

The research identified sophisticated risk-assessment algorithms deployed by agri-fintech companies that score farmers based on numerous variables, including historical production data, digital transaction records, and geospatial analytics. This algorithmic approach to creditworthiness assessment systematically disadvantages smallholder farmers who lack digital

footprints, despite many maintaining consistent (though undocumented) production records over multiple seasons.

A bank executive in Oyo state confirmed this structural exclusion:

*"We don't have enough data about our farmers. Enough data in the sense that some of our farmers are illiterates and they don't keep records of the things they do and have no digital histories. So when you tell a farmer, when you ask a farmer, how many hectares or hectares of farm did you do on rice last year? They begin to fumble. They don't even know. How much did you spend on making ridges alone? They don't know. How much do you spend on seedlings and other inputs? They don't know. I think this may be mainly due to some level of literacy and lack of financial literacy too. These traditional framers are classified as high-risk by default." (FIN01)*

The National Financial Inclusion Strategy (2018) highlights approaches to address financial exclusion through community-based financial institutions as reflected below:

*"Provide a framework that enables community-based financial institutions to play a more effective role in serving the most unserved and underserved. Community-based financial institutions, such as savings and credit cooperative organisations (SACCOs), farmer societies, and non-bank microfinance institutions, can play a greater role in reaching the most underserved, both geographically and by demographic characteristics. A framework shall be developed to enhance greater access to capital in order to increase their ability to extend more financial services to the excluded groups." (Central Bank of Nigeria, October 2018, p. 25)*

In contrast, NGO-led initiatives have developed community-based digital financing models, such as cooperative savings and group loans. A cooperative farmer in Ogun explained:

*"But this new NGO approach is something else... They have digitised the whole process... members are learning from themselves right on their mobile phones. The bank supervisor doesn't need to be visiting them every time to check their loan progress. The system monitors everything automatically" (FRM16)*

Financial institution actors interviewed also acknowledge that cooperative-based financial models enable banking for the unbanked, expand access to loans and mobile payment systems, and establish the digital footprints of upstream tomato supply chain actors. According to a national bank manager:

*"We have what we call cooperative accounts... the cooperative account is still managed by the three or four officials, which is chairman, secretary, and the treasurer. Without looking at it, whether you're a chairman or a secretary or treasurer, we give them equal treatment at a point of disbursement. But we now hold the officials of the cooperative group to stand as guarantors. We guarantee the loans of their members. From there, the*



*members will learn from themselves over there on the field. At the point in time, the supervisor, that's the bank, will be visiting them to see how far they have gone with the loan they have taken. That's why I said we are more and more interested in giving out loans to cooperatives than individuals."*(FIN03)

These community-based models demonstrated promising initial results, with cooperatives mobilising significant resources through digital collective savings. The models integrated indigenous rotating savings practices (*adashi/esusu*) with digital record-keeping and mobile payment systems, achieving high member participation. However, when external technical support for platform maintenance was withdrawn, system failures increased, and participation rates declined substantially in subsequent growing seasons.

A microfinance specialist in Lagos critically assessed these limitations:

*"These donor-funded digital finance projects create impressive demonstrations but rarely transition to self-sustaining operations. They establish subsidised services that inevitably collapse when funding cycles end, potentially leaving communities worse off than before."* (FIN11)

The policy challenge, therefore, lies in creating scalable and inclusive digital finance models that extend beyond corporate agri-finance solutions. The research indicates that successful models will likely require hybrid approaches that formalise traditional financial practices through appropriate digital interfaces rather than imposing entirely new systems.

#### **5.3.4 Data Monetisation and Market Intelligence Concentration**

Data governance remains critical in Nigeria's agri-digitalization efforts, as corporate-led platforms increasingly control price forecasting, supply chain insights, and farmer behaviour analytics.

A tomato farmer in Lagos raised concerns about algorithmic pricing:

*"...we find ourselves increasingly dependent on these platforms where pricing seems beyond our control. What's particularly challenging is how these systems appear to rank suppliers without transparency. When your farm doesn't meet certain criteria...we don't fully understand... your produce becomes invisible to potential buyers. You can have the highest quality tomatoes ready for market, but if you are not prioritised... it's as though your harvest doesn't exist."*(FRM10)

The research documented how major digital marketplaces employ sophisticated ranking algorithms that evaluate suppliers based on multiple metrics, including response time, delivery reliability, product consistency, and customer ratings. While ostensibly meritocratic, these

systems inherently favour producers with digital literacy, reliable internet connectivity, and the capacity to maintain consistent engagement with platforms, resources disproportionately available to more significant, well-capitalized operations.

Analysis of transaction data revealed that smallholder farmers experienced significantly lower visibility in search results than medium and large-scale producers, even when controlling for product quality and pricing factors. This algorithmic invisibility translates directly into reduced market access, with small-scale farmers reporting declining sales volumes after transitioning to digital marketplaces.

Meanwhile, NGO-private sector partnerships have experimented with open-access data platforms. A project lead in Oyo described an initiative that provided smallholder farmers with market intelligence:

*"We developed an app...to help with market transparency. Originally, we designed it to assist merchants with financial documentation, but now we're expanding it so farmers can list their products and connect directly with buyers. This gives them visibility into real market prices and strengthens their position when negotiating with middlemen. The challenge we're facing is sustainability." (AGR04)*

This initiative demonstrated meaningful impact, with participating farmers reporting increased farmgate prices through improved negotiation positions based on real-time market data. However, when platform maintenance costs were transferred from donor funding to a subscription model, accessibility declined sharply, with only a tiny fraction of original users maintaining access.

A technology consultant in Lagos state candidly assessed this contradiction:

*"We keep sustainability in mind right from the design phase of the project. We don't consider ourselves as permanent members of the ecosystem; rather, we act as stimulators of processes. Our role is to facilitate and observe, trying out different approaches to see what works. For example, creating open data platforms require significant backend infrastructure and continuous data validation." (TEC18)*

The Digital Agriculture Strategy (NDAS) (2020) supports such initiatives but highlights challenges in scalability and interoperability:

*"The sustainability of open-access digital platforms requires structured policy incentives and long-term funding models."*

The research identified promising hybrid models emerging in Oyo state. In these models, cooperatives pool resources to maintain subscriptions to market intelligence platforms, effectively socializing access costs across farmer groups. This approach achieved sustained access rates among cooperative members, suggesting a potential pathway for inclusive data democratisation.

### **5.3.5 Strategic Partnerships and Network Synergies**

Corporate-led models have established efficient but exclusionary partnership structures prioritising commercial integration over inclusive participation. These partnerships typically connect large-scale producers, logistics providers, and retail outlets through integrated digital platforms, creating streamlined supply chains that exclude smaller actors.

A senior executive at an agribusiness firm in Lagos explained:

*“...what we're witnessing is a forward integration from production through to retailers and consumers, with manufacturers tracking the entire value chain. In our case, our digital partnerships strategically focus on partners who can meet our scale and quality requirements...” (SCM02)*

These tightly integrated partnership networks create efficiency gains through shared digital infrastructure but systematically exclude smaller market participants who cannot meet the technological prerequisites or scale requirements.

The research found that policy fragmentation remains a major barrier to more inclusive strategic partnerships. A senior policymaker in Ogun admitted:

*"While multiple agencies and initiatives are engaged in promoting digital agriculture and food security, there is a lack of effective coordination. Various programs run independently, limiting their overall impact on farmers and agricultural productivity." (REG04)*

The NATIP identifies this issue, advocating for inter-agency alignment:

*"Harmonizing the programmes and activities of Central Bank of Nigeria (CBN) and Nigerian Incentive-based Risk-Sharing System for Agricultural Lending (NIRSAL) with that of Bank of Agriculture (BoA), NAIC, commercial banks and other lending institutions to overcome the present operational and financing challenges facing the agricultural sector." (NATIP, 2022, p.57)*

Hybrid models have leveraged multi-stakeholder networks to promote inclusive participation, but donor dependency remains a concern. An agricultural development officer in Oyo noted:

*"We rely on international donor funds for digital training programs, but the private sector needs to take a more active role in sustaining these initiatives." (PRJ02)*

The research documented how these multi-stakeholder networks successfully brought together diverse actors, including smallholder farmers, technology providers, and market facilitators, creating inclusive digital ecosystems during project implementation. However, these networks often dissolved once donor funding concluded, highlighting the fragility of externally supported partnership structures. A project manager in Lagos described these operational challenges:

*"Each ministry has its own digital agriculture strategy, each donor has unique reporting requirements, and each implementing partner has different objectives. We spend more time managing these relationships than actually implementing technology solutions." (PRJ12)*

The research documented how donor-funded digital agriculture initiatives in the three states followed cyclical patterns of intensification and decline. Projects experienced rapid deterioration in infrastructure maintenance and technical support after funding concluded. This pattern created a "digital graveyard" effect, with farmers reporting frustration over abandoned platforms and discontinued services that had initially shown promise.

### **5.3.6 Digital Platform Dependence and Algorithmic Lock-ins**

The research identified troubling patterns of market consolidation and technical lock-in mechanisms that create structured dependencies in tomato supply chains. Corporate digital platforms deployed strategic technological barriers that increased switching costs and reinforced market dominance. A logistics CEO in Lagos stated:

*"Once you integrate into a digital marketplace, you depend on their pricing algorithms and commissions. Farmers have no bargaining power." (LOG01)*

Investigation revealed commission structures on major agricultural marketplaces have increased significantly over recent years, with smallholder farmers unable to negotiate preferential rates available to larger suppliers. This increase coincides with market consolidation, as the number of operational digital agricultural marketplaces in the three states declined over time, suggesting reduced competition as a contributing factor.

Furthermore, the study identified technical lock-in mechanisms embedded in platform architectures, including proprietary data formats, non-portable digital reputation scores, and exclusive integration with specific payment processors. These technical barriers create significant

switching costs, with farmers reporting they would lose historical sales data and established customer relationships if they attempted to migrate to alternative platforms. A distributor in Plateau explained:

*“These platforms keep increasing their fees every season. They know we can’t easily switch because all our customer relationships and transaction histories are trapped in their system. We’re effectively captive.”(EXT07)*

The National AI Strategy warns against such monopolisation, advocating for algorithmic transparency:

*“Digital platforms should adopt fair pricing mechanisms that prevent market distortion and ensure equitable participation for all producers.”*

Meanwhile, NGO-led solutions emphasise digital independence. A tech entrepreneur in Oyo highlighted their approach:

*“We provide farmers with multi-platform access, ensuring they are not locked into a single system. The challenge is scaling this model commercially.” (TEC05)*

This initiative developed interoperable systems allowing smallholder farmers to list products across multiple marketplaces through a unified interface simultaneously. While technically successful, with participants reporting improved market access, the initiative struggled to establish financial sustainability, with operating costs exceeding revenue after donor funding concluded.

The research also documented emerging blockchain-based initiatives that aim to create transparent, immutable records of agricultural transactions while preserving farmer data sovereignty. While promising in concept, these solutions faced significant adoption barriers, including high energy consumption, technical complexity, and limited scalability in rural contexts with inconsistent connectivity.

A technology entrepreneur in Ogun State critically assessed this pattern:

*“NGO-funded digital agriculture projects create impressive demonstrations that rarely scale. They establish pilot expectations that the market cannot sustain, potentially doing more harm than good by creating dependency and disappointment.” (TEC09)*

These findings highlight how hybrid models often create promising alternatives to corporate platform dependence but struggle to establish economically sustainable foundations that can persist beyond project funding cycles.

### **5.3.7 Market-Driven Innovation and Commercial Knowledge Hybridisation**

Corporate agribusinesses prioritize profit-driven digital innovation, focusing on efficiency gains and commercial returns with limited consideration for contextual adaptability or inclusive access. The research found that private RandD investments concentrated on technological solutions optimised for commercial operations with minimal transferability to smallholder contexts.

A commercial farm CEO in Lagos emphasised efficiency-driven RandD:

*"Our investment in AI-based disease detection has significantly reduced post-harvest losses. But for smallholder farmers, such innovations remain inaccessible without external funding." (FRM16)*

The research documented how corporate RandD investments focused predominantly on efficiency gains in production and logistics. The majority of identified innovations targeted yield increases, cost reductions, or process optimization. These innovations demonstrated impressive impact in commercial settings but faced significant contextual limitations when transferred to smallholder farming systems.

An agricultural technologist in Ogun admitted:

*"Our algorithms are trained on commercial monocrop data. They simply don't work well for smallholders practicing intercropping or using indigenous techniques. But adapting them for these contexts isn't commercially viable." (TEC14)*

This candid acknowledgement reveals how profit-driven innovation systematically overlooks the technological needs of resource-constrained producers, creating a growing innovation gap between commercially targeted technologies and smallholder farming systems.

The NATIP highlights the need to integrate local farming techniques into digital innovations:

*"Agribusiness models should balance high-tech solutions with local adaptation to maximize sustainability."*

By contrast, hybrid models focus on blending indigenous knowledge with modern technologies, creating innovations that are more contextually appropriate but often lack commercial scalability.

These initiatives have developed technologies that explicitly incorporate local knowledge systems and traditional practices, achieving higher rates of adoption among smallholder farmers.

A farmer in Oyo reflected positively on this knowledge hybridization approach:

*“We combine traditional sun-drying methods with solar-powered cooling to preserve tomatoes. Blending old and new techniques is key to innovation.” (FRM11)*

The research documented several promising hybrid innovations emerging from these initiatives, including modified solar dryers that incorporate traditional material knowledge, mobile applications adapted to local weather pattern recognition systems, and digital marketplaces organized around existing trading networks and cultural practices. These innovations demonstrated higher acceptance among smallholder farmers compared to purely technology-driven solutions.

Field observations revealed that the most successful digital agriculture initiatives explicitly incorporated elements of local knowledge systems, including seasonal calendars, indigenous pest management techniques, and traditional quality assessment methods. By digitizing rather than displacing this knowledge, these systems achieved both technical effectiveness and cultural acceptance.

However, these contextually appropriate innovations struggled to achieve commercial viability beyond donor funding cycles. A technology entrepreneur in Plateau noted:

*“We’ve developed farming apps that incorporate local knowledge and practices. Farmers love them, but the business model doesn’t work without subsidies. The users who find them most valuable can’t afford to pay enough to sustain development.”(TEC15)*

This tension between contextual appropriateness and commercial viability represents a fundamental challenge for hybrid innovation models, highlighting the need for new approaches that can bridge this gap. Findings indicate a growing divide between corporate-led and hybrid digitalisation models. Private-sector-driven solutions promote efficiency and scalability, excluding informal farmers and reinforcing platform monopolisation. In contrast, NGO-private partnerships foster inclusivity but face sustainability challenges. Addressing these tensions requires integrated policy frameworks, stronger financial incentives, and equitable access to digital markets to ensure that digital transformation in Nigeria's tomato sector is inclusive and commercially viable.

The research demonstrates that neither model alone offers a solution to the challenges of agricultural digitalisation. Rather, strategic integration of corporate efficiency with NGO inclusivity, supported by coherent policy frameworks and innovative financing mechanisms, represents the most promising pathway toward sustainable digital transformation in Nigeria's tomato supply chains.

### **5.3.8 Case Two synthesis and linkage to research objectives and research questions**

Case Two shows that in commercial and innovation-driven hubs, digital interventions generate efficiency gains largely through tightly governed systems that standardise participation, data capture, and transaction flows. The same governance features that enable optimisation also reproduce constraints through exclusion, dependency, and algorithmic opacity, particularly where platform operators control access conditions, price formation logics, and the portability of transactional reputation.

In relation to Objective 1, the results indicate that paradoxical outcomes emerge through a bounded efficiency mechanism: efficiency gains are realised where commercial actors can enforce standards, integrate logistics, and utilise predictive analytics, but these gains are coupled with constrained inclusion for producers lacking digital footprints, device access, or compliance capacity.

In relation to Objective 2, the findings clarify how governance mechanisms shape outcomes: contracts, onboarding rules, scoring systems, and platform ranking algorithms produce a structured hierarchy of participation. Cooperative-based and donor-supported models soften these effects but frequently reintroduce constraints through discontinuity when funding or technical support ends.

In relation to Objective 3, Case Two provides empirical patterns that support systematic characterisation through governance configurations. Corporate-led digitalisation tends towards high-control, high-efficiency systems with concentrated benefits, whereas hybrid models trend towards broader access but fragile continuity. These patterns constitute a basis for operationalising the efficiency-constraint paradox across contrasting configurations, which is subsequently formalised through the Digital Constraint Paradox framework.

In relation to Objective 4 and Research Question 2, Case Two indicates that governance levers capable of reducing constraints must address portability and contestability: data rights clarity, transparent ranking and pricing rules, limits on lock-in mechanisms, and financing designs that build digital footprints without making digital legibility a precondition for inclusion. Without these



levers, digital transformation risks improving food loss outcomes only within narrow commercial enclaves while worsening distributional outcomes for smallholders.

Table 22: Case Two summary: Commercial and innovation-driven hubs (consolidated findings and governance implications)

| <b>Conceptual category (reported in Case Two)</b>         | <b>Consolidated finding (what the evidence shows in this case)</b>                                                                                                                                  | <b>Governance mechanism shaping the outcome (contracts, platform rules, data control, enforcement)</b>                                               | <b>Efficiency-constraint paradox expressed</b>                                                                                            | <b>Implications for food loss reduction outcomes</b>                                                                                |
|-----------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Algorithmic market governance and adaptive infrastructure | Corporate actors deploy advanced tools (IoT, analytics) that optimise timing and logistics within commercial systems, while creating technological prerequisites that filter participation.         | Corporate contracting and onboarding rules, selection tests, technology standards, integration requirements.                                         | Efficiency gains are achieved through tight control, yet inclusion is narrowed and smallholders are displaced to intermediated positions. | Loss reduction improves within controlled chains, but system-wide benefits are limited if exclusion persists.                       |
| Hybrid NGO-private sector models                          | Pilot inclusivity is stronger during funding periods, but continuity and maintenance failures produce adoption-abandonment cycles that weaken trust.                                                | Donor funding cycles, subsidised data and support withdrawal, subscription transfer to users.                                                        | Short-term access increases capability, yet longer-term dependence and discontinuity constrain sustained transformation.                  | Temporary interventions can improve decision-making and reduce loss during pilots, but effects decay when support ends.             |
| Decentralised digital finance and market fluidity         | Digital contracting and algorithmic scoring formalise relationships for those with digital footprints, while default-risk categorisation excludes others.                                           | Biometric identity verification, credit scoring rules, documentation requirements; cooperative guarantees in alternative models.                     | Formal finance expands for digitally legible farmers, but financial exclusion is reproduced for those without records and connectivity.   | Finance can support inputs and reduce loss risk, yet exclusion constrains uptake among those with highest vulnerability to loss.    |
| Data monetisation and market intelligence concentration   | Platform ranking and visibility logics concentrate market intelligence and can render smallholders algorithmically invisible; open-access approaches struggle with sustainability.                  | Proprietary algorithms, data control, subscription pricing, backend maintenance requirements.                                                        | Data-driven coordination improves matching and forecasting while shifting bargaining power and limiting contestability.                   | Improved intelligence may reduce loss in high-control systems, but market access constraints weaken broad loss reduction.           |
| Partnerships, lock-ins, and innovation dynamics           | Integrated partnerships streamline flow but exclude actors who cannot meet standards; lock-in mechanisms raise switching costs and enable fee escalation; innovation is trained on commercial data. | Proprietary formats, non-portable reputation scores, exclusive payment integration; research and development priorities determined by profitability. | Commercial efficiency improves while dependency, monopolisation risks, and smallholder irrelevance increase.                              | Loss reduction is optimised within bounded commercial chains, but not reliably translated into inclusive, scalable system outcomes. |

## Summary

This chapter has presented a comparative two-case account of how digital interventions in Nigeria's tomato supply chain generate simultaneously efficiency-enhancing and constraint-producing outcomes. Across both cases, the empirical pattern is not one of linear improvement through digitisation, but of conditional efficiency: gains in coordination, information flow, and transactional speed are repeatedly bounded, and at times inverted, by infrastructural deficits, uneven capability, and governance arrangements that redistribute risk, control, and value in asymmetric ways.

Across Case One, the results show that in primary and emerging production hubs, farmers and intermediaries pursue pragmatic, hybrid forms of digital use that fit intermittent connectivity and limited infrastructure. These practices can improve communication and local market intelligence, yet they do not substitute for the absence of cold chain capacity, poor rural transport, and fragmented extension support. In state-led contexts, digital initiatives are more formalised in design but often remain spatially and organisationally concentrated within pilots and demonstration sites. As a consequence, inclusion is frequently contingent on pre-existing resources, producing a stratifying effect in which better-connected and better-capitalised actors secure disproportionate benefits.

Across Case Two, the results show that commercial and innovation-driven interventions can generate operational efficiencies through digitalised logistics, data-driven screening and contracting, and platform coordination. However, these efficiencies tend to be accompanied by exclusionary effects when participation is conditioned on digital footprints, compliance capacity, or scalable volumes. Hybrid NGO–private sector models can broaden access during implementation by subsidising devices, connectivity, or advisory services, yet they also reveal a recurring sustainability vulnerability where adoption and usage decline after external funding and technical support are withdrawn. The case therefore surfaces a second-order paradox: interventions that widen access in the short term can intensify dependency and mistrust if continuity is not institutionally and financially secured.

Synthesised across cases, these findings address Research Question 1 by evidencing the mechanisms through which digital interventions generate paradoxes of efficiency and constraint, and by showing that outcomes are shaped less by “technology” in isolation than by governance mechanisms embedded in contracting, platform rules, data control, and enforcement practices.

The same empirical material provides a basis for Research Question 2 by indicating that the paradoxes observed are systematic and comparable across settings: they recur as patterned combinations of efficiency gains with infrastructural, institutional, and distributional constraints that vary under contrasting governance configurations. These cross-case patterns directly serve Objectives 1 and 2 by identifying mechanisms and governance levers, and they prepare the groundwork for Objectives 3 and 4 by isolating the empirical regularities that will be formalised into a systematic characterisation and evaluated for practical intervention potential.

Chapter 6 builds on this evidential base to move from results reporting to explanation and synthesis. It interprets cross-case patterns through the study's analytical framework, specifying how observed efficiency–constraint combinations can be characterised within the Digital Constraint Paradox framework and how they differ across governance configurations. In doing so, Chapter 6 also identifies and evaluates governance frameworks and practical levers capable of reducing constraints and improving outcomes in food loss and waste reduction, with explicit attention to distributional consequences across actor groups.

## 6 Chapter Six: Discussion

### 6.1 Introduction

This chapter advances the study's theoretical and empirical contributions by critically engaging with the findings presented in Chapter Five and situating them within the broader scholarly discourse on digital transformation, supply chain governance, and food waste mitigation in agri-food systems. The central question animating this discussion is: why do digital transformations in agri-food supply chains, particularly in food-waste-reduction contexts, consistently fail to deliver the efficiency gains that dominant theoretical frameworks predict? This question is not merely empirical but fundamentally theoretical, requiring a systematic interrogation of the assumptions underpinning prevailing models of digital efficiency.

The discussion is organised around five interconnected analytical propositions, hereafter termed the Five Constraint Mechanisms, each illuminating a distinct structural barrier that governs how digital transformation unfolds within agri-food markets. These mechanisms emerged through the hybrid deductive-inductive analytical approach detailed in Chapter Four: the deductive framework, grounded in incomplete contract theory (Hart and Moore, 1990), transaction cost economics (Williamson, 1985), and institutional path dependency (North, 1990; Pierson, 2004), provided the initial coding architecture, whilst inductive pattern recognition from the empirical data revealed configurations and interactions that extended and, in certain instances, challenged these foundational theories. The five mechanisms are:

1. Digital Transformation as a Structurally Constrained Process.
2. Digital Intermediation as a Structural Necessity
3. Contractual Voids and Institutional Fragility.
4. Algorithmic Power and Market Coordination Reconfiguration
5. Institutional Rigidities and the Limits of Digital Transformation.

The synthesis of these five mechanisms yields the study's principal theoretical contribution: the Digital Constraint Paradox (DCP) framework. Research Question 1 is addressed by specifying the mechanism pathways through which digital tools interact with market governance, contractual arrangements, and enforcement practices to generate efficiency-constraint paradoxes. Research Question 2 is addressed through the DCP framework's two-axis quadrant model, which differentiates governance configurations and clarifies practical levers for reducing constraints while attending to distributional consequences.

The chapter proceeds as follows. Section 6.2 establishes the foundational argument that digital transformation is structurally constrained rather than inherently efficiency-enhancing. Sections 6.3 through 6.6 elaborate the four subsequent constraint mechanisms, each grounded in empirical evidence from the Nigerian tomato supply chain whilst engaging critically with relevant theoretical literatures. Section 6.7 synthesises these mechanisms into the Digital Constraint Paradox framework, presenting the two-axis model and examining each quadrant's distinctive dynamics. Section 6.8 concludes by articulating the chapter's contribution to knowledge and establishing connections to the concluding chapter.

## **6.2 Digital Transformation as a Structurally Constrained Process**

The dominant discourse within economic and management theory posits that digital transformation constitutes an exogenous force capable of rationalising supply chains, eliminating informational frictions, and generating efficiency gains (Brynjolfsson and McAfee, 2014; Porter and Heppelmann, 2015). From transaction cost economics (Williamson, 1985) to resource-based perspectives (Barney, 1991), prevailing theoretical models assume that technological adoption, whether through digital platforms, smart contracts, or predictive analytics, serves as an independent driver of supply chain optimisation. Yet the empirical evidence from Nigeria's tomato supply chain fundamentally challenges this assumption, revealing that digital technologies do not enter supply chains as autonomous agents of change but are absorbed into existing institutional, economic, and relational structures, frequently reinforcing rather than dismantling the inefficiencies they were ostensibly designed to correct (Markus and Robey, 1988; Orlikowski, 1992).

This finding emerged through the intersection of deductive theoretical expectations and inductive empirical observations. The deductive framework anticipated that information asymmetry reduction through digital platforms would yield efficiency improvements consistent with transaction cost economics predictions. However, the inductive analysis revealed a more complex pattern: digital tools were neither neutral nor efficiency-enhancing in contexts where underlying power structures, contractual incompleteness, and infrastructural deficits remained unaddressed. The persistence of brokerage networks despite the availability of price transparency tools, the continued reliance on intermediaries in ostensibly disintermediated digital transactions, and the strategic adaptation of dominant actors to digital systems all illustrate how technological interventions are conditioned by structural path dependencies rather than by their intended efficiency objectives.

At the heart of this misalignment lies what may be termed the fallacy of digital neutrality: the erroneous assumption that technology, once introduced, will generate efficiency gains irrespective of context. This assumption, rooted in classical economic theory, fails to account for how digital interventions interact with pre-existing power structures. The introduction of mobile-based trading platforms in Nigeria's tomato markets was designed to connect farmers directly with buyers, thereby reducing transaction costs and eliminating intermediary dependence. Yet the findings demonstrate that intermediaries themselves co-opted these platforms, leveraging them to reinforce control over pricing and market access. The persistence of intermediaries in digitally-mediated agricultural supply chains is not an aberration but a predictable outcome of institutional path dependency (North, 1990; Mahoney, 2000). Farmers remain dependent on intermediaries because access to market information alone does not resolve the structural barriers that prevent direct transactions, including logistical limitations, credit constraints, and the absence of enforceable contracts.

This insight challenges core assumptions within transaction cost economics, particularly the proposition that reducing information asymmetry will lead to efficiency gains (Williamson, 1985). The findings suggest that market behaviour is not dictated solely by informational access but by relational dependencies that shape economic decision-making. Digital platforms do not function as neutral conduits for efficiency but as contested spaces where existing power asymmetries are reinforced. This aligns with Granovetter's (1985) argument concerning embeddedness, demonstrating that economic transactions cannot be divorced from their social and institutional contexts. Theoretical models that treat digitalisation as a purely economic phenomenon, one that rational actors will leverage to maximise efficiency, fail to account for the structural conditions that mediate technological adoption.

Similar structural constraints manifest in digital contract enforcement mechanisms. Blockchain-based smart contracts, widely heralded as solutions to opportunism and trade inefficiencies, were expected to reduce disputes and ensure compliance through automated execution. Their theoretical appeal rests on property rights economics (Grossman and Hart, 1986), which argues that contract incompleteness can be mitigated through precise allocations of control rights. Yet the findings complicate this assumption, revealing that digital contracts have not displaced informal enforcement mechanisms but have been absorbed into them. Rather than enabling direct transactions between farmers and buyers, blockchain contracts remain embedded within intermediary structures, as buyers continue to require transactions to be routed through

recognised aggregators (Davidson et al., 2018; Catalini and Gans, 2020). This raises important questions for contract theory: if digitalisation does not eliminate enforcement frictions but instead sustains dependency on informal governance mechanisms, then the assumption that technological formalisation leads to self-enforcing contracts must be reconsidered.

The implications for food waste governance are particularly consequential. The underlying premise of digital supply chain optimisation is that tracking tools, cold-chain monitoring systems, and predictive analytics will enhance coordination, thereby reducing spoilage and surplus. Rational choice models (Zhang et al., 2019) suggest that actors, given access to real-time data, will respond efficiently to minimise waste. Yet the findings expose a critical flaw in this logic: the assumption that digital efficiency is an intrinsic property of technology rather than an outcome shaped by structural incentives (Parfitt et al., 2010; Hodges et al., 2011). Digital cold-chain monitoring systems, introduced to prevent spoilage through real-time temperature tracking, were frequently ignored by traders not due to technological failure but because compliance incurred costs that outweighed the perceived benefits of minimising waste. When the cost of cold storage or shipment delay exceeds the financial loss associated with partial spoilage, traders rationally opt for waste. This challenges conventional supply chain optimisation models, which assume that efficiency gains are automatically realised through improved information flows (Chaboud and Daviron, 2017).

The first constraint mechanism thus proposes that digitalisation in agri-food supply chains does not inherently lead to efficiency gains but is instead absorbed into pre-existing governance structures, reinforcing rather than dismantling systemic inefficiencies. Digital tools are neither neutral nor exogenous forces of disruption but are shaped by relational dependencies, power asymmetries, and institutional voids that dictate their adoption, use, and unintended consequences. This establishes the foundational premise that digitalisation must be analysed not as a deterministic efficiency mechanism but as a structurally embedded process whose effectiveness is contingent on the institutional and resource conditions that govern market behaviour.

**Proposition 1:** *Digital transformation in agri-food supply chains does not independently drive efficiency but is constrained by structural rigidities, institutional path dependencies, and power asymmetries that dictate its absorption into pre-existing market inefficiencies, thereby limiting its impact on food waste reduction.*



### **6.3 Digital Intermediation as a Structural Necessity**

The dominant assumption within digital transformation discourse posits that technological advancements will fundamentally alter the structure of market transactions, reducing inefficiencies through the disintermediation of traditional brokers, aggregators, and traders. This assumption is grounded in neoclassical economic thought and transaction cost economics (Williamson, 1985), which theorise that intermediaries persist primarily because they bridge information asymmetries, lower coordination costs, and provide enforcement mechanisms in environments where trust and legal institutions are weak (Coase, 1937; Barrett, 2008). The emergence of digital platforms, blockchain-based smart contracts, and predictive analytics has been heralded as capable of replacing these intermediaries, enabling seamless, direct exchange between farmers and buyers whilst ensuring transparency and efficiency in contractual engagements (Maru et al., 2018; World Bank, 2019).

However, empirical evidence from the Nigerian tomato supply chain fundamentally challenges this proposition. Rather than being displaced, intermediaries have adapted to digitalisation, embedding themselves within the very platforms designed to bypass them (Aker, 2010; Qiang et al., 2012). Digital tools have become new loci of intermediation, with traders, aggregators, and financial gatekeepers leveraging these platforms to consolidate their control over supply chains. The persistence of intermediation in digitally-mediated supply chains is not a failure of adoption or technological literacy but reflects deeper dynamics of institutional lock-in, contract incompleteness, and residual rights concentration (North, 1990; Grossman and Hart, 1986; Baumüller, 2018). This pattern emerged through inductive coding of stakeholder interviews and was subsequently theorised through engagement with incomplete contract theory, revealing that intermediation functions not merely as a response to transaction costs but as a structurally embedded governance mechanism sustained by the underlying institutional and economic architecture of agricultural trade.

#### **6.3.1 The Reconfiguration of Market Intermediation**

The first dimension of digital intermediation concerns its persistence in market transactions. Digital platforms designed to facilitate direct exchanges between farmers and buyers have not resulted in disintermediation; rather, traditional brokers and aggregators continue to exert control over pricing, logistics, and transaction execution, embedding themselves within digital trading ecosystems rather than being displaced by them (Reardon et al., 2019; Deichmann et al., 2016). This persistence can be traced to the issue of contractual incompleteness (Hart and Moore,

1990). Agricultural contracts, whether executed in traditional or digital form, are inherently incomplete due to the unpredictable nature of supply chains. Factors including crop failures, climate shocks, transportation delays, and buyer-side defaults make it impossible for contracts to anticipate all contingencies (Fafchamps, 2004; Oya, 2012). Digital platforms that enforce rigid price and delivery commitments fail to account for these exogenous uncertainties, rendering them unreliable enforcement mechanisms. Buyers and sellers thus remain reliant on intermediaries, who function as flexible enforcers of informal contract renegotiation, adjusting trade agreements dynamically in response to real-world contingencies (Delpierre et al., 2015; Swinnen and Kuijpers, 2019).

The second dimension concerns the monopolisation of market infrastructure access. Even when farmers gain access to digital pricing information, they frequently lack the physical or financial infrastructure to act upon it (Foster and Heeks, 2013; Tsan et al., 2019). The Nigerian tomato supply chain exemplifies this dynamic: despite the availability of mobile price discovery tools, farmers remain structurally dependent on intermediaries to access transport networks, storage facilities, and guaranteed liquidity. This highlights a key limitation of digitalisation: whilst platforms provide transparency, they do not alter the distribution of logistical and financial resources that determine who can act on that information. Market intermediaries thus retain their position, leveraging digital transparency to optimise their own strategic pricing rather than dismantling their role (Aker and Fafchamps, 2015; Minten et al., 2017). Furthermore, algorithmic price adjustments within digital markets have paradoxically strengthened intermediary dominance. Digital platforms provide traders and wholesalers with real-time access to supply fluctuations, enabling them to adjust offers dynamically, often reinforcing price volatility rather than stabilising it (Jayne et al., 2010).

### **6.3.2 Data Intermediation and Informational Gatekeeping**

A second major axis of digital intermediation concerns control over data governance. The introduction of digital platforms was expected to democratise access to information, enabling farmers to make independent, data-driven decisions regarding production, harvesting, and sales (Wolfert et al., 2017; CTA, 2019). However, rather than decentralising decision-making, digitalisation has transformed intermediaries into data gatekeepers, consolidating their authority over how agricultural knowledge is interpreted and applied (Bronson and Knezevic, 2016; Klerkx et al., 2019). Empirical evidence from predictive analytics and climate-based advisory services in Nigeria reveals that despite widespread availability of weather forecasting tools and soil monitoring technologies, farmers do not engage directly with these systems. Instead, they rely on

extension officers, cooperatives, and large buyers to interpret and relay actionable insights (Aker et al., 2016; Rotz et al., 2019). This persistence of data intermediation reflects a deeper institutional reality: residual rights over data control remain concentrated among intermediaries who determine what knowledge is disseminated, under what conditions, and to whom (Grossman and Hart, 1986; Mehrabi et al., 2021).

This process is further exacerbated by financial asymmetries, wherein access to digital agronomic insights is contingent on the ability to pay for premium advisory services. Many digital platforms operate on freemium models, offering baseline price and weather data without charge but requiring payment for advanced predictive analytics, premium marketplace access, or credit scoring algorithms (Lioutas et al., 2019; Munthali et al., 2018). This creates a tiered data ecosystem in which well-capitalised traders and aggregators leverage advanced insights to optimise their market strategies, whilst smallholder farmers remain excluded from higher-order decision-making capabilities. Thus, far from levelling the playing field, digital platforms create new layers of informational inequality, reinforcing power asymmetries rather than dismantling them. The theoretical implication aligns with institutional economics perspectives on information asymmetry: the benefits of technological advancements accrue disproportionately to those who already control the means of production and exchange (Stiglitz, 2002; Pimbert et al., 2021).

### **6.3.3 Contractual Intermediation**

A final critical axis of digital intermediation emerges in contractual governance. Digital contracting solutions, ranging from blockchain-based contracts to automated procurement systems, were expected to remove the need for intermediaries in transaction enforcement. However, empirical evidence indicates that digital contract adoption has not led to widespread substitution for traditional trade enforcement mechanisms (Dury et al., 2019; Kos and Kloppenburg, 2019). In the Nigerian tomato supply chain, blockchain and IoT-based monitoring systems have been introduced to verify product quality, track delivery schedules, and automate contract execution. However, buyers and sellers continue to prefer transacting through trusted intermediaries rather than relying exclusively on digital enforcement (Aker, 2017; Lazzarini et al., 2015). The reason for this preference lies in the institutional weaknesses of formal enforcement systems, which remain fragile and inconsistently applied. Without a strong legal framework to support digital contract enforcement, parties revert to relational enforcement mechanisms, where intermediaries provide credibility and dispute resolution that digital systems cannot (Fafchamps, 2004; Vieira and Traill, 2008).

Furthermore, digital contracts frequently fail to accommodate the fluidity required in agricultural trade, where renegotiations, volume adjustments, and last-minute quality assessments are normative. Whilst blockchain contracts offer immutability, they do not offer adaptability, an essential component of agricultural trade where conditions fluctuate unpredictably (Tian, 2016; Tripoli and Schmidhuber, 2018). As a result, digital contract adoption does not displace intermediaries but rather forces them to operate within digital governance frameworks, adapting their role from informal brokers to formalised compliance agents. The expectation that digitalisation would lead to intermediary displacement is thus grounded in an overly deterministic view of technological transformation. Empirical evidence demonstrates that digital platforms, rather than eliminating intermediation, have reconfigured it, shifting the locus of control without altering its fundamental function.

**Proposition 2:** *Digitalisation does not eliminate intermediation in agri-food supply chains but reconfigures it into new governance structures that sustain existing power asymmetries. The persistence of intermediaries is a function of contractual incompleteness, residual rights concentration, and institutional fragility, ensuring that digital platforms serve as adaptive mechanisms for intermediation rather than substitutes for it.*

#### **6.4 Contractual Voids and the Institutional Fragility of Digital Market Governance**

The promise of digital transformation in agri-food supply chains is underpinned by the assumption that digital contracts, algorithmic enforcement mechanisms, and automated transaction infrastructures will eliminate uncertainty, mitigate opportunism, and enhance predictability in exchange relationships. This belief is rooted in neoclassical contract theory and new institutional economics, which suggest that digitalisation will reduce transaction costs, eliminate information asymmetries, and stabilise contracting environments through the formalisation and automation of agreements (North, 1990; Williamson, 1985; Coase, 1937). By shifting governance mechanisms from informal negotiation to pre-defined digital execution, digital contracts are expected to ensure that all market actors can engage in transactions with minimal risk, predictable enforcement, and seamless efficiency (Barrett et al., 2012; World Bank, 2019).

Yet empirical evidence from Nigeria's tomato supply chain fundamentally challenges this premise. Rather than eliminating contractual uncertainty, digital transformation amplifies contractual voids: gaps between the formal obligations encoded within digital contracts and the realities of enforcement, negotiation, and dispute resolution in structurally precarious markets (Aker and Mbiti, 2010; Fafchamps, 2004). Far from mitigating uncertainty, digitalisation has reconfigured

contract governance into a site of institutional fragility, where weaker actors, including smallholder farmers, independent traders, and transporters, are disproportionately exposed to the rigidities, algorithmic opacity, and enforcement asymmetries embedded in digital transactions (Sitko and Jayne, 2014; Foster and Heeks, 2013). This finding emerged inductively from stakeholder accounts describing experiences of contract abandonment, payment default, and algorithmic manipulation, subsequently theorised through engagement with incomplete contract theory and institutional void literatures.

#### **6.4.1 The Structural Persistence of Contractual Incompleteness**

At the heart of this contractual dysfunction lies contractual incompleteness: the inherent inability of contracts to fully specify all contingencies in an exchange relationship (Hart and Moore, 1990; Hart, 1995). Agricultural markets are characterised by extreme volatility, including weather disruptions, logistical failures, price fluctuations, and unpredictable demand shifts. Contracts in these markets cannot fully account for all potential disruptions, meaning that ex-post renegotiation, informal mediation, and discretionary adjustments are necessary for contract fulfilment (Fafchamps, 2004; Dorward et al., 2009). Digital contracts, despite their promise of greater enforceability, do not resolve this incompleteness; instead, they rigidify transactions, creating new forms of vulnerability for actors who cannot renegotiate terms or absorb exogenous shocks within digitally enforced agreements (Qiang et al., 2012; Williamson, 1991).

In Nigeria's tomato supply chain, digital contracting platforms have been introduced to predefine price terms, delivery schedules, and quality requirements, with payments automatically triggered upon fulfilment. These mechanisms ostensibly reduce uncertainty for all parties. However, contract rigidity exacerbates the precariousness of weaker actors, particularly smallholder farmers who struggle to meet predefined conditions due to external disruptions (Aker et al., 2016; Lazzarini et al., 2015). When adverse weather conditions affect yields or transportation bottlenecks delay delivery, digital contracts do not permit adaptation; instead, they automatically enforce penalties, default on payment, or exclude non-compliant actors from future transactions (Minten et al., 2017). Further exacerbating this issue is the asymmetric enforcement of digital contracts, where large buyers and aggregators retain flexibility to adjust contract terms whilst farmers and transporters remain locked into rigid compliance requirements (Reardon et al., 2019). Traditional informal markets permit discretionary adjustments based on market conditions; digital contracting platforms function as binary execution mechanisms, in which compliance is either met or breached, leaving no room for contingency-based adjustments (Barrett, 2008). This

exclusionary rigidity transfers market risk onto the most vulnerable actors, reinforcing supply chain inequalities rather than mitigating them.

#### **6.4.2 Algorithmic Enforcement and the Technocratic Shift in Contract Governance**

A central feature of digital contracting is the introduction of algorithmic enforcement mechanisms, including automated dispute resolution, algorithmic price adjustments, and smart contract verification tools. These systems are promoted as objective, neutral, and tamper-proof, eliminating the discretion and arbitrariness associated with human mediation (Zhang et al., 2019; Wolfert et al., 2017). Yet empirical evidence suggests that algorithmic enforcement does not function as an impartial governance mechanism; instead, it redistributes decision-making power toward dominant actors who control the parameters of algorithmic execution (Deichmann et al., 2016; Mehrabi et al., 2021). Many digital trading platforms employ automated price adjustment algorithms that dynamically alter contract values based on supply-demand conditions. Whilst these adjustments are framed as rational market corrections, they disproportionately favour large buyers and aggregators who possess the ability to override algorithmic decisions when necessary (Jayne et al., 2010; Lioutas et al., 2019). Farmers and small traders, by contrast, remain bound by algorithmic pricing, unable to contest or renegotiate rates even when market conditions necessitate deviation.

Additionally, the opacity of algorithmic decision-making presents significant challenges for weaker market actors, who lack the technological literacy or institutional recourse to challenge automated contract enforcement (Foster and Heeks, 2013; Munthali et al., 2018). When disputes arise, digital platforms rarely provide transparent rationales for contract rejections, pricing fluctuations, or compliance penalties, leaving farmers with little recourse to contest unfair or unforeseen outcomes. This technocratic shift in contract governance reflects a broader structural transformation in market power, where control over digital infrastructure equates to control over market participation itself (Gibbon and Ponte, 2005; Ouma et al., 2017).

#### **6.4.3 Residual Benefits and Digital Market Enclosure**

The theory of incomplete contracts (Hart and Moore, 1990; Grossman and Hart, 1986) has traditionally focused on residual rights of control that emerge when contracts cannot fully specify all possible contingencies. However, this literature has largely neglected a critical dimension of digital transformation: the emergence of residual benefits, a category of value creation that remains unaccounted for in existing contract frameworks (Zuboff, 2015; Lazzarini et al., 2015). In the digital economy, efficiency gains, cost reductions, and productivity enhancements are not the

only forms of value generated. The integration of digital platforms, algorithmic decision-making, and sensor-driven optimisation in agri-food supply chains produces intangible benefits, including data-driven insights, knowledge externalities, network effects, and ecosystem-wide learning effects, that are difficult to foresee at contractual inception (Wolfert et al., 2017; Kos and Kloppenburg, 2019). These residual benefits are not merely unintended byproducts of digitalisation but are central to its transformative potential. Yet existing contract structures do not account for how these benefits should be distributed among actors, creating structural asymmetries in value appropriation.

By failing to incorporate mechanisms for sharing residual benefits, digital contracting models exacerbate power imbalances within supply chains. Large agribusinesses and digital service providers, who control platforms, data infrastructures, and algorithmic governance mechanisms, capture the majority of the value created, whilst smallholder farmers and intermediary market actors remain locked into transactional relationships that provide them with limited long-term gains (Deichmann et al., 2016; Swinnen and Kuijpers, 2019). The findings reveal that whilst digitalisation is often justified on the basis of efficiency improvements, its deeper impact lies in its capacity to generate new forms of economic value that are systematically appropriated by dominant players, reinforcing structural inequalities rather than alleviating them. This process of digital market enclosure creates a paradox: whilst digital transformation is often justified as a democratising force, its actual implementation results in the centralisation of value extraction among a small number of actors who control digital infrastructure (Gereffi et al., 2005).

**Proposition 3A:** *Digital contracts in agri-food supply chains do not eliminate contractual uncertainty; they exacerbate structural vulnerabilities by enforcing rigid compliance, embedding algorithmic opacity, and failing to distribute residual benefits equitably.*

**Proposition 3B:** *The persistence of contractual voids ensures that digital platforms remain sites of power concentration rather than efficiency, reinforcing exclusion rather than democratising market participation.*

## **6.5 Algorithmic Power and the Reconfiguration of Market Coordination**

A clear distinction must be established between the preceding analysis of digital contracts and this examination of algorithmic systems. Whilst the third constraint mechanism explored the limitations of digital contracts and their inability to resolve contractual incompleteness, this fourth mechanism interrogates the role of algorithmic systems in structuring decision-making processes, shaping market participation, and concentrating power in digital agri-food supply chains. This

distinction is crucial: the third mechanism critiques digitalisation at the level of contract design, whilst the fourth critiques digitalisation at the level of market coordination and economic governance. Algorithmic decision-making is not merely a tool for improving efficiency; it is a mechanism that actively restructures power, determining which actors gain or lose access to key market opportunities (Foster and Heeks, 2013; Mehrabi et al., 2021).

Whilst the literature on digital transformation often assumes that algorithmic optimisation will reduce inefficiencies by improving coordination and enhancing decision-making transparency, this analysis challenges that assumption by demonstrating that algorithmic governance is neither neutral nor inherently beneficial (Rotz et al., 2019; Klerkx et al., 2019). Instead, it functions as a mechanism for power reallocation, embedding asymmetries and systematically disadvantaging actors with weaker digital footprints, lower capital access, and limited control over computational infrastructures (Deichmann et al., 2016; Zuboff, 2015). The inductive analysis revealed three mechanisms through which algorithmic infrastructures produce exclusion, stratification, and dependency: algorithmic price-setting and the erosion of bargaining autonomy; predictive optimisation and the foreclosure of market access; and data-driven scoring mechanisms and the algorithmic stratification of opportunity.

#### **6.5.1 Algorithmic Price-Setting and the Erosion of Bargaining Autonomy**

One of the core promises of digital transformation is that algorithmic pricing will improve market efficiency, reduce price manipulation, and create more transparent and competitive agricultural markets. The assumption is that AI-driven pricing models, automated auction mechanisms, and predictive price analytics will enable farmers and traders to react dynamically to supply and demand fluctuations, reducing transaction costs and levelling the playing field (World Bank, 2019; Maru et al., 2018). However, empirical findings from Nigeria's tomato supply chain reveal a striking paradox: whilst algorithmic price-setting enhances market visibility, it does not enhance market power for small-scale actors. On the contrary, it actively erodes bargaining autonomy, concentrating pricing authority in the hands of digital platforms, agribusiness conglomerates, and retail chains (Reardon et al., 2019; Pimbert et al., 2021).

Farmers who use digital price discovery platforms report that algorithmic models often impose price ceilings, restricting the ability of sellers to negotiate for higher rates even when demand conditions suggest they should be able to do so. The paradox is that whilst farmers have more visibility into price fluctuations than ever before, they simultaneously have less control over price



determination, as platforms impose automated price adjustments that disproportionately favour large-scale buyers (Aker, 2010; Munthali et al., 2018). This contradicts the fundamental assumptions of transaction cost economics (Williamson, 1985), which posit that reducing information asymmetry should empower market actors and facilitate fairer pricing. However, the findings align more closely with emerging critiques in platform capitalism (Srnicek, 2016) and algorithmic governance studies (Zuboff, 2019), which argue that algorithmic infrastructures do not passively reflect market conditions but actively construct them, embedding the priorities of dominant firms into pricing models that extract value asymmetrically.

### **6.5.2 Predictive Optimisation and the Foreclosure of Market Access**

Beyond pricing, algorithmic infrastructures reshape market participation, determining who gains access to key trading opportunities and under what conditions. The growing adoption of AI-driven procurement models, automated supplier ranking systems, and predictive analytics-based contract allocation has led to a new paradigm of algorithmic gatekeeping, where participation in high-value agricultural markets is increasingly restricted to actors who meet digital eligibility criteria (Tsan et al., 2019; CTA, 2019). Theoretically, predictive optimisation should enhance supply chain efficiency by ensuring that only the most reliable and capable suppliers gain market access. However, empirical findings indicate that these predictive models systematically privilege large, well-integrated agribusinesses whilst marginalising smallholder farmers, informal traders, and actors who lack digital transaction histories (Barrett et al., 2012; Swinnen and Kuijpers, 2019).

Major retail chains and food processors increasingly rely on algorithmic procurement systems that rank potential suppliers based on digital performance metrics, including past delivery consistency, quality compliance, and traceable financial transactions. This means that suppliers with limited digital footprints, those who have not previously engaged with digital supply chains or whose transaction histories are incomplete, are automatically classified as high-risk, even if their actual performance is competitive (Qiang et al., 2012). This trend aligns with broader critiques in platform governance (Gillespie, 2018), which argue that algorithmic infrastructures function as selective filters rather than neutral efficiency tools, determining which actors are deemed credible market participants and which are systematically excluded.

### **6.5.3 Data-Driven Scoring and the Algorithmic Stratification of Opportunity**

Perhaps the most far-reaching impact of algorithmic governance in agri-food supply chains is the rise of digital scoring systems that determine financial access, operational legitimacy, and risk assessment for individual farmers and traders. As digital financialisation accelerates, lenders,

insurers, and buyers increasingly rely on algorithmic credit assessment models, machine-learning risk analytics, and digital transaction monitoring to evaluate the trustworthiness of market participants (Wolfert et al., 2017; Baumüller, 2018). This process extends beyond financial credit scoring to include algorithmic assessments of GPS-tracked farm activity, IoT-based yield monitoring, predictive weather impact modelling, and even sentiment analysis from digital communication platforms. Whilst these scoring mechanisms are framed as tools for enhancing financial inclusion, they introduce new forms of economic stratification by embedding structural biases into the algorithms that determine opportunity (Mehrabi et al., 2021; Rotz et al., 2019).

A farmer who lacks an extensive digital transaction record, either because they operate in a predominantly cash-based economy or because they are newly integrated into digital supply chains, will receive a lower algorithmic credibility score, restricting their access to competitive loans, digital marketplace contracts, and preferential trade agreements. In contrast, actors with deeper digital engagement histories and algorithmically verified production patterns gain preferential treatment, leading to a self-reinforcing cycle of inclusion and exclusion (Aker et al., 2016; Donovan et al., 2015). This aligns with critical financialisation studies (Chiapello, 2017), which argue that algorithmic finance does not simply reflect risk but actively constructs it, embedding systemic biases that disproportionately disadvantage those with lower technological integration.

**Proposition 4:** *As algorithmic governance structures become more deeply embedded in agri-food supply chains, market coordination is increasingly dictated by computational systems rather than direct economic interaction. This shift privileges actors with superior access to algorithmic infrastructures, reinforcing structural disparities in pricing, market access, and financial inclusion, whilst systematically disadvantaging those with weaker digital footprints and lower algorithmic visibility.*

## 6.6 Institutional Rigidities and the Limits of Digital Transformation

The widespread optimism surrounding digital transformation in agri-food supply chains is built on a fundamental assumption: that inefficiencies in agricultural markets are primarily technical or informational in nature and can be resolved by introducing digital tools that enhance transparency, coordination, and accountability. This perspective assumes that once technologies such as blockchain-enabled traceability systems, Internet of Things-based logistics, digital financial infrastructure, and algorithmic decision-making models are deployed, supply chains will naturally evolve toward more efficient and sustainable configurations (World Bank, 2019; Wolfert et al., 2017; Maru et al., 2018). However, this analysis argues that such assumptions are

fundamentally flawed, as they fail to account for the deeply entrenched institutional rigidities that systematically constrain digital transformation (Khanna and Palepu, 2010; Dorward et al., 2009).

Whilst prior sections have interrogated the structural constraints imposed by intermediation, the limitations of digital contracts, and the reallocation of market power through algorithmic infrastructures, this section shifts focus to the broader institutional landscape that governs digitalisation itself. It explores how regulatory, bureaucratic, and governance-related rigidities systematically undermine the potential efficiency gains of digital tools, ensuring that even where digital adoption is widespread, systemic transformation remains elusive (Mair et al., 2012; Foster and Heeks, 2013). The core argument is that institutional rigidities are not simply barriers to be overcome; rather, they are active forces that shape, constrain, and in some cases redirect the trajectory of digital transformation. These rigidities manifest in three interrelated forms: the fragmentation and misalignment of regulatory frameworks; the inertia of bureaucratic institutions that resist digital adaptation; and the structural incompatibility between digital governance mechanisms and existing market logics.

#### **6.6.1 Regulatory Fragmentation and the Limits of Policy Coherence**

One of the most pervasive yet underexamined barriers to digital transformation is the misalignment between technological innovation and existing regulatory frameworks. Digitalisation does not occur in a vacuum; it unfolds within a legal and policy environment that determines how digital tools can be deployed, scaled, and institutionalised. However, empirical evidence from emerging and industrialised agricultural markets alike reveals that regulatory fragmentation consistently undermines the coherence and effectiveness of digital initiatives (Fafchamps, 2004; Dury et al., 2019). In many national and transnational supply chains, multiple regulatory bodies oversee different facets of agricultural trade, data governance, financial transactions, and technological standards. Ministries of agriculture, food safety authorities, trade commissions, data protection agencies, and financial regulators often operate in isolation, each with distinct and sometimes conflicting mandates. This creates significant regulatory ambiguities that complicate the implementation of digital solutions.

In Nigeria's tomato supply chain, the introduction of blockchain traceability platforms was initially perceived as a breakthrough for food safety and export compliance. However, the initiative was hindered by overlapping mandates from agricultural regulators, national cybersecurity agencies, and state-level trade ministries. Conflicting requirements, including different standards for digital record-keeping and competing policies on how agricultural data should be shared, led to

protracted deadlock, preventing the platform from being fully operationalised. The problem was not a lack of technological readiness but rather the absence of a coordinated institutional framework that could integrate blockchain solutions into existing governance mechanisms (Tian, 2016; Tripoli and Schmidhuber, 2018). This fragmentation aligns with institutional economics (North, 1990), which argues that economic inefficiencies are often not market failures but the result of competing institutional arrangements that create uncertainty and policy paralysis. Moreover, regulatory fragmentation introduces discretionary enforcement gaps that enable certain actors, especially well-connected intermediaries and agribusiness conglomerates, to exploit legal ambiguities to their advantage.

### **6.6.2 Bureaucratic Inertia and the Resistance to Digital Adaptation**

Beyond regulatory fragmentation, bureaucratic inertia presents a significant impediment to the institutionalisation of digital technologies. Whilst digital transformation is frequently framed as a process of market-driven innovation, its success ultimately depends on the willingness and capacity of public institutions to integrate and adapt to new digital governance models. However, empirical findings indicate that bureaucratic agencies responsible for overseeing agricultural trade, food safety, and financial inclusion often lack both the expertise and the incentive to incorporate digital tools into their regulatory frameworks (Deichmann et al., 2016; Swinnen and Kuijpers, 2019). This inertia manifests in two forms: resistance to digital oversight mechanisms that could improve regulatory enforcement, and failure to develop adaptive policy frameworks that respond to the evolving nature of digital supply chains.

Evidence from Kenya's horticultural export sector illustrates this dynamic. AI-driven quality inspection tools were expected to reduce corruption, standardise grading systems, and enhance food safety compliance. However, government inspectors actively resisted AI-based assessments, arguing that automated certification threatened their discretionary authority and could lead to job displacement. Rather than embracing AI as a tool for regulatory efficiency, inspectors continued to rely on subjective, manual inspection methods that were more susceptible to bribery and inconsistent enforcement (Humphrey, 2004; Munthali et al., 2018). This finding aligns with bureaucratic inertia theories (Kaufman, 1977; Pierson, 2004), which argue that institutional actors resist reform when it threatens established power dynamics and discretionary decision-making authority. Moreover, public institutions often lack the capacity to regulate digital technologies effectively, leading to situations where new digital contracting, finance, and logistics systems operate in legal grey zones.

### **6.6.3 The Systematic Marginalisation of Food Waste as a Policy Priority**

In addition to regulatory fragmentation and bureaucratic inertia, a fourth critical dimension of institutional rigidity lies in the rigidity of metric selection within food system governance. This form of rigidity is distinct in that it does not stem from resistance to digitalisation per se but rather from the ways in which institutions codify, prioritise, and entrench specific metrics, such as yield, food security, and food safety, whilst neglecting others, including food waste. This institutional preoccupation with certain predefined metrics shapes policy design, resource allocation, and infrastructural development in ways that systematically exclude food waste reduction from meaningful policy intervention (Godfray et al., 2010; CTA, 2019). This argument builds on historical institutionalism (Pierson, 2004; Thelen, 1999), which emphasises that once institutions lock in a particular policy framework, the subsequent development of infrastructure, resource flows, and regulatory focus aligns rigidly with those initial priorities, making alternative concerns structurally peripheral.

One of the clearest examples of how metric selection rigidity shapes food system inefficiencies is the overwhelming emphasis on yield maximisation as the dominant metric of agricultural productivity. Food policy interventions, agricultural subsidies, research funding, and technological innovations are overwhelmingly designed to optimise for higher yields, assuming that increasing production is the primary solution to food insecurity (Pretty et al., 2010; Jayne et al., 2010). This singular focus has led to the development of agricultural infrastructure, supply chain models, and food distribution networks that prioritise production volume over post-harvest efficiency. Even digital interventions within the food system, such as precision farming, satellite monitoring, and automated irrigation, are typically designed to enhance input-output efficiency rather than minimise surplus waste (Wolfert et al., 2017). Empirical evidence from both cases demonstrates how yield-maximising policies inadvertently exacerbate food waste: government agricultural extension programmes provided input subsidies, mechanisation support, and financial incentives for smallholder farmers to increase their harvest volumes. However, because no corresponding investment was made in cold-chain logistics, market coordination mechanisms, or flexible off-take agreements, a significant portion of surplus production was lost due to spoilage or market saturation (Reardon et al., 2019; Minten et al., 2017).

A fundamental misconception in food system governance is the assumption that food waste reduction will naturally occur as a result of interventions that enhance food security, improve logistics, or streamline supply chains. However, as the empirical evidence demonstrates, food waste persists not because it is technically unsolvable but because it has not been institutionally prioritised in the same way as other food system objectives (Parfitt et al., 2010; Barrett et al., 2012). This aligns with insights from policy inertia theory (Hacker, 2004), which suggests that policy frameworks, once established, tend to resist recalibration even when evidence suggests that new priorities should be incorporated.

**Proposition 5A:** *The transformative potential of digitalisation in agri-food supply chains is constrained not by technological limitations but by institutional rigidities, manifesting in regulatory fragmentation, bureaucratic inertia, and the structural incompatibility between digital governance models and existing market logics. Without addressing these institutional constraints, digital transformation will remain an incomplete process, reinforcing inefficiencies rather than resolving them.*

**Proposition 5B:** *The persistence of food waste in agri-food supply chains is not merely a result of market failures or technological inefficiencies but is a direct consequence of institutional rigidity in metric selection. Because food governance structures prioritise yield maximisation, food security, and food safety as their primary objectives, food waste remains a secondary concern that is left to market actors rather than being embedded within formal policy frameworks.*

## 6.7 The Digital Constraint Paradox Framework

The synthesis of the five constraint mechanisms yields this study's principal theoretical contribution: the Digital Constraint Paradox (DCP) framework. This framework represents a fundamental reconceptualisation of how digital transformation unfolds within structurally constrained market environments, particularly in agri-food supply chains. Whilst prevailing discourse on digitalisation assumes that technological interventions will naturally yield efficiency, transparency, and improved coordination (Dahlman et al., 2016; Foster and Heeks, 2013), the DCP framework reveals a paradox: digital tools, rather than resolving inefficiencies, often become embedded within existing structural constraints, reinforcing rather than dismantling the very barriers they are designed to overcome. The paradox is not rooted in technological failure but in the erroneous assumption that digital solutions operate independently of the institutional and contractual architectures that govern economic behaviour (Barrett et al., 2022; Rodrik, 2008).

The five constraint mechanisms elaborated in Sections 6.2 through 6.6 correspond to five paradoxes that structure the Digital Constraint Paradox framework. Table 23 specifies these correspondences; the governance implications and policy levers associated with each paradox are developed in Chapter Seven (Table 24).

Table 23: Constraint Mechanisms and Corresponding Paradoxes

| Section | Constraint Mechanism                                              | Corresponding Paradox           |
|---------|-------------------------------------------------------------------|---------------------------------|
| 6.2     | Digital Transformation as a Structurally Constrained Process      | <b>Constrained Efficiency</b>   |
| 6.3     | Digital Intermediation as a Structural Necessity                  | <b>Disrupted Informality</b>    |
| 6.4     | Contractual Voids and Institutional Fragility                     | <b>Fragmented Formalisation</b> |
| 6.5     | Algorithmic Power and Market Coordination Reconfiguration         | <b>Algorithmic Mistrust</b>     |
| 6.6     | Institutional Rigidities and the Limits of Digital Transformation | <b>Residual Governance</b>      |

The DCP framework advances and extends key strands of incomplete contract theory, institutional economics, and digital efficiency models, weaving them into a broader theoretical construct that accounts for the persistent failures of digital adoption to generate anticipated efficiency gains. At the heart of the framework is recognition that technological transformation is conditioned by two fundamental dimensions: the nature of institutional support and the availability and organisation of resource capabilities. These two structural constraints are not merely technical limitations but deeply embedded governance and economic realities that define the trajectories of digitalisation in agri-food markets (Acemoglu and Robinson, 2012; Gowda et al., 2018). The synthesis of the five constraint mechanisms reveals that digital inefficiencies are not

incidental disruptions but structurally embedded realities arising from the misalignment between digital technologies and market logics, governance frameworks, and resource infrastructures.

### 6.7.1 The Two Axes of the Digital Constraint Paradox

From the synthesis of the five constraint mechanisms, two fundamental axes emerge as the defining determinants that shape digital transformation trajectories: institutional support and resource capabilities. These axes are not merely descriptive but function as structural determinants of how digitalisation unfolds in agri-food supply chains. They define the necessary preconditions for digital success and predict where and why technological interventions either generate efficiency, become performative, or exacerbate structural failures.

**Institutional Support: The Governance Axis.** The first axis captures the degree of institutional support, referring to the coherence, adaptability, and enforcement capacity of formal and informal governance structures that regulate digital adoption. Institutional support is not merely a function of regulatory presence or absence but is shaped by a broader set of governance conditions, including contract enforceability, policy alignment, and actor coordination. This axis draws directly from institutional economics (North, 1990; Pierson, 2004) and extends its insights into the domain of digital governance (Goldfarb and Tucker, 2019). When institutional support is strong, governance mechanisms create stability, trust, and enforcement structures that ensure digital transformation aligns with market incentives; digital tools are integrated into a coherent policy environment, allowing for structured efficiency gains. When institutional support is weak, fragmentation, regulatory voids, and enforcement failures prevent digital technologies from delivering their intended benefits; digital platforms and smart contracts may exist in theory but remain functionally disconnected from actual market realities (Ganne, 2018; Zanello, 2012).

**Resource Capabilities: The Structural Axis.** The second axis captures resource capabilities, referring to the availability, distribution, and coordination of financial, material, and technological resources necessary for digital interventions to function effectively. This axis builds on resource-based perspectives (Barney, 1991) and extends insights from the five constraint mechanisms by illustrating how logistical gaps, infrastructural inadequacies, and financial constraints impose hard limits on the effectiveness of digital tools (Heeks, 2010; World Bank, 2016). When resource capabilities are high, digital technologies can be leveraged effectively because the surrounding physical and financial infrastructures support their integration; logistics, financial liquidity, and supply chain coordination are aligned with technological interventions, allowing for structured



efficiency improvements. When resource capabilities are low, digital solutions become performative rather than functional, as they are introduced into supply chains that lack the necessary logistical, financial, and infrastructural foundations to sustain them (Donovan, 2012; Aker et al., 2016).

The interaction between these two axes defines four distinct digital transformation trajectories, creating the Digital Constraint Paradox framework. Each quadrant captures a unique pattern of digital inefficiency or success, providing a structured means to classify and predict how digital interventions unfold across different market configurations. Fig. 24 presents the visual representation of this framework, which should be examined before proceeding to the detailed analysis of each quadrant.

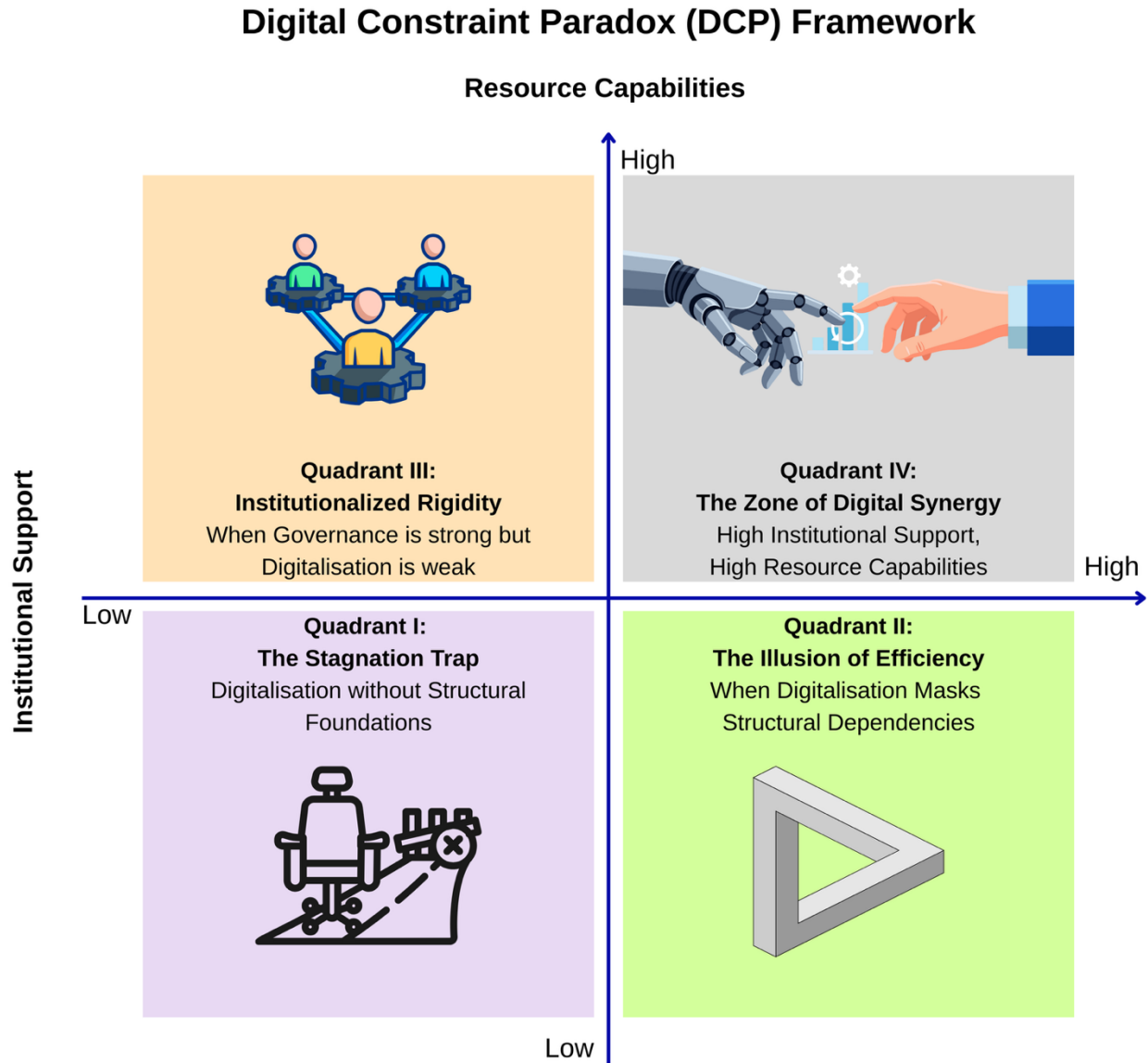


Fig. 24: The Digital Constraint Paradox Framework

As depicted in Fig. 24, the four quadrants represent distinct structural configurations: Quadrant I (Low Institutional Support, Low Resource Capabilities) represents the Stagnation Trap, where digitalisation remains performative rather than functional; Quadrant II (Low Institutional Support, High Resource Capabilities) represents the Illusion of Efficiency, where digital tools appear to function but fail to produce systemic transformation; Quadrant III (High Institutional Support, Low Resource Capabilities) represents Institutionalised Rigidity, where strong governance frameworks paradoxically inhibit digital adoption; and Quadrant IV (High Institutional Support, High Resource Capabilities) represents the Zone of Digital Synergy, where both conditions are

favourable yet new challenges of algorithmic monopolisation and digital exclusion emerge. The following sub-sections analyse each quadrant in detail.

### **6.7.2 Quadrant I: The Stagnation Trap**

The first quadrant represents digital stagnation: a scenario where digital interventions are introduced into agri-food supply chains characterised by both low institutional support and low resource capabilities. In this environment, digitalisation does not catalyse efficiency or transformation; instead, it constitutes a performative exercise in technological adoption that fails to produce tangible benefits. Digital tools become mere artefacts of progress rather than enablers of economic or logistical advancement, trapped within a structurally deficient market that lacks the necessary scaffolding to support their integration (Heeks, 2002; Toyama, 2015). The stagnation trap reveals a profound limitation of contemporary digital transformation discourse: technology alone cannot induce structural change in supply chains where governance mechanisms, market coordination, and logistical infrastructures are weak or entirely absent.

This quadrant is characterised by two interwoven failures. The first is the inability of digital tools to replace institutional voids. Digital platforms, blockchain contracts, mobile-based price discovery mechanisms, and algorithmic market matching are all designed on the assumption that markets fail due to information asymmetries, high transaction costs, and inefficient coordination mechanisms (Aker, 2010; Jensen, 2007). However, in environments where regulatory frameworks are weak, contract enforcement is unreliable, and informal trust-based networks dominate trade, digitalisation does not enhance efficiency; it simply coexists with existing inefficiencies, unable to alter the fundamental dynamics that shape market behaviours (Mair and Marti, 2009; Rodrik, 2008). The second failure is the inability of digital technologies to overcome infrastructural and financial constraints. Even when digital tools are made accessible, the surrounding conditions, including limited transport infrastructure, unreliable electricity, weak storage networks, and fragmented financial systems, prevent them from functioning effectively. Digital platforms become ornamental rather than instrumental, unable to address the material deficiencies that sustain market inefficiencies (Donovan, 2012; Graham, 2011).

This phenomenon is particularly evident in Case One, where digitalisation has been heavily promoted through government initiatives, donor-funded projects, and private sector-led solutions, yet the persistence of underlying deficiencies renders these technologies ineffective. The failure of mobile-based price discovery platforms to improve market efficiency exemplifies this dynamic.

The introduction of these tools was based on the assumption that smallholder farmers' lack of real-time price information kept them at a disadvantage, allowing intermediaries to manipulate prices. By giving farmers direct access to market rates, the platforms were expected to enable them to negotiate better deals, bypass exploitative middlemen, and optimise their sales decisions. However, this assumption failed to consider that price information alone does not equate to market power. In practice, farmers who accessed digital price discovery platforms remained structurally dependent on intermediaries. Even with real-time price knowledge, they lacked the transport capacity, storage facilities, and contractual protections necessary to act on that information. Thus, digital price discovery became an awareness tool rather than an empowerment mechanism, failing to alter the structural dependencies that defined farmer-market relationships (Burrell and Oreglia, 2015; Srinivasan and Burrell, 2013).

In contrast to conventional policy recommendations that emphasise increasing digital adoption, the stagnation trap requires a fundamental reconsideration of sequencing in digital transformation strategies. The assumption that technology leads and institutions follow must be reversed: structural governance, infrastructure, and financial coordination must be strengthened before digital tools can meaningfully enhance efficiency (Galperin and Vicens, 2017; Kleine, 2010). Effective interventions must prioritise structural reforms before or alongside digital adoption, ensuring that governance, enforcement, and infrastructure gaps are addressed before technological solutions can yield meaningful transformation.

### **6.7.3 Quadrant II: The Illusion of Efficiency**

In the second quadrant, digitalisation occurs within environments characterised by high resource capabilities but low institutional support. Unlike Quadrant I, where digitalisation remains a performative exercise constrained by lack of fundamental enablers, Quadrant II presents a different paradox: technology appears to function effectively, yet it does not produce transformative structural change. The illusion of efficiency emerges as digital tools enable local optimisations, including better price discovery, improved logistics coordination, and more streamlined transactions, whilst simultaneously reinforcing existing power asymmetries, deepening contractual uncertainties, and failing to create broader system-wide resilience.

This quadrant challenges conventional wisdom in digital transformation literature, particularly the assumption that once the right digital tools are made available and resource constraints are alleviated, efficiency gains will automatically materialise (Aker and Fafchamps, 2015; Reardon et

al., 2019). Instead, what occurs is a form of constrained optimisation, where digital interventions increase functional efficiency in isolated areas of the supply chain whilst leaving structural inefficiencies untouched. The failure of digital tools to drive systemic transformation is not due to technological inadequacy but because they operate within institutional voids, where enforcement mechanisms, regulatory coherence, and market governance are absent or underdeveloped (North, 1990; Mahoney and Thelen, 2010). The key paradox is that digitalisation does not eliminate inefficiencies but redistributes them. Digital tools are often designed to optimise at the level of the individual transaction, the firm, or the market segment, without addressing the broader coordination failures, governance gaps, and power dynamics that shape supply chain behaviour. This results in partial efficiencies that mask systemic dysfunction.

The illusion of efficiency is sustained by three reinforcing mechanisms. First, algorithmic rationalisation of market inefficiencies: digital platforms optimise transactions within the existing market structure rather than transforming it, reinforcing price-setting mechanisms that favour dominant actors (Zuboff, 2019). Second, technological substitution for institutional governance: automated enforcement mechanisms replace human oversight without addressing fundamental gaps in legal and financial accountability (Fourcade and Healy, 2017). Third, data-driven entrenchment of power asymmetries: digital platforms, instead of democratising market access, increase the advantage of actors who already possess the infrastructure, capital, and leverage to manipulate data flows (Singh et al., 2018; Srnicek, 2017). This creates a system where digital tools function but in ways that consolidate rather than resolve inefficiencies. The result is an ecosystem that appears digitally advanced yet remains structurally fragile, operating at high efficiency in some areas whilst failing to address the fundamental constraints that prevent real transformation.

Case Two illustrates this dynamic, where commercial-scale actors, often supported by private capital or donor-driven projects, introduce digital innovations to streamline supply chain operations. These interventions, ranging from blockchain-driven contract management to automated logistics coordination, appear to significantly enhance operational efficiency at the firm or network level. However, because these hubs operate in weakly governed institutional environments, digital efficiency does not translate into broader market transformation. To transition beyond the efficiency illusion, digital transformation strategies must shift from optimisation-focused interventions toward institutional integration. Unlike Quadrant I, where the emphasis must be on foundational governance and infrastructure, Quadrant II requires a

rethinking of digital governance structures themselves, embedding institutional flexibility into digital enforcement mechanisms and rebalancing data ownership models to prevent asymmetric market power.

#### **6.7.4 Quadrant III: Institutionalised Rigidity**

In the third quadrant, the paradox of digital transformation emerges within supply chains that benefit from high institutional support but suffer from low digital resource capabilities. Unlike Quadrant II, where digitalisation is extensive but fails to create systemic transformation, here the opposite occurs: strong governance frameworks, regulatory oversight, and market coordination mechanisms exist, yet digital adoption remains fragmented, inconsistent, or structurally constrained. This quadrant challenges prevailing assumptions that institutional robustness naturally facilitates digital transformation. Much of the digital efficiency literature assumes that if governance structures are in place, technological adoption will follow (North, 1990; Acemoglu and Robinson, 2012). However, empirical evidence reveals that strong institutional frameworks do not inherently translate into digital integration; in many cases, they actively inhibit it.

The central paradox in this quadrant is that the very structures that provide market stability, legal enforceability, and supply chain coordination also create bureaucratic inertia, policy misalignment, and regulatory inflexibility that hinder digital innovation (Janssen and Estevez, 2013; Singh, 2019). The structural constraint is not an absence of governance but its rigidity and misalignment with digital transformation. Institutions that have long governed agricultural markets, contract enforcement, and supply chain logistics often do so through deeply entrenched regulatory frameworks that predate contemporary digital interventions. These frameworks were built for analogue, paper-based, and manually coordinated systems, and as a result, their legal, financial, and operational models frequently fail to accommodate the flexibility, interconnectivity, and dynamic adaptation required for digitalisation.

Three key mechanisms reinforce this rigidity. First, overregulation and compliance burdens: when institutional oversight is high but digital adaptability is low, strict compliance regimes stifle innovation; licensing requirements, standardised contract structures, and highly proceduralized transaction mechanisms leave little room for digital experimentation, adaptive pricing models, or real-time data-driven decision-making (Goldfarb and Tucker, 2019). Second, market lock-in and path dependency: institutional systems designed to stabilise and de-risk supply chains often reinforce market structures that are resistant to technological change; long-standing producer-

buyer agreements, regulatory protectionism, and highly structured financial mechanisms discourage the entry of digital platforms that might introduce disruptive efficiencies (Pierson, 2004). Third, policy misalignment and fragmentation: even where digital transformation policies exist, they often operate in isolation from broader institutional frameworks, resulting in policies that encourage digitalisation without the necessary legal, financial, or logistical integration to make adoption viable at scale (Kleine, 2013).

This illustrates the core constraint: institutions function with high effectiveness in their established analogue models yet resist adaptation to digital mechanisms that could enhance their operational efficiency. Digitalisation, rather than being perceived as a tool for optimisation, is often perceived as a disruptive force that threatens entrenched institutional roles, regulatory certainty, and policy coherence (Avgerou, 2010). Overcoming this constraint requires hybrid governance models, regulatory sandboxes, and market-driven digital experimentation to progressively align policy structures with digital capabilities.

#### **6.7.5 Quadrant IV: The Zone of Digital Synergy**

In the fourth quadrant, we arrive at what is often assumed to be the ideal scenario: a digital transformation environment characterised by both robust institutional support and extensive resource capabilities. This is the space where digitalisation in agri-food supply chains is expected to yield the most substantial efficiency gains, market inclusivity, and resilience. However, contrary to the conventional assumption that strong institutions and abundant resources naturally lead to a frictionless digital economy, the dynamics of this quadrant reveal a more complex interplay of governance structures, digital coordination, and evolving power asymmetries. The high-high configuration does not automatically guarantee digital success; rather, it introduces new challenges related to market control, algorithmic governance, and the structural risks of digital monopolisation.

The widespread belief that a strong institutional framework, when coupled with high digital resource availability, will seamlessly drive efficiency gains and inclusivity in supply chains is rooted in traditional economic theories of institutional stability and market coordination. Classical transaction cost economics (Williamson, 1985) suggests that efficiency follows when institutions provide stability, enforcement mechanisms, and a competitive market structure, whilst firms possess the necessary financial, infrastructural, and technical resources to deploy digital solutions effectively. Yet, as institutional economics (North, 1990) and market coordination theories (Gereffi et al., 2005) caution, simply having strong institutions and abundant resources

does not guarantee that digitalisation unfolds optimally. These theories highlight the structural constraints of power concentration, regulatory capture, and strategic adaptation of dominant actors, which persist even in highly digitalised and well-governed environments.

Empirical insights from digitally mature agri-food markets, including India's Farmer Producer Organisation model, Kenya's digitally integrated horticulture sector, and China's government-backed e-commerce ecosystems, demonstrate that high institutional support and robust digital infrastructure do not inherently guarantee efficiency. Instead, the effectiveness of digital transformation in this quadrant depends on how well digital governance aligns with market realities, how openly digital resources are distributed, and whether digital adoption remains decentralised or concentrated among a few powerful actors (Reardon et al., 2019; Qiang et al., 2011). One of the most significant paradoxes is that even under optimal institutional and resource conditions, power asymmetries do not dissipate; they evolve. The rise of platform capitalism (Srnicsek, 2017) and algorithmic governance (Fourcade and Healy, 2017) provides insight into how power is exercised in digitally mature agri-food ecosystems. Digital transformation does not necessarily empower all actors equally; rather, dominant firms leverage their control over data-driven pricing models, predictive analytics, and contract enforcement mechanisms to shape market outcomes in their favour.

Given these structural dynamics, the challenge in this quadrant is not about achieving digital adoption, as both institutional and resource conditions are strong, but about ensuring that digital transformation remains inclusive, decentralised, and structurally resilient. In environments where digital governance is left to market forces alone, the risks of digital exclusion and monopolisation become evident. To navigate these risks, proactive governance mechanisms must be in place to ensure that digital platforms, financial structures, and market coordination mechanisms remain open, accessible, and fair (Goldfarb and Tucker, 2019; Singh et al., 2018). Key solutions include the development of decentralised digital governance models that prevent the monopolisation of agri-food data and digital financial tools; the implementation of interoperable digital contracting and algorithmic transparency mechanisms; and the incentivisation of digital commons and public digital infrastructure to ensure that well-developed institutional and resource environments do not become privatised digital ecosystems that crowd out public innovation.

**Proposition 6:** *When both institutional support and digital resource capabilities are high, the central governance challenge shifts from enabling digitalisation to ensuring that digital platforms,*



*contracts, and financial structures remain open, accountable, and equitably distributed. The failure to regulate digital ecosystems proactively in this quadrant risks the emergence of algorithmic monopolisation, data-driven exclusion, and financialised market asymmetries.*

## **6.8 Conclusion**

This chapter has developed the theoretical and empirical contributions of this study through a systematic examination of five constraint mechanisms that govern digital transformation in agri-food supply chains. Beginning with the foundational argument that digitalisation is structurally constrained rather than inherently efficiency-enhancing, the analysis demonstrated how digital tools are absorbed into pre-existing governance structures, reinforcing rather than dismantling systemic inefficiencies. The persistence of intermediation despite disintermediation technologies, the amplification of contractual voids through algorithmic enforcement, the reconfiguration of market power through computational systems, and the institutional rigidities that limit transformative potential collectively reveal that digital transformation cannot be understood through the lens of technological determinism.

The synthesis of these five mechanisms into the Digital Constraint Paradox framework constitutes this study's principal theoretical contribution. The two-axis model, structured around institutional support and resource capabilities, provides a systematic means of classifying and predicting digital transformation trajectories across varying governance and resource configurations. Each of the four quadrants, the Stagnation Trap, the Illusion of Efficiency, Institutionalised Rigidity, and the Zone of Digital Synergy, captures a distinct pattern of digital inefficiency or conditional success, offering both explanatory power for observed outcomes and prescriptive guidance for intervention design. The framework extends foundational theories in incomplete contract theory (Hart and Moore, 1990), institutional path dependency (North, 1990; Pierson, 2004), and transaction cost economics (Williamson, 1985) by demonstrating how these theoretical insights apply specifically to digital transformation contexts and interact in previously untheorised ways.

The implications for food waste governance are particularly significant. The findings demonstrate that food waste persists not because of technological inadequacy but because institutional frameworks systematically deprioritise waste reduction in favour of yield maximisation, food security metrics, and food safety standards. Digital interventions designed to address food waste will remain ineffective unless accompanied by institutional reforms that elevate waste reduction to a core policy objective. This insight challenges the dominant narrative that digital

transformation will inherently lead to food system sustainability, revealing instead that sustainability outcomes are contingent on the structural conditions within which technologies are deployed.

The chapter establishes the foundation for the concluding chapter, which will articulate the study's contributions to knowledge, derive practical implications for policy and practice, acknowledge limitations, and identify directions for future research. The Digital Constraint Paradox framework, grounded in the empirical realities of Nigeria's tomato supply chain and theoretically integrated with established scholarly traditions, offers a new paradigm for understanding digital transformation in structurally constrained markets, one that moves beyond simplistic optimisation narratives toward a more rigorous engagement with the governance, institutional, and economic conditions that shape technological outcomes.

## 7 Chapter Seven: Conclusion

### 7.1 Introduction

Chapter Seven consolidates the thesis argument and articulates its contributions. It returns to the two research questions by explaining how digital interventions in Nigeria's tomato supply chain simultaneously generate efficiency gains and constraint effects, and by specifying the governance mechanisms through which these paradoxes are produced and stabilised. The chapter then presents a theory-grounded synthesis in the form of the Digital Constraint Paradox (DCP) framework, alongside a set of propositions that translate the empirical insights into testable, transferable claims. It closes by outlining theoretical and practical implications, clarifying the boundary conditions of the study, and setting out a focused agenda for future research.

### 7.2 The Digital Constraint Paradox and the Institutional Embedding of Digital Transformation

This thesis began from a recurring operational observation: despite the rapid diffusion of digital tools across agri-food supply chains, expected improvements in coordination, traceability, and loss reduction are often partial, delayed, or unevenly distributed. The persistence of inefficiency is not treated here as a residual of slow adoption, user error, or infrastructure deficits alone. Rather, the study shows how digital interventions can become institutionally embedded in ways that reorganise incentives, redistribute information, and reallocate control, producing a paradoxical pattern in which localised efficiency co-exists with system-level constraint.

The central claim developed and defended in this thesis is that digital transformation in constrained agri-food contexts should be analysed as a governance problem before it is framed as a technology problem. Digital tools do not enter a neutral organisational space. They are enrolled into existing contractual relations, regulatory expectations, informal norms, and enforcement realities. Through that enrolment, digital systems can formalise practices selectively, intensify monitoring without strengthening recourse, and standardise workflows without resolving the institutional frictions that make coordination costly. These mechanisms explain why efficiency gains can appear in particular nodes or transactions while constraints intensify elsewhere in the chain, including in ways that matter for food loss reduction outcomes.

The DCP framework captures this interaction by treating outcomes as jointly shaped by two structural conditions: the resource capability of actors to implement and use digital systems

(ranging from low to high), and the institutional support available to stabilise digital coordination (ranging from low to high). The framework is not a typology of technologies. It is a configuration logic that links resource capability and institutional support to distinct governance patterns, with each pattern generating characteristic combinations of efficiency and constraint.

Across the cases analysed in this thesis, governance mechanisms are the proximate drivers of paradox. Contractual terms define the allocation of risk and discretion. Platform rules determine participation, ranking, and penalties. Data control shapes the capacity to audit performance, contest decisions, and enforce obligations. Enforcement practices determine whether formal provisions operate as credible commitments or as symbolic compliance. The DCP framework integrates these mechanisms to explain why digital systems can reduce some frictions while simultaneously amplifying others.

### **7.3 From Empirical Puzzles to Theoretical Synthesis**

The empirical contribution of the thesis is to move beyond adoption-centred explanations of digital performance and to examine what happens after implementation, during routine operation. The fieldwork demonstrates that the relevant puzzle is not whether actors use digital tools, but how digital coordination becomes organised as a set of rules, obligations, and enforcement practices. In the studied supply chain, actors frequently engaged with digital systems while still facing high coordination costs, weak recourse, and persistent volatility. These conditions created incentives to comply superficially, work around platforms, or reallocate risk downstream, even where transaction-level efficiency gains were visible.

Interpretively, these patterns cannot be explained by a single theoretical lens. Efficiency changes associated with digitisation are often consistent with transaction cost and contract-based perspectives, particularly where platforms reduce search costs, accelerate matching, or standardise basic documentation. Yet the same interventions may raise new costs and constraints when institutions do not support credible enforcement, dispute resolution, and equitable information rights. The thesis therefore synthesises complementary insights from contract theory, institutional theory, and governance scholarship to show how digital performance is produced through the interaction of formal arrangements with the institutional environment.

On this basis, the DCP framework is developed as an analytically disciplined way of characterising digital transformation trajectories. It specifies how resource capability and

institutional support condition the feasibility of particular governance arrangements, and how those arrangements shape the distribution of efficiency and constraint. This synthesis supports the thesis's second research question by offering a systematic characterisation of paradox, and by identifying governance levers through which constraint effects can be reduced in ways that advance food loss reduction outcomes.

#### **7.4 Synthesising the Core Propositions of the Study**

The framework is accompanied by a set of propositions that translate the empirical insights into claims that can be examined in other contexts. The propositions are written at a mechanism level. Each specifies how particular combinations of contractual terms, platform rules, data control, and enforcement practices are expected to shape efficiency and constraint outcomes under distinct resource and institutional conditions. They are not intended as deterministic laws. They are conditional statements designed to support cumulative theory building.

Table 24: Consolidated Propositions of the Digital Constraint Paradox Framework

| P# | Proposition Statement                                                                                                                                                                                         | Source Paradox                     | Empirical Basis                                             | Theoretical Anchor                              | DCP Quadrant                 |
|----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|-------------------------------------------------------------|-------------------------------------------------|------------------------------|
| P1 | Digital transformation in agri-food supply chains is constrained by pre-existing institutional rigidities that condition technology absorption rather than being disrupted by it.                             | Thesis 1: Constrained Efficiency   | Cases 1 and 2: persistence of inefficiency despite adoption | North (1990); Mahoney (2000)                    | All quadrants                |
| P2 | The efficiency outcomes of digitalisation are path-dependent, shaped by historical governance arrangements and accumulated institutional logics that resist technological disruption.                         | Thesis 1: Constrained Efficiency   | Case 1: state-led hub governance patterns                   | Pierson (2000); path dependency theory          | Low Support/ Low Capability  |
| P3 | Digitalisation introduces new forms of contractual incompleteness characterised by algorithmic opacity, platform-mediated enforcement, and the transfer of residual control rights to digital intermediaries. | Thesis 2: Fragmented Formalisation | Case 2: platform pricing mechanisms                         | Hart and Moore (1990); Grossman and Hart (1986) | Low Support/ High Capability |
| P4 | Algorithmic governance in digital supply chains reconfigures contractual power by embedding decision-making authority in technical systems that are opaque to contracting parties.                            | Thesis 2: Fragmented Formalisation | Cases 1 and 2: dispute resolution patterns                  | Williamson (1985); algorithmic governance       | Low Support/ High Capability |
| P5 | Digital platforms in agri-food supply chains do not merely mediate transactions but actively govern them, determining pricing mechanisms, access conditions, and enforcement protocols.                       | Thesis 3: Algorithmic Mistrust     | Case 2: platform governance analysis                        | Srnicek (2016); Gillespie (2018)                | Low Support/ High Capability |
| P6 | Power asymmetries in digitalised supply chains manifest not primarily through data monopolisation but through the reconfiguration of control over contractual decision-making and residual rights allocation. | Thesis 3: Algorithmic Mistrust     | Cases 1 and 2: bargaining dynamics                          | Zuboff (2019); platform capitalism              | All quadrants                |
| P7 | Digital price transparency can paradoxically weaken smallholder bargaining power by providing dominant actors with informational justification for                                                            | Thesis 3: Algorithmic Mistrust     | Case 1: farmer interview data                               | Information asymmetry theory; Akerlof (1970)    | Low Support/ Low Capability  |

| P#  | Proposition Statement                                                                                                                                                                                                                                                 | Source Paradox                | Empirical Basis                            | Theoretical Anchor                        | DCP Quadrant                  |
|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|--------------------------------------------|-------------------------------------------|-------------------------------|
|     | price-setting whilst eliminating spaces for negotiation.                                                                                                                                                                                                              |                               |                                            |                                           |                               |
| P8  | Digital transformation trajectories are determined by the interaction of institutional support and resource capability, producing four distinct outcome configurations: stagnation, suboptimal digitalisation, fragmented markets, and transformative digitalisation. | Thesis 4: DCP Framework       | Cross-case synthesis                       | Resource-based view; institutional theory | Framework-level               |
| P9  | Transformative digitalisation requires simultaneous alignment of institutional support structures and resource capabilities; partial alignment produces suboptimal or fragmented outcomes.                                                                            | Thesis 4: DCP Framework       | Comparative case analysis                  | Complementarity theory; strategic fit     | High Support/ High Capability |
| P10 | The exclusion of food waste reduction from core governance metrics structurally constrains digital interventions, directing digitalisation toward compliance and transaction facilitation rather than sustainability optimisation.                                    | Thesis 5: Residual Governance | Case 1: policy analysis                    | Institutional rigidity theory             | High Support/ Low Capability  |
| P11 | Algorithmic pricing mechanisms can amplify supply chain volatility and contribute to food waste by creating price unpredictability that discourages long-term commitments and stable market relationships.                                                            | Thesis 5: Residual Governance | Case 2: price volatility data              | Market volatility; relational contracting | Low Support/ High Capability  |
| P12 | Residual benefits from digital efficiency gains are systematically captured by platform intermediaries rather than being equitably distributed among supply chain participants, creating new forms of digital rent extraction.                                        | Thesis 2 and 3 Integration    | Cases 1 and 2: value distribution analysis | Rent theory; platform economics           | Low Support/ High Capability  |

*Note: DCP Quadrants: LS/LC = Low Support/Low Capability (Digital Stagnation); HS/LC = High Support/Low Capability (Suboptimal Digitalisation); LS/HC = Low Support/High Capability (Fragmented Digital Markets); HS/HC = High Support/High Capability (Transformative Digitalisation). Source: Author's theoretical synthesis*

The propositions collectively express the thesis's core theoretical move: paradox is not an incidental by-product of technology roll-out, but a patterned outcome of governance under constraint. The DCP framework therefore provides both a descriptive map of digital transformation pathways and an explanatory account of the mechanisms that produce those pathways.

### **7.5 Positioning the Contribution within Corley and Gioia's Framework**

To clarify the nature of the thesis contribution, it is useful to distinguish between conceptual refinement and revelatory extension. The thesis refines existing thinking by specifying the conditions under which digital coordination reduces transaction frictions and the conditions under which it reproduces or intensifies constraints. This refinement is achieved by integrating contract-based explanations of coordination with institutional explanations of enforcement, legitimacy, and rule stability.

The thesis also provides a revelatory extension by showing how digital systems can operationalise and scale contractual incompleteness. In settings where enforcement is uneven and dispute resolution is weak, the introduction of algorithmic rule application and centralised data control can shift bargaining and accountability away from negotiated adjustment and toward unilateral rule execution. This extension offers a mechanism-level account of why digital interventions can intensify power asymmetries while still generating visible efficiency gains in selected transactions.

These contributions have practical utility because they identify governance levers that are actionable. They locate intervention not only in technical design, but in the terms of participation, the distribution of data rights, and the credibility of enforcement. This positioning supports cumulative research by enabling future studies to operationalise the framework, test propositions, and compare configurations across commodities and institutional environments.

### **7.6 Final Reflections and Theoretical Roadmap for Future Research**

The DCP framework is designed to travel, but it travels with conditions. Future research should therefore focus on specifying how contractual, platform, and institutional mechanisms evolve over time, and how those dynamics shape the durability of loss reduction outcomes. Several avenues follow directly from the thesis findings and argument.



One priority is the micro-dynamics of digital contract adaptation. Longitudinal research could trace how contractual terms, penalty regimes, and dispute processes change as platforms mature, as new intermediaries emerge, and as regulatory attention fluctuates. Such work would help explain when digital coordination stabilises into credible commitment and when it remains a volatile rule system.

A second priority concerns platform governance and data control. Comparative studies could examine how different data rights regimes, auditability arrangements, and appeals processes shape trust, compliance behaviour, and the distribution of value. This includes assessment of whether shared data governance reduces informational lock-in and improves collective capacity for loss prevention.

A further priority is the measurement of food loss outcomes under different governance configurations. Research designs that connect digital traceability and reporting systems to independently verified loss measures would help identify when quantification translates into reduction. This would strengthen the evidence base by linking governance design to outcome change rather than to compliance indicators alone.

Finally, cross-sector comparative work could test the DCP configuration logic beyond tomatoes, including perishable commodities with similar volatility and coordination problems. Such studies would enable refinement of the framework and support the development of mid-range theory on digital governance under constraint.

Taken together, these directions extend the thesis's contribution by treating digital transformation as an evolving governance system and by testing whether particular combinations of capabilities and institutional supports reliably produce predictable patterns of efficiency and constraint.

### **7.6.1 Theoretical Contributions**

The thesis advances theory by shifting the unit of analysis from technology adoption to the governance arrangements through which digital coordination is enacted. It contributes to contract theory by showing how digital intermediation can alter the allocation of discretion, monitoring, and enforcement, and by demonstrating that incompleteness can be operationalised through platform rule systems that are applied algorithmically yet remain contestable in practice. The contribution

is not to claim that digital systems inevitably produce control, but to specify the mechanisms and conditions under which control becomes the dominant governance pattern.

### **7.6.2 From Incomplete Contracts to Digital Intermediation and Algorithmic Control**

Classical contract theory explains why parties cannot specify all contingencies *ex ante* and why governance is needed to manage adaptation *ex post*. The thesis extends this logic by identifying how digital platforms can reconfigure adaptation. When platform rules substitute for negotiated adjustment, and when appeal processes are weak, contractual incompleteness is not resolved; it is encoded and scaled. In such settings, algorithmic decision-making can serve as a vehicle for exercising discretion without the reciprocal accountability mechanisms that would ordinarily accompany renegotiation.

This argument also clarifies why efficiency gains can co-exist with rising constraint. Algorithmic standardisation may reduce transactional delays and improve documentation. Yet where enforcement is uneven and information rights are concentrated, the same standardisation can increase participant vulnerability to penalties, exclusion, or reclassification decisions that are difficult to contest. The contribution is therefore a mechanism-based account of how digitisation shapes contractual power.

### **7.6.3 A Structuralist Perspective on Digital Failure**

The thesis contributes to scholarship on digital failure by treating failure as structural rather than episodic. Digital interventions often appear to fail when evaluated against a narrow expectation of efficiency improvements. The thesis shows that apparent failure may be the predictable outcome of governance misalignment: platforms can improve specific transaction functions while leaving the broader institutional causes of volatility untouched. Under such conditions, digital systems can amplify risk-shifting and can reproduce coordination problems at new points in the chain.

This structural account moves beyond explanations that locate failure in user behaviour or technology design alone. It highlights the joint role of institutional support, credible enforcement, and rights to information in determining whether digital coordination can produce system-level performance improvement.

#### **7.6.4 Institutional Rigidity and the Marginalisation of Digital Waste Reduction**

A further contribution is to show how institutional rigidity can marginalise loss reduction even where digital systems produce improved visibility. Where incentives and accountability are not aligned to loss outcomes, data capture becomes decoupled from corrective action. In such contexts, quantification may increase reporting activity without generating enforceable obligations to change handling, storage, or timing decisions. This explains why improved measurement can co-exist with persistent loss, and it underscores that governance arrangements must connect information to accountability.

#### **7.7 Final Reflections on the Theoretical Legacy of the Digital Constraint Paradox**

The DCP framework offers a mid-range theory contribution. It specifies a configuration logic that can be operationalised in future research, and it offers a language for comparing digital transformation pathways in constrained supply chains. The framework also encourages theoretical integration: it keeps efficiency mechanisms in view while requiring explicit treatment of institutional support and governance credibility. This combination is necessary to explain why digital transformation can be simultaneously productive and restrictive.

#### **7.8 Practical Contributions of the Study**

The practical value of the thesis lies in translating the paradox logic into governance-sensitive guidance. The study does not treat digital tools as inherently beneficial or harmful. It treats them as interventions whose performance depends on institutional embedding and governance design. Accordingly, the practical contributions are framed as implications for how digital interventions should be specified, governed, and evaluated in contexts characterised by volatility and uneven institutional capacity.

Table 24 translates the DCP logic into governance-sensitive policy and design levers. The table should be read as a structured set of implications derived from the mechanisms identified in the thesis. It is not presented as a universal recipe or as a substitute for context-specific institutional analysis. Each lever is mapped to the DCP configuration it primarily targets, or marked as cross-configuration where the mechanism can arise under multiple conditions.

Table 25: Policy and design levers aligned to the Digital Constraint Paradox (DCP) framework.

| <b>Paradox</b>           | <b>DCP mapping</b>                                                                                                                             | <b>Core governance insight</b>                                                                                                                                                                                                                  | <b>Theoretical anchors used in this thesis</b>                                                                          | <b>Policy and design imperatives</b>                                                                                                                                                    | <b>Strategic implementation pathways</b>                                                                                                                                                                                      |
|--------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Constrained efficiency   | Primarily low capability and low institutional support; can persist under low capability and high support where infrastructure remains binding | Digital tools fail to deliver system-level gains where infrastructural deficits and coordination failures remain unresolved; efficiency is conditional on resource capability and governance architecture rather than endogenous to technology. | Incomplete Contract Theory (Hart & Moore, 1999)<br>Resource-Based View (Barney, 1991)<br>Critical Infrastructure Theory | Sequence digital subsidies and platform expansion with minimum viable logistics capacity; co-invest in shared infrastructure that supports verifiable coordination and loss prevention. | Establish regional agri-tech infrastructure trusts with blended capital; incentivise cooperative-led cold-chain and aggregation networks; attach minimum physical infrastructure conditions to major digital roll-outs.       |
| Fragmented formalisation | Low capability with varying support; risk is highest where compliance demands rise faster than support mechanisms                              | Formalisation through platforms can impose compliance burdens and exclusion where capability, trust, and support services are insufficient; formal rules without support can widen inequality within platform economies.                        | Institutional Logics (Thornton et al., 2012)<br>Transaction Cost Economics (Williamson, 1985)<br>Governance Theory      | Develop graduated participation regimes that reduce exclusion and enable capability building; align onboarding requirements with realistic documentation and verification pathways.     | Enable tiered registration and progressive compliance; provide digital identity, micro-certification, and adaptive regulation; co-locate legal aid, grievance redress, and digital literacy services.                         |
| Disrupted informality    | Cross-configuration, with heightened risk where platform rules displace relational coordination without providing credible substitutes         | Informality is a governance system built on relational contracts, intermediaries, and social enforcement; abrupt displacement can reduce trust and unravel coordination that previously stabilised exchange.                                    | Relational Contracting (Baker et al., 2002)<br>Embeddedness Theory (Granovetter, 1985)<br>Social Capital Theory         | Design hybrid ecosystems that interface with, rather than displace, trusted intermediaries and community enforcement mechanisms.                                                        | Formalise trusted intermediaries as accountable digital brokers; implement community-verifiable reputation systems; protect locally legitimate dispute resolution channels within platform terms and governance arrangements. |
| Residual governance      | Primarily low institutional support, even where capability is high; also relevant in                                                           | Institutional incoherence generates contradictory mandates, duplicative compliance, and policy                                                                                                                                                  | Polycentric and multi-level governance perspectives; state capacity and regulatory                                      | Create durable coordination structures that align digital agriculture, data governance, infrastructure, and market                                                                      | Establish an inter-ministerial digital agri-food governance board; align federal and state actors;                                                                                                                            |

|                      |                                                                                                       |                                                                                                                                                                              |                                                                                                                                                           |                                                                                                                                                                                   |                                                                                                                                                                                                                     |
|----------------------|-------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                      | fragmented polycentric settings                                                                       | drift; without institutional complementarity, digital strategies remain brittle.                                                                                             | coordination accounts (Ostrom, 2005).                                                                                                                     | regulation across ministries and levels of government.                                                                                                                            | develop unified compliance frameworks and shared standards for interoperability and data accountability.                                                                                                            |
| Algorithmic mistrust | Cross-configuration, with elevated risk where data control is concentrated and contestability is weak | Opaque scoring, pricing, and enforcement can erode legitimacy and reduce participation; procedural unfairness turns efficiency tools into instruments of asymmetric control. | Algorithmic governance and transparency perspectives; data justice; behavioural responses to perceived unfairness (Ananny & Crawford, 2018; Taylor, 2017) | Embed procedural fairness, explainability, and contestability into platform governance; treat algorithmic decisions as accountable governance acts rather than technical outputs. | Require algorithm impact assessments for high-stakes systems; embed right-to-reason and appeal processes in platform contracts; establish independent ombuds or grievance mechanisms for digital platform disputes. |

The logic of Table 24 is consistent with the propositions in Section 7.3: when governance mechanisms are re-specified to strengthen credibility, contestability, and capability, constraint effects reduce and efficiency gains are more likely to translate into durable loss reduction outcomes.

#### **7.8.1 Rethinking Digital Interventions**

For policymakers and funders, the thesis implies that digital initiatives should be designed as governance programmes rather than as standalone technology deployments. This includes specifying enforceable participation rights, building credible dispute resolution channels, and aligning platform rule systems with the realities of connectivity and documentation capacity. Where these conditions are absent, platforms may increase exclusion or may create perverse incentives that displace risks and costs onto less powerful actors.

#### **7.8.2 Addressing Food Loss and Waste**

For actors seeking to reduce food loss, the thesis suggests that measurement is necessary but insufficient. Loss reduction improves when quantification is coupled to accountability, incentives, and feasible operational changes. Interventions should therefore connect data capture to targeted governance actions, such as enforceable handling standards, coordinated logistics support, and transparent feedback loops that enable corrective learning rather than punitive compliance alone.

#### **7.8.3 Digital Inclusion Strategies to Counteract Power Asymmetries**

For platform operators and intermediaries, the thesis highlights that inclusion is a governance issue. Inclusion is not achieved solely through access to devices or training. It also depends on whether participation rules are realistic, whether decision processes are auditable, and whether participants have channels to contest penalties and classifications. Shared data governance arrangements, clear appeals processes, and proportional sanctioning regimes reduce the likelihood that digital coordination becomes a mechanism of asymmetric control.

#### **7.8.4 Designing for Residual Benefits, Not Just Residual Risks**

The thesis also implies that interventions should be evaluated against system-level outcomes rather than against narrow compliance metrics. Where platforms emphasise reporting targets and activity counts, efficiency can be overestimated and constraint effects can be hidden. Evaluation should therefore incorporate independent outcome measures, including loss reduction indicators and distributional effects across actor categories, to ensure that efficiency gains are not achieved through the displacement of costs and vulnerabilities.

## 7.9 Limitations

The study has boundary conditions that shape how its claims should be interpreted. Empirically, the thesis is based on an in-depth case study of Nigeria's tomato supply chain, with primary data that captures a complex set of actors and governance arrangements in a context characterised by volatility. The case design strengthens internal validity for mechanism explanation, but it does not provide statistical generalisability.

Analytically, the DCP framework abstracts from a rich empirical reality into a two-dimensional configuration logic. This abstraction is necessary for clarity and for transferability, but it necessarily simplifies. Particular institutional features, such as sub-national regulatory variation, informal enforcement practices, and power relations shaped by non-contractual dependencies, may operate differently in other settings. Future research should therefore test the propositions comparatively and refine measurement strategies for both axes.

Finally, while the thesis links governance mechanisms to food loss reduction outcomes at the level of plausibility and process evidence, independent outcome measurement across time would strengthen causal inference. Longitudinal designs and mixed-method outcome verification would therefore be valuable extensions, particularly for assessing whether governance reforms translate into durable reductions in loss.

## 8 List of References

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## 9 Appendices

### 9.1 Appendix 1: Details of Quality Assessment Criteria

Table A 1: Quality Assessment Criteria

| No | Quality Criteria                                                            | 0                                                                        | 1                                                                              | 2                                                                        | 3                                                                                          |
|----|-----------------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| 1  | Methodology                                                                 | The article does not provide enough information to assess the criterion  | Flawed research design with inappropriate quantitative methods                 | Justified research design; poor execution of the idea                    | Research design adequately examines the research argument                                  |
| 2  | Theory robustness                                                           | Lack of information to assess this criterion                             | Weak theoretical base                                                          | Incomplete theoretical base                                              | Robust theoretical grounding; contribution to the theory of practice                       |
| 3  | Data analysis: sample design and composition                                | Lack of information to assess this criterion                             | Inadequate data sample; inconclusive research results                          | The appropriate data sample, adequate results but inadequate explanation | Appropriate data sample: properly explained research results support theoretical arguments |
| 4  | Implications for practices                                                  | Lack of information to assess this criterion                             | Study fails to inform the practice of implications                             | Provides limited implications for practice                               | Provides critical implications for practice                                                |
| 5  | Contribution plus a short statement summarising the article's contributions | The article does not provide enough information to assess this criterion | Does not make an important contribution. It is not clear the advances it makes | Although using others' ideas, builds upon the existing theory            | Further develops existing knowledge, expanding the way the issue was examined              |

## 9.2 Appendix 2: Included Papers in Systematic Review 1

Table A 2: Characteristics of Included Studies (n=95)

| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                                                  | Country      | Commodity            | SC Stage                      | Study Design                                                                        | Quantification Method                                                                                                                                           |
|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|----------------------|-------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1   | Abass, A. B., Ndunguru, G., Mamiro, P., Alenkhe, B., Mlingi, N., & Bekunda, M. (2014). Post-harvest food losses in a maize-based farming system of semi-arid savannah area of Tanzania. <i>Journal of Stored Products Research</i> , 57, 49–57. <a href="https://doi.org/10.1016/j.jspr.2013.12.004">https://doi.org/10.1016/j.jspr.2013.12.004</a>                                                             | Tanzania     | Multiple crops       | Multiple stages               | Cross-sectional survey with focus groups and observational validation               | Survey-based estimation (farmer recall of losses by stage), supported by focus groups and storage inspections                                                   |
| 2   | Abera, G., Ibrahim, A. M., Forsido, S. F., & Kuyu, C. G. (2020). Assessment on post-harvest losses of tomato ( <i>Lycopersicon esculentum</i> Mill.) in selected districts of East Shewa Zone of Ethiopia using a commodity system analysis methodology. <i>Heliyon</i> , 6(4), e03749. <a href="https://doi.org/10.1016/j.heliyon.2020.e03749">https://doi.org/10.1016/j.heliyon.2020.e03749</a>               | Ethiopia     | tomato               | Multiple stages               | Value-chain case study                                                              | Commodity System Assessment Methodology (CSAM): semi-structured interviews, questionnaires, direct observation, FGDs                                            |
| 3   | Adams, F., Aidoo, R., Mensah, J. O., Mensah, A., Etuah, S., Akey, E. A. A., & Quaye, J. (2023). The synergy between farmers' declaration of qualitative and quantitative maize postharvest losses in the transition agroecological zone of Ghana. <i>Journal of Stored Products Research</i> , 104, 102198. <a href="https://doi.org/10.1016/j.jspr.2023.102198">https://doi.org/10.1016/j.jspr.2023.102198</a> | Ghana        | maize                | Multiple stages               | Cross-sectional survey with econometric modelling.                                  | Survey-based/self-report ("farmers' declarations" in kg/acre and %)                                                                                             |
| 4   | Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., & Rounsevell, M. D. A. (2017). Losses, inefficiencies and waste in the global food system. <i>Agricultural Systems</i> , 153, 190–200. <a href="https://doi.org/10.1016/j.agsy.2017.01.014">https://doi.org/10.1016/j.agsy.2017.01.014</a>                                                                                                       | Global.      | System-wide          | Multiple stages               | Modelling study                                                                     | System modelling using FAO production and commodity balance data                                                                                                |
| 5   | Ali, A., Tan, Y., Yang, S., Xia, C., & Long, W. (2025). Optimizing farmers' and intermediaries' practices as determinants of food waste reduction across the supply chain. <i>Foods</i> , 14(13), 2351. <a href="https://doi.org/10.3390/foods14132351">https://doi.org/10.3390/foods14132351</a>                                                                                                               | Egypt        | Grapes               | Multiple stages               | Cross-sectional survey with econometric modelling                                   | Survey-based estimation (structured questionnaires)                                                                                                             |
| 6   | Ali, A., Xia, C., Ouattara, N., Mahmood, I., & Faisal, M. (2021). Economic and environmental consequences' of postharvest loss across food supply Chain in the developing countries. <i>Journal of Cleaner Production</i> , 323, 129146. <a href="https://doi.org/10.1016/j.jclepro.2021.129146">https://doi.org/10.1016/j.jclepro.2021.129146</a>                                                              | Egypt        | tomatoes             | Multiple stages               | Cross-sectional primary survey with modelling of economic and environmental impacts | Survey-based estimation using Category Method (C-Method) for farmers and intermediaries plus aggregate self-report for processors                               |
| 7   | Alshabanat, Z., Alkhorayef, A., Ben Haddad, H., Mezghani, I., Gouider, A., Tlili, A., Allouche, M. A., & Gannouni, K. A. (2021). Quantifying food loss and waste in Saudi Arabia. <i>Sustainability</i> , 13, 9444. <a href="https://doi.org/10.3390/su13169444">https://doi.org/10.3390/su13169444</a>                                                                                                         | Saudi Arabia | Multiple commodities | Multiple stages               | Modelling study                                                                     | Mass-balance style FAO model calculations (building from food balance sheet logic) combined with structured questionnaires to estimate FLW percentages by stage |
| 8   | Amicarelli, V., Bux, C., & Lagioia, G. (2021). How to measure food loss and waste? A material flow analysis application. <i>British Food Journal</i> , 123(1), 67–85. <a href="https://doi.org/10.1108/BFJ-03-2020-0241">https://doi.org/10.1108/BFJ-03-2020-0241</a>                                                                                                                                           | Italy        | ready-to-eat chips   | Multiple stages               | Modelling study                                                                     | Material Flow Analysis (MFA) using mass-balance principle                                                                                                       |
| 9   | Ansah, I. G. K., Ehwi, J., & Donkoh, S. A. (2018). Effect of postharvest management practices on welfare of farmers and                                                                                                                                                                                                                                                                                         | Ghana        | yam                  | On-farm storage (farmers) and | Cross-sectional survey with econometric analysis.                                   | Survey-based self-report of tubers lost and stored                                                                                                              |

| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                                                            | Country                      | Commodity                      | SC Stage                                                                               | Study Design                                                                       | Quantification Method                                                                                                                                                                                                                                             |
|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------|--------------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     | traders in Tamale metropolis and Zabzugu District, Ghana. Cogent Food & Agriculture, 4(1), 1475916. <a href="https://doi.org/10.1080/23311932.2018.1475916">https://doi.org/10.1080/23311932.2018.1475916</a>                                                                                                                                                                                                             |                              |                                | market/storage by traders (storage duration explicitly analysed).                      |                                                                                    |                                                                                                                                                                                                                                                                   |
| 10  | Baker, G. A., Gray, L. C., Harwood, M. J., Osland, T. J., & Tooley, J. B. C. (2019). On-farm food loss in northern and central California: Results of field survey measurements. Resources, Conservation & Recycling, 149, 541–549. <a href="https://doi.org/10.1016/j.resconrec.2019.03.022">https://doi.org/10.1016/j.resconrec.2019.03.022</a>                                                                         | United States                | Multiple vegetables and fruits | H/PH (unharvested produce in harvested fields; “walk-by” fields not harvested at all). | Field measurement study with interview-based supplementation                       | Direct measurement: in-field post-harvest plot sampling and weighing of edible produce remaining                                                                                                                                                                  |
| 11  | Balana, B. B., Aghadi, C. N., & Ogunniyi, A. I. (2022). Improving livelihoods through postharvest loss management: Evidence from Nigeria. Food Security, 14(1), 249–265. <a href="https://doi.org/10.1007/s12571-021-01196-2">https://doi.org/10.1007/s12571-021-01196-2</a>                                                                                                                                              | Nigeria                      | fresh tomato                   | Multiple stages                                                                        | Cross-sectional survey with econometric modelling                                  | Survey-based estimation of tomato damage via “Percent_spoilt (%)”                                                                                                                                                                                                 |
| 12  | Baoua, I. B., Amadou, L., Ousmane, B., Baributsa, D., & Murdock, L. L. (2014). PICS bags for post-harvest storage of maize grain in West Africa. Journal of Stored Products Research, 58, 20–28. <a href="https://doi.org/10.1016/j.jspr.2014.03.001">https://doi.org/10.1016/j.jspr.2014.03.001</a>                                                                                                                      | Benin                        | maize                          | OFS (post-harvest storage).                                                            | Field trial                                                                        | Direct measurement: insect counts, grain damage and weight loss                                                                                                                                                                                                   |
| 13  | Bechoff, A., Shee, A., Mvumi, B. M., Ngwenyama, P., Debelo, H., Ferruzzi, M. G., Nyanga, L. K., Mayanja, S., & Tomlins, K. I. (2022). Estimation of nutritional postharvest losses along food value chains: A case study of three key food security commodities in sub-Saharan Africa. Food Security, 14(3), 571–590. <a href="https://doi.org/10.1007/s12571-021-01238-9">https://doi.org/10.1007/s12571-021-01238-9</a> | Sub-Saharan Africa: Zimbabwe | maize                          | Multiple stages                                                                        | Modelling study using combined laboratory, field, and secondary datasets.          | Hybrid/multi-method: cumulative weight-loss calculations (derived from APHLIS loss data) + laboratory and field storage trials + predictive regression equations for qualitative nutrient losses                                                                  |
| 14  | Blanckenberg, A., Opara, U. L., & Fawole, O. A. (2021). Postharvest losses in quantity and quality of table grape (cv. Crimson Seedless) along the supply chain and associated economic, environmental and resource impacts. Sustainability, 13(8), 4450. <a href="https://doi.org/10.3390/su13084450">https://doi.org/10.3390/su13084450</a>                                                                             | South Africa                 | Table grapes                   | Multiple stages                                                                        | Case study with experimental/simulated supply chain storage trials across seasons. | Direct measurement (weight of berries removed at trimming as % of bunch                                                                                                                                                                                           |
| 15  | Boiteau, J. M., & Pingali, P. (2022). Food loss of perishable produce from farm to retail: Evidence from tomato supply chains in South India. The American Journal of Clinical Nutrition, 115(6), 1535–1548. <a href="https://doi.org/10.1093/ajcn/nqac039">https://doi.org/10.1093/ajcn/nqac039</a>                                                                                                                      | India                        | tomato                         | Multiple stages                                                                        | Mixed methods: repeated harvest surveys                                            | Hybrid: (i) declared FLW (participant-reported losses) and (ii) destination FLW (counted crates diverted to destinations). Also includes pile-sort focus group discussions to examine quality grading, and mixed-effects two-part models to analyse determinants. |
| 16  | Caldeira, C., De Laurentiis, V., Corrado, S., van Holsteijn, F., & Sala, S. (2019). Quantification of food waste per product group along the food supply chain in the European Union: A mass flow analysis. Resources, Conservation & Recycling, 149, 479–488. <a href="https://doi.org/10.1016/j.resconrec.2019.06.011">https://doi.org/10.1016/j.resconrec.2019.06.011</a>                                              | European Union               | Multiple food groups           | Multiple stages                                                                        | Modelling study                                                                    | Mass Flow Analysis (MFA) with closed mass balance                                                                                                                                                                                                                 |
| 17  | Das, T. (2025). Exploring the drivers of banana postharvest losses: A case study in Northeast India. World Food Policy, 11, e70006. <a href="https://doi.org/10.1002/wfp2.70006">https://doi.org/10.1002/wfp2.70006</a>                                                                                                                                                                                                   | India                        | banana                         | Farm-level postharvest losses “before dispatching them to the market for               | Cross-sectional survey with retrospective periodisation; econometric modelling.    | Survey-based estimation using participatory “bean exercise” for perceived quantitative losses                                                                                                                                                                     |



| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Country  | Commodity             | SC Stage                                                                                           | Study Design                                                               | Quantification Method                                                                                                                                                                            |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|-----------------------|----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                |          |                       | sale" [unclear stage granularity].                                                                 |                                                                            |                                                                                                                                                                                                  |
| 18  | De Groote, H., Muteti, F. N., & Bruce, A. Y. (2023). On-farm storage loss estimates of maize in Kenya using community survey methods. <i>Journal of Stored Products Research</i> , 102, 102107. <a href="https://doi.org/10.1016/j.jspr.2023.102107">https://doi.org/10.1016/j.jspr.2023.102107</a>                                                                                                                                                            | Kenya    | maize                 | OFS (on-farm storage).                                                                             | Cross-sectional community survey                                           | Survey-based estimation using focus group discussions: $r = F_a \times r_a$ , where $F_a$ is proportion of farmers affected and $r_a$ is loss among affected farmers                             |
| 19  | Debebe, S. (2022). Post-harvest losses of crops and its determinants in Ethiopia: Tobit model analysis. <i>Agriculture &amp; Food Security</i> , 11, 13. <a href="https://doi.org/10.1186/s40066-022-00357-6">https://doi.org/10.1186/s40066-022-00357-6</a>                                                                                                                                                                                                   | Ethiopia | Multiple crops        | Multiple stages                                                                                    | Secondary analysis of nationally representative survey data                | Survey-based estimation (perceived loss reporting by stage) plus Tobit modelling of determinants.                                                                                                |
| 20  | dos Santos, S. F., Cardoso, R. C. V., Borges, Í. M. P., Almeida, A. C. E., Andrade, E. S., Ferreira, I. O., & Ramos, L. C. (2020). Post-harvest losses of fruits and vegetables in supply centers in Salvador, Brazil: Analysis of determinants, volumes and reduction strategies. <i>Waste Management</i> , 101, 161–170. <a href="https://doi.org/10.1016/j.wasman.2019.10.007">https://doi.org/10.1016/j.wasman.2019.10.007</a>                             | Brazil   | Fruits and vegetables | Multiple stages                                                                                    | Cross-sectional descriptive quantitative study with observations.          | Survey-based estimation (vendor-reported weekly purchases and weekly losses in kg, totalised to tonnes) plus structured observation and basic statistical analysis (correlation and regression). |
| 21  | Emana, B., Afari-Sefa, V., Nenguwo, N., Ayana, A., Kebede, D., & Mohammed, H. (2017). Characterization of pre- and postharvest losses of tomato supply chain in Ethiopia. <i>Agriculture &amp; Food Security</i> , 6, 3. <a href="https://doi.org/10.1186/s40066-016-0085-1">https://doi.org/10.1186/s40066-016-0085-1</a>                                                                                                                                     | Ethiopia | tomato                | Multiple stages                                                                                    | Case study with mixed methods                                              | Hybrid: actor surveys (perceived losses) plus direct sample-based measurement (2 kg tomato purchased per sampled respondent, sorted by damage categories and weighed).                           |
| 22  | Eriksson, M., Ghosh, R., Mattsson, L., & Ismatov, A. (2017). Take-back agreements in the perspective of food waste generation at the supplier-retailer interface. <i>Resources, Conservation and Recycling</i> , 122, 83–93. <a href="https://doi.org/10.1016/j.resconrec.2017.02.006">https://doi.org/10.1016/j.resconrec.2017.02.006</a>                                                                                                                     | Sweden.  | Bread                 | W; PRD (supplier–retailer interface). Waste separated into “pre-store waste” and “in-store waste”. | Case-study comparative analysis using mixed data sources                   | Mixed: primary company data and routine monitoring records plus semi-structured interviews and participatory observations                                                                        |
| 23  | Falola, A., Mukaila, R., Uddin II, R. O., Ajewole, C. O., & Gbadebo, W. (2023). Postharvest losses in onion: Causes and determinants. <i>KSÜ Journal of Agriculture and Nature</i> , 26(2), 346–354. <a href="https://doi.org/10.18016/ksutarimdog.vi.1091225">https://doi.org/10.18016/ksutarimdog.vi.1091225</a>                                                                                                                                             | Nigeria  | onion                 | Multiple stages                                                                                    | Cross-sectional survey with econometric determinants analysis.             | Survey-based estimation (kg postharvest loss) plus regression determinants                                                                                                                       |
| 24  | Fassinou Hotegni, N. V., Agbo, N. F. M., Salaou, M. A. B., Odjo, S., Bokonon-Ganta, A. H., & Achigan-Dako, E. G. (2024). Granaries used in maize storage and conservation across agroecological zones in the Republic of Benin: Distribution, characteristics and associated postharvest losses. <i>Journal of Stored Products Research</i> , 107, 102348. <a href="https://doi.org/10.1016/j.jspr.2024.102348">https://doi.org/10.1016/j.jspr.2024.102348</a> | Benin    | maize                 | On-farm storage (granary-based maize storage and conservation).                                    | Cross-sectional survey with regression analysis.                           | Survey-based estimation using “proportional piling method” (10 stones representing stored maize and losses)                                                                                      |
| 25  | Fernández-Zamudio, M.-A., Barco, H., & Schneider, F. (2020). Direct measurement of mass and economic harvest and post-harvest losses in Spanish persimmon primary production. <i>Agriculture</i> , 10(12), 581. <a href="https://doi.org/10.3390/agriculture10120581">https://doi.org/10.3390/agriculture10120581</a>                                                                                                                                          | Spain    | Persimmon             | Multiple stages                                                                                    | Case study with direct field measurement plus administrative data linkage. | Direct measurement (on-site counting and mass estimation at tree level)                                                                                                                          |
| 26  | Geremew, M., Molla, A., Gabbiye, N., Harvey, J., Mahroof, R., & Abay, F. (2023). Effects of threshing and storage conditions on post-harvest insect infestation and physical characteristics                                                                                                                                                                                                                                                                   | Ethiopia | maize                 | H/OFH (threshing) and OFS (storage).                                                               | Experimental factorial storage study.                                      | Direct measurement: broken kernels, live adult weevils per kg, grain damage (%), weight loss                                                                                                     |

| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                                 | Country       | Commodity                 | SC Stage                                                                                                                                                                                     | Study Design                                                                                 | Quantification Method                                                                                                                                               |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|---------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     | of maize grain. Journal of Stored Products Research, 103, 102131. <a href="https://doi.org/10.1016/j.jspr.2023.102131">https://doi.org/10.1016/j.jspr.2023.102131</a>                                                                                                                                                                                                                          |               |                           |                                                                                                                                                                                              |                                                                                              | (%), bulk density, thousand-grain weight, germination                                                                                                               |
| 27  | Gummert, M., Nguyen-Van-Hung, Cabardo, C., Quilloy, R., Aung, Y. L., Thant, A. M., Kyaw, M. A., Labios, R., Htwe, N. M., & Singleton, G. R. (2020). Assessment of post-harvest losses and carbon footprint in intensive lowland rice production in Myanmar. Scientific Reports, 10, 19797. <a href="https://doi.org/10.1038/s41598-020-76639-5">https://doi.org/10.1038/s41598-020-76639-5</a> | Myanmar       | rice                      | Multiple stages                                                                                                                                                                              | Field experiment with comparative scenario analysis                                          | Direct measurement in field experiment (losses at harvest and postharvest processes), combined with LCA-based accounting for energy and GHGE and economic analysis. |
| 28  | Hartikainen, H., Mogensen, L., Svanes, E., & Franke, U. (2017). Food waste quantification in primary production – The Nordic countries as a case study. Waste Management. Advance online publication. <a href="https://doi.org/10.1016/j.wasman.2017.10.026">https://doi.org/10.1016/j.wasman.2017.10.026</a>                                                                                  | Finland       | Multiple primary products | Multiple stages                                                                                                                                                                              | Mixed methods                                                                                | Hybrid/multi-method: survey questionnaires (used for final quantification)                                                                                          |
| 29  | Hengsdijk, H., & de Boer, W. J. (2017). Post-harvest management and post-harvest losses of cereals in Ethiopia. Food Security, 9(5), 945–958. <a href="https://doi.org/10.1007/s12571-017-0714-y">https://doi.org/10.1007/s12571-017-0714-y</a>                                                                                                                                                | Ethiopia      | Cereals                   | Unspec upstream: post-harvest period losses “to rotting, insects, rodents, theft, etc.”; survey notes “post-harvest” may include handling, drying, storage and marketing (author’s caution). | Secondary analysis of nationally representative survey data with machine-learning modelling. | Survey-based estimation (LSMS-ISA farmer-reported loss percentages and/or computed percentages) plus statistical modelling (Random Forests).                        |
| 30  | Herrera-Quinteros, G., & Jara-Rojas, R. (2023). Food losses perceived by family farms: Challenges and policy implications from a micro-approach quantification. Frontiers in Sustainable Food Systems, 6, 961120. <a href="https://doi.org/10.3389/fsufs.2022.961120">https://doi.org/10.3389/fsufs.2022.961120</a>                                                                            | Chile         | Vegetables and berries    | Multiple stages                                                                                                                                                                              | Cross-sectional survey with econometric modelling.                                           | Survey-based estimation (self-reported % losses by stage) plus statistical modelling (Fractional Regression Model).                                                 |
| 31  | Htwe, N. M., Singleton, G. R., & Maw, P. P. (2017). Post-harvest impacts of rodents in Myanmar; how much rice do they eat and damage? Pest Management Science, 73(2), 318–324. <a href="https://doi.org/10.1002/ps.4292">https://doi.org/10.1002/ps.4292</a>                                                                                                                                   | Myanmar       | rice                      | H/OFH (field piling of unthreshed rice awaiting threshing 4–6 weeks); OFS (granary storage 3–6 months).                                                                                      | Field observational measurement study                                                        | Direct measurement: excavating rodent burrows and weighing hoarded grain                                                                                            |
| 32  | Jia, L., Zhang, J., & Qiao, G. (2023). Scale and environmental impacts of food loss and waste in China: A material flow analysis. International Journal of Environmental Research and Public Health, 20(1), 460. <a href="https://doi.org/10.3390/ijerph20010460">https://doi.org/10.3390/ijerph20010460</a>                                                                                   | China         | Multiple food groups      | Multiple stages                                                                                                                                                                              | Modelling study                                                                              | Material Flow Analysis (MFA) using food balance and coefficients                                                                                                    |
| 33  | Johnson, L. K., Bloom, J. D., Dunning, R. D., Gunter, C. C., Boyette, M. D., & Creamer, N. G. (2019). Farmer harvest decisions and vegetable loss in primary production. Agricultural Systems, 176, 102672. <a href="https://doi.org/10.1016/j.agsy.2019.102672">https://doi.org/10.1016/j.agsy.2019.102672</a>                                                                                | United States | Vegetables                | H; PH (loss conceptualised as edible produce left unharvested in field due to harvest stop decision).                                                                                        | Case study, qualitative interview study.                                                     | Diary/self-report (semi-structured interviews with growers)                                                                                                         |

| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                                     | Country       | Commodity                                                  | SC Stage                                                                                                                      | Study Design                                                                                 | Quantification Method                                                                                       |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| 34  | Johnson, L. K., Dunning, R. D., Bloom, J. D., Gunter, C. C., Boyette, M. D., & Creamer, N. G. (2018). Estimating on-farm food loss at the field level: A methodology and applied case study on a North Carolina farm. <i>Resources, Conservation &amp; Recycling</i> , 137, 243–250. <a href="https://doi.org/10.1016/j.resconrec.2018.05.017">https://doi.org/10.1016/j.resconrec.2018.05.017</a> | United States | Vegetables                                                 | H/OFH (post-harvest field stage: crops remaining on plants after farmer ceases harvest; ultimate destination: left in field). | Methodological case study with direct field measurement.                                     | Direct measurement: field sampling and weighing after harvest cessation                                     |
| 35  | Johnson, L. K., Dunning, R. D., Gunter, C. C., Bloom, J. D., Boyette, M. D., & Creamer, N. G. (2018). Field measurement in vegetable crops indicates need for reevaluation of on-farm food loss estimates in North America. <i>Agricultural Systems</i> , 167, 136–142. <a href="https://doi.org/10.1016/j.agsy.2018.09.008">https://doi.org/10.1016/j.agsy.2018.09.008</a>                        | United States | Vegetable crops                                            | Multiple stages                                                                                                               | Field measurement study                                                                      | Direct measurement (field sampling and scaling)                                                             |
| 36  | Ju, M., Osako, M., & Harashina, S. (2017). Food loss rate in food supply chain using material flow analysis. <i>Waste Management</i> , 61, 443–454. <a href="https://doi.org/10.1016/j.wasman.2017.01.021">https://doi.org/10.1016/j.wasman.2017.01.021</a>                                                                                                                                        | Japan.        | Multiple food categories representing whole Japanese meals | Multiple stages                                                                                                               | Modelling study                                                                              | Material Flow Analysis and mass-balance style modelling using Japan food balance sheet                      |
| 37  | Kadjo, D., Ricker-Gilbert, J., Abdoulaye, T., Shively, G., & Baco, M. N. (2018). Storage losses, liquidity constraints, and maize storage decisions in Benin. <i>Agricultural Economics</i> , 49, 435–454. <a href="https://doi.org/10.1111/agec.12427">https://doi.org/10.1111/agec.12427</a>                                                                                                     | Benin         | maize                                                      | On-farm storage decision post-harvest; storage losses from pests/mould during storage.                                        | Panel econometric study                                                                      | Panel survey                                                                                                |
| 38  | Kasso, M., & Bekele, A. (2018). Post-harvest loss and quality deterioration of horticultural crops in Dire Dawa Region, Ethiopia. <i>Journal of the Saudi Society of Agricultural Sciences</i> , 17, 88–96. <a href="https://doi.org/10.1016/j.jssas.2016.01.005">https://doi.org/10.1016/j.jssas.2016.01.005</a>                                                                                  | Ethiopia      | Multiple horticultural crops                               | Multiple stages                                                                                                               | Cross-sectional field survey with mixed qualitative and descriptive quantitative components. | Survey-based estimation (perceived loss percentages) supported by observations, interviews and focus groups |
| 39  | Kebede, L. M., Garbaba, C. A., Kuyu, C. G., Atnafu, B., & Mendesil, E. (2024). Evaluation of the performance of maize storage facilities for control of storage insect pests in Ethiopia. <i>Journal of Stored Products Research</i> , 107, 102336. <a href="https://doi.org/10.1016/j.jspr.2024.102336">https://doi.org/10.1016/j.jspr.2024.102336</a>                                            | Ethiopia      | maize                                                      | OFS (on-farm storage; bag storage and gombisa storage).                                                                       | Experimental storage study                                                                   | Direct measurement (count-and-weigh method for weight loss)                                                 |
| 40  | Khader, B. F. Y., Yigezu, A. Y., Duwayri, M. A., Niane, A. A., & Shideed, K. (2019). Where in the value chain are we losing the most food? The case of wheat in Jordan. <i>Food Security</i> , 11, 1009–1027. <a href="https://doi.org/10.1007/s12571-019-00962-7">https://doi.org/10.1007/s12571-019-00962-7</a>                                                                                  | Jordan.       | Wheat                                                      | Multiple stages                                                                                                               | Value-chain case study with mixed methods                                                    | Direct measurement (quadrats)                                                                               |
| 41  | Kikulwe, E. M., Okurut, S., Ajambo, S., Nowakunda, K., Stoian, D., & Naziri, D. (2018). Postharvest losses and their determinants: A challenge to creating a sustainable cooking banana value chain in Uganda. <i>Sustainability</i> , 10(7), 2381. <a href="https://doi.org/10.3390/su10072381">https://doi.org/10.3390/su10072381</a>                                                            | Uganda        | cooking banana                                             | Multiple stages                                                                                                               | Cross-sectional value chain study with econometric determinants analysis.                    | Survey-based estimation of physical and economic losses by node and season                                  |
| 42  | Łaba, S., Cacak-Pietrzak, G., Łaba, R., Sulek, A., & Szczepański, K. (2022). Food losses in consumer cereal production in Poland in the context of food security and environmental impact. <i>Agriculture</i> , 12(5), 665. <a href="https://doi.org/10.3390/agriculture12050665">https://doi.org/10.3390/agriculture12050665</a>                                                                  | Poland        | Consumer cereals                                           | Multiple stages                                                                                                               | Mixed methods: mass-balance modelling plus cross-sectional farm survey.                      | Mass balance                                                                                                |
| 43  | Liu, G., Kuang, Z., Tang, J., Kuang, S., Tian, Q., Zou, Y., & Li, Q. (2024). Calculation and utility analysis of lychee life-cycle carbon emissions considering food loss and waste. <i>Journal of</i>                                                                                                                                                                                             | China         | Fruit                                                      | Multiple stages                                                                                                               | Modelling study with primary experiment and scenario-based LCA.                              | Process modelling and experimental measurement:                                                             |

| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Country  | Commodity                             | SC Stage                                                                                                                                                                                   | Study Design                                                                        | Quantification Method                                                                                                                                                                                                                      |
|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|---------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     | Cleaner Production, 434, 140013.<br><a href="https://doi.org/10.1016/j.jclepro.2023.140013">https://doi.org/10.1016/j.jclepro.2023.140013</a>                                                                                                                                                                                                                                                                                                                   |          |                                       |                                                                                                                                                                                            |                                                                                     | Arrhenius-based kinetic model of quality/weight loss                                                                                                                                                                                       |
| 44  | López-Sánchez, A., Luque-Badillo, A. C., Orozco-Nunnally, D., Alencastro-Larios, N. S., Ruiz-Gómez, J. A., García-Cayuela, T., & Gradilla-Hernández, M. S. (2021). Food loss in the agricultural sector of a developing country: Transitioning to a more sustainable approach. The case of Jalisco, Mexico. <i>Environmental Challenges</i> , 5, 100327.<br><a href="https://doi.org/10.1016/j.envc.2021.100327">https://doi.org/10.1016/j.envc.2021.100327</a> | Mexico   | sugar cane                            | Multiple stages                                                                                                                                                                            | Cross-sectional survey with qualitative interviews                                  | Survey-based estimation (self-reported loss shares) plus qualitative interviews                                                                                                                                                            |
| 45  | Lu, S., Cheng, G., Li, T., Xue, L., Liu, X., Huang, J., & Liu, G. (2022). Quantifying supply chain food loss in China with primary data: A large-scale, field-survey based analysis for staple food, vegetables, and fruits. <i>Resources, Conservation &amp; Recycling</i> , 177, 106006.<br><a href="https://doi.org/10.1016/j.resconrec.2021.106006">https://doi.org/10.1016/j.resconrec.2021.106006</a>                                                     | China    | Staple food                           | Multiple stages                                                                                                                                                                            | Large-scale field survey and interview study with structured stage-loss accounting. | Hybrid: structured questionnaires (farmer households) and semi-structured interviews (other stakeholders), with stage-specific loss-rate calculation formulas (LAP, LPH, LST, LP, LD) and weighted aggregation to total supply-chain loss. |
| 46  | Ludwig-Ohm, S., Dirksmeyer, W., & Klockgether, K. (2019). Approaches to reduce food losses in German fruit and vegetable production. <i>Sustainability</i> , 11(23), 6576.<br><a href="https://doi.org/10.3390/su11236576">https://doi.org/10.3390/su11236576</a>                                                                                                                                                                                               | Germany  | Strawberries                          | Multiple stages                                                                                                                                                                            | NR                                                                                  | Survey-based estimation (structured interviews with value chain actors)                                                                                                                                                                    |
| 47  | Macheka, L., Spelt, E. J. H., Bakker, E.-J., van der Vorst, J. G. A. J., & Luning, P. A. (2018). Identification of determinants of postharvest losses in Zimbabwean tomato supply chains as basis for dedicated interventions. <i>Food Control</i> , 87, 135–144.<br><a href="https://doi.org/10.1016/j.foodcont.2017.12.017">https://doi.org/10.1016/j.foodcont.2017.12.017</a>                                                                                | Zimbabwe | tomato                                | Multiple stages                                                                                                                                                                            | Case-based cross-sectional survey with diagnostic tool + modelling.                 | Survey-based quantification of crates removed as “unfit for human consumption” across stages (three deliveries)                                                                                                                            |
| 48  | March, M. D., Toma, L., Thompson, B., & Haskell, M. J. (2019). Food waste in primary production: Milk loss with mitigation potentials. <i>Frontiers in Nutrition</i> , 6, 173.<br><a href="https://doi.org/10.3389/fnut.2019.00173">https://doi.org/10.3389/fnut.2019.00173</a>                                                                                                                                                                                 | Scotland | dairy                                 | OFH/production to farm gate; PRD interface (includes “rejected by processor” and “rejected at processor gate” as reported).                                                                | Cross-sectional farm survey with partial LCA and scenario analysis.                 | Survey-based estimation (farm reporting) combined with partial life cycle assessment and scenario modelling (withdrawal-day reduction)                                                                                                     |
| 49  | Martindale, W., Wright, I., Korir, L., Opiyo, A. M., Karanja, B., Nyalala, S., Kumar, M., Pearson, S., & Swainson, M. (2020). Framing food security and food loss statistics for incusive supply chain improvement and knowledge transfer between Kenyan, Indian and United Kingdom food manufacturers. <i>Emerald Open Research</i> , 2, 12.<br><a href="https://doi.org/10.35241/emeraldopenres.13414.1">https://doi.org/10.35241/emeraldopenres.13414.1</a>  | Kenya    | Multiple FAOSTAT food item categories | Unspec upstream: FAOSTAT “supply chain losses” defined as losses “during storage and transportation” between production recording and household; pre-harvest and household waste excluded. | Modelling/index study using secondary national datasets.                            | Coefficients/production statistics and ranking/association method: ranks protein supply (g/capita/day) and benchmarks against domestic supply quantity and FAOSTAT losses (tonnes) using spreadsheet ranking and MATCH functions.          |

| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                         | Country      | Commodity   | SC Stage                                                                                                                                                                                    | Study Design                                                                                  | Quantification Method                                                                                                                                                                           |
|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 50  | Masamba, K., Changadeya, W., Ntawuruhunga, P., Pankomera, P., Mbewe, W., & Chipungu, F. (2022). Exploring farmers' knowledge and approaches for reducing post-harvest physiological deterioration of cassava roots in Malawi. <i>Sustainability</i> , 14(5), 2719. <a href="https://doi.org/10.3390/su14052719">https://doi.org/10.3390/su14052719</a> | Malawi       | cassava     | Multiple stages                                                                                                                                                                             | Cross-sectional survey.                                                                       | Survey-based estimation of constraints, knowledge and reported practices                                                                                                                        |
| 51  | Mebratie, M. A., Haji, J., Woldetsadik, K., & Ayalew, A. (2015). Determinants of postharvest banana loss in the marketing chain of central Ethiopia. <i>Food Science and Quality Management</i> , 37, 52–59. DOI: NR                                                                                                                                   | Ethiopia     | banana      | Multiple stages                                                                                                                                                                             | Cross-sectional survey with regression determinants analysis.                                 | Survey-based estimation of loss at farm, wholesale and retail                                                                                                                                   |
| 52  | Melese, B., Satheesh, N., Fanta, S. W., & Bishaw, Z. (2022). Quantitative and qualitative post-harvest loss of emmer wheat in selected value chain in Bale zone, Ethiopia. <i>Cogent Food &amp; Agriculture</i> , 8(1), 2147554. <a href="https://doi.org/10.1080/23311932.2022.2147554">https://doi.org/10.1080/23311932.2022.2147554</a>             | Ethiopia     | emmer wheat | Multiple stages                                                                                                                                                                             | Mixed-methods value-chain assessment with load tracking and laboratory analysis.              | Hybrid: survey (semi-structured questionnaires), FAO 4S methodology, load tracking (quadrats for harvest and subsequent steps), storage loss estimation (bored grain)                           |
| 53  | Mingione, M., Fabi, C., & Jona Lasinio, G. (2021). Measuring and modeling food losses. <i>Journal of Official Statistics</i> , 37(1), 171–211. <a href="https://doi.org/10.2478/JOS-2021-0008">https://doi.org/10.2478/JOS-2021-0008</a>                                                                                                               | Global       | Cereals     | Unspec upstream (operational definition: quantity losses along supply chain for all utilisations up to but not including retail/consumption; includes storage, transportation, processing). | Modelling study                                                                               | Statistical modelling: Beta regression in a fully Bayesian framework with Bayesian variable selection (spike-and-slab and horseshoe priors) and latent random effects.                          |
| 54  | Minten, B., Tamru, S., & Reardon, T. (2021). Post-harvest losses in rural-urban value chains: Evidence from Ethiopia. <i>Food Policy</i> , 98, 101860. <a href="https://doi.org/10.1016/j.foodpol.2020.101860">https://doi.org/10.1016/j.foodpol.2020.101860</a>                                                                                       | Ethiopia     | liquid milk | Multiple stages                                                                                                                                                                             | Large-scale multi-actor value-chain surveys plus econometric retail analysis.                 | Survey-based estimation of self-reported losses at each node, with structural mapping of value-chain “nodes” and scenario aggregation                                                           |
| 55  | Mlambo, S., Mvumi, B. M., Stathers, T., Mubayiwa, M., & Nyabako, T. (2017). Field efficacy of hermetic and other maize grain storage options under smallholder farmer management. <i>Crop Protection</i> , 98, 198–210. <a href="https://doi.org/10.1016/j.cropro.2017.04.001">https://doi.org/10.1016/j.cropro.2017.04.001</a>                        | Zimbabwe     | maize       | OFS (household grain storage).                                                                                                                                                              | Field trial                                                                                   | Direct measurement: insect grain damage and grain weight loss using count-and-weigh method                                                                                                      |
| 56  | Molelekoa, T., Karoney, E. M., Siyoum, N., Gokul, J. K., & Korsten, L. (2025). Quality and quantity losses of tomatoes grown by small-scale farmers under different production systems. <i>Horticulturae</i> , 11(8), 884. <a href="https://doi.org/10.3390/horticulturae11080884">https://doi.org/10.3390/horticulturae11080884</a>                   | South Africa | tomatoes    | Multiple stages                                                                                                                                                                             | Mixed-methods field study with direct loss quantification and questionnaire-based assessment. | Hybrid: indirect assessment (questionnaires and interviews) plus direct quantification (visual defect assessment and categorisation of fruits at harvest and during consumer-simulated storage) |
| 57  | Mujuka, E., Mburu, J., Ogutu, A., & Ambuko, J. (2020). Returns to investment in postharvest loss reduction technologies among mango farmers in Embu County, Kenya. <i>Food and Energy Security</i> , 9, e195. <a href="https://doi.org/10.1002/fes3.195">https://doi.org/10.1002/fes3.195</a>                                                          | Kenya        | mango       | Unspec upstream (postharvest loss reduction technologies framed across handling,                                                                                                            | Modelling study                                                                               | Economic modelling (economic surplus model and cost–benefit analysis), not direct loss measurement.                                                                                             |

| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                           | Country      | Commodity                       | SC Stage                                                                                                                                                                                | Study Design                                                                    | Quantification Method                                                                                                                                           |
|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     |                                                                                                                                                                                                                                                                                                                                                                          |              |                                 | aggregation and storage; stages not quantified as a loss audit).                                                                                                                        |                                                                                 |                                                                                                                                                                 |
| 58  | Mwangi, J. K., Mutungi, C. M., Midingoyi, S.-K. G., Faraj, A. K., & Affognon, H. D. (2017). An assessment of the magnitudes and factors associated with postharvest losses in off-farm grain stores in Kenya. <i>Journal of Stored Products Research</i> , 73, 7–20. <a href="https://doi.org/10.1016/j.jspr.2017.05.006">https://doi.org/10.1016/j.jspr.2017.05.006</a> | Kenya        | maize                           | Off-farm storage (public warehouses and private stores).                                                                                                                                | Cross-sectional survey with econometric modelling                               | Survey-based estimation of perceived losses by cause                                                                                                            |
| 59  | Nath, B. C., Hossen, M. A., Islam, A. K. M. S., Huda, M. D., Paul, S., & Rahman, M. A. (2016). Postharvest loss assessment of rice at selected areas of Gazipur district. <i>Bangladesh Rice Journal</i> , 20(1), 23–32. DOI: NR                                                                                                                                         | Bangladesh   | rice                            | Multiple stages                                                                                                                                                                         | Field measurement study with comparative operational testing across seasons.    | Direct measurement: field and laboratory procedures (loss components weighed and converted to 14% moisture basis)                                               |
| 60  | Ndegwa, M. K., De Groote, H., Gitonga, Z. M., & Bruce, A. Y. (2016). Effectiveness and economics of hermetic bags for maize storage: Results of a randomized controlled trial in Kenya. <i>Crop Protection</i> , 90, 17–26. <a href="https://doi.org/10.1016/j.cropro.2016.08.007">https://doi.org/10.1016/j.cropro.2016.08.007</a>                                      | Kenya        | maize                           | OFS.                                                                                                                                                                                    | Randomised controlled trial with measurement subsample and economic evaluation. | Experimental/quasi-experimental: RCT with treatment (hermetic bags) and control (farmer practice)                                                               |
| 61  | Ndungu, M. M., Lagat, J. K., & Langat, J. K. (2019). Determinants and causes of postharvest milk losses among milk producers in Nyandarua North subcounty, Kenya. <i>East African Agricultural and Forestry Journal</i> , 83(4), 269–280. <a href="https://doi.org/10.1080/00128325.2019.1667648">https://doi.org/10.1080/00128325.2019.1667648</a>                      | Kenya        | milk                            | OFH/producer-level postharvest handling and marketing choice (formal and informal milk marketing channels; losses conceptualised from farm handling and delivery to collection points). | Cross-sectional survey with Heckman selection modelling.                        | Survey-based estimation with econometric modelling: two-step Heckman selection model (channel choice) and outcome equation for “milk losses in litres (total)”. |
| 62  | Ng'ang'a, J., Mutungi, C., Imathiu, S. M., & Affognon, H. (2016). Low permeability triple-layer plastic bags prevent losses of maize caused by insects in rural on-farm stores. <i>Food Security</i> , 8, 621–633. <a href="https://doi.org/10.1007/s12571-016-0567-9">https://doi.org/10.1007/s12571-016-0567-9</a>                                                     | Kenya        | maize                           | OFS (on-farm storage).                                                                                                                                                                  | On-farm comparative storage trial                                               | Direct measurement: gas composition (O <sub>2</sub> /CO <sub>2</sub> ), moisture, insect counts, grain damage and weight loss (count-and-weigh)                 |
| 63  | Nguyen-Van-Hung, Tran-Van-Tuan, Meas, P., Tado, C. J. M., Kyaw, M. A., & Gummert, M. (2019). Best practices for paddy drying: case studies in Vietnam, Cambodia, Philippines, and Myanmar. <i>Plant Production Science</i> , 22(1), 107–118. <a href="https://doi.org/10.1080/1343943X.2018.1543547">https://doi.org/10.1080/1343943X.2018.1543547</a>                   | Vietnam      | rice                            | OFH (drying).                                                                                                                                                                           | Modelling study                                                                 | Process modelling and LCA: comparative analysis of energy efficiency, GHG emissions, and cost-benefit for drying systems                                        |
| 64  | Nohamba, S., Musara, J. P., Bahta, Y. T., & Ogundeji, A. A. (2022). Drivers of postharvest loss among citrus farmers in Eastern Cape Province of South Africa: A zero-inflated Poisson (ZIP) regression model analysis. <i>Agriculture</i> , 12(10), 1651. <a href="https://doi.org/10.3390/agriculture12101651">https://doi.org/10.3390/agriculture12101651</a>         | South Africa | Nova, Navel, Cara Cara, lemons) | Farm-level postharvest handling and loss dimensions (sorting, picking, mechanical, secondary spoilage).                                                                                 | Cross-sectional survey with ZIP econometric modelling and constructed indices.  | Survey-based estimation combined with count modelling: PHL score (PHLS) as count of dimensions                                                                  |



| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                | Country      | Commodity       | SC Stage                                                                                                   | Study Design                                                            | Quantification Method                                                                                                                                               |
|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|-----------------|------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 65  | Nwankwo, E. C., & Chiekezie, N. R. (2024). Agricultural productivity and postharvest loss among cassava farmers, in Anambra State, Nigeria. <i>Global Journal of Agricultural Research</i> , 12(1), 37–50. <a href="https://doi.org/10.37745/gjar.2013/vol12n13750">https://doi.org/10.37745/gjar.2013/vol12n13750</a>                                                        | Nigeria      | cassava         | Unspec upstream (postharvest loss framed broadly; farmers, processors and marketers sampled).              | Cross-sectional survey with logit determinants analysis.                | Survey-based estimation using “postharvest management index” comparing weight at harvest and weight at market                                                       |
| 66  | Ogoudedji, S. A., Egyir, I. S., Osei-Asare, Y., Seini, A.-H. W., & Honlonkou, A. (2019). Assessing drivers of maize storage losses in south west Benin using a fractional response model. <i>Journal of Stored Products Research</i> , 83, 281–291. <a href="https://doi.org/10.1016/j.jspr.2019.07.013">https://doi.org/10.1016/j.jspr.2019.07.013</a>                       | Benin        | maize           | OFS (storage period at farm level).                                                                        | Cross-sectional survey with econometric modelling                       | Survey-based self-reported loss measurement (kg and %), analysed using a fractional response model (GLM with binomial family and logit link) and marginal effects.  |
| 67  | Omotilewa, O. J., Ricker-Gilbert, J., Ainembabazi, J. H., & Shively, G. E. (2018). Does improved storage technology promote modern input use and food security? Evidence from a randomized trial in Uganda. <i>Journal of Development Economics</i> , 135, 176–198. <a href="https://doi.org/10.1016/j.jdeveco.2018.07.006">https://doi.org/10.1016/j.jdeveco.2018.07.006</a> | Uganda       | maize           | OFS (on-farm storage; self-reported quantitative dry-weight losses).                                       | Randomised controlled trial with panel survey and econometric analysis. | Experimental/quasi-experimental: RCT (intention-to-treat and FE/DiD estimators) using panel survey                                                                  |
| 68  | Opara, I. K., Fawole, O. A., Kelly, C., & Opara, U. L. (2021). Quantification of on-farm pomegranate fruit postharvest losses and waste, and implications on sustainability indicators: South African case study. <i>Sustainability</i> , 13, 5168. <a href="https://doi.org/10.3390/su13095168">https://doi.org/10.3390/su13095168</a>                                       | South Africa | Acco            | Multiple stages                                                                                            | Case study                                                              | Direct measurement: sorting and counting individual fruit by defect category in on-farm “waste bins”                                                                |
| 69  | Ortiz-Gonzalo, D., Ørtenblad, S. B., Larsen, M. N., Suebpongsang, P., & Bruun, T. B. (2021). Food loss and waste and the modernization of vegetable value chains in Thailand. <i>Resources, Conservation &amp; Recycling</i> , 174, 105714. <a href="https://doi.org/10.1016/j.resconrec.2021.105714">https://doi.org/10.1016/j.resconrec.2021.105714</a>                     | Thailand     | Chinese cabbage | Multiple stages                                                                                            | Case study with mixed methods                                           | Direct measurement (individual cabbage-head weighing pre/post trimming across stakeholders) plus qualitative methods (semi-structured interviews and focus groups). |
| 70  | Parmar, A., Fikre, A., Sturm, B., & Hensel, O. (2018). Post-harvest management and associated food losses and by-products of cassava in southern Ethiopia. <i>Food Security</i> , 10(2), 419–435. <a href="https://doi.org/10.1007/s12571-018-0774-7">https://doi.org/10.1007/s12571-018-0774-7</a>                                                                           | Ethiopia     | cassava         | Multiple stages                                                                                            | Value-chain case study using mixed methods with FLW-standard framing.   | Hybrid: direct weighing                                                                                                                                             |
| 71  | Pastolero, A., & Sassi, M. (2022). Food loss and waste accounting: the case of the Philippine food supply chain. <i>Bio-based and Applied Economics</i> , 11(3), 207–218. <a href="https://doi.org/10.36253/bae-11501">https://doi.org/10.36253/bae-11501</a>                                                                                                                 | Philippines  | banana          | Multiple stages                                                                                            | Modelling/accounting study                                              | Coefficients/production statistics and mass-flow accounting: percentage accumulation and volume estimation following Gustavsson et al. methodology                  |
| 72  | Pietrangeli, R., & Cicatiello, C. (2024). Lost vegetables, lost value: Assessment of carrot downgrading and losses at a large producer organisation. <i>Journal of Cleaner Production</i> , 478, 143873. <a href="https://doi.org/10.1016/j.jclepro.2024.143873">https://doi.org/10.1016/j.jclepro.2024.143873</a>                                                            | Italy        | carrots         | EP (post-harvest operations at PO warehouse: washing, selection, calibration, re-processing for industry). | Case study with direct quantification and scenario modelling.           | Direct measurement (bin-based and stream weighing at multiple assessment points)                                                                                    |

| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                                                       | Country                | Commodity             | SC Stage                                                                                                                       | Study Design                                                           | Quantification Method                                                                                                                                                                        |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|-----------------------|--------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 73  | Porter, S. D., Reay, D. S., Bomberg, E., & Higgins, P. (2018). Avoidable food losses and associated production-phase greenhouse gas emissions arising from application of cosmetic standards to fresh fruit and vegetables in Europe and the UK. <i>Journal of Cleaner Production</i> , 201, 869–878. <a href="https://doi.org/10.1016/j.jclepro.2018.08.079">https://doi.org/10.1016/j.jclepro.2018.08.079</a>      | European Economic Area | Fruits and vegetables | PH/H (production-phase, on-farm cosmetic grade-outs; includes pre-harvest non-harvest decisions discussed).                    | Modelling study                                                        | Coefficients/production statistics with scenario modelling: crop-specific loss factors for on-farm grade-outs applied to Eurostat harvested production                                       |
| 74  | Principato, L., Ruini, L., Guidi, M., & Secondi, L. (2019). Adopting the circular economy approach on food loss and waste: The case of Italian pasta production. <i>Resources, Conservation &amp; Recycling</i> , 144, 82–89. <a href="https://doi.org/10.1016/j.resconrec.2019.01.025">https://doi.org/10.1016/j.resconrec.2019.01.025</a>                                                                          | Italy.                 | durum wheat and pasta | Multiple stages                                                                                                                | Single case study with mixed data sources                              | Hybrid: FLW Accounting and Reporting Standard inventory                                                                                                                                      |
| 75  | Qange, S., Mdoda, L., & Mditshwa, A. (2024). Exploring the relationship between agribusiness investments and postharvest losses among smallholder vegetable farmers in the eThekweni Municipality. <i>Frontiers in Sustainable Food Systems</i> , 8, 1420460. <a href="https://doi.org/10.3389/fsufs.2024.1420460">https://doi.org/10.3389/fsufs.2024.1420460</a>                                                    | South Africa           | Vegetables            | Multiple stages                                                                                                                | Cross-sectional survey with econometric modelling.                     | Survey-based estimation with econometric analysis (Ordinary Least Squares regression). Postharvest losses measured as physical (% produce lost) and economic (market value of lost produce). |
| 76  | Qange, S., Mdoda, L., & Mditshwa, A. (2024). Modeling drivers of postharvest losses among smallholder vegetable farmers in eThekweni Metropolitan: an examination of a zero-inflated Poisson (ZIP) approach. <i>Cogent Food &amp; Agriculture</i> , 10(1), 2383316. <a href="https://doi.org/10.1080/23311932.2024.2383316">https://doi.org/10.1080/23311932.2024.2383316</a>                                        | South Africa           | Vegetables            | Multiple stages                                                                                                                | Cross-sectional survey with count-data econometric modelling           | Survey-based estimation                                                                                                                                                                      |
| 77  | Redlingshöfer, B., Coudurier, B., & Georget, M. (2017). Quantifying food loss during primary production and processing in France. <i>Journal of Cleaner Production</i> , 164, 703–714. <a href="https://doi.org/10.1016/j.jclepro.2017.06.173">https://doi.org/10.1016/j.jclepro.2017.06.173</a>                                                                                                                     | France                 | four plant sectors    | Multiple stages                                                                                                                | National sectoral synthesis with recalculation of food loss estimates. | Hybrid synthesis/accounting: wide array of reports, published studies and interviews with experts and businesses                                                                             |
| 78  | Schneider, F., Part, F., Göbel, C., Langen, N., Gerhards, C., Kraus, G. F., & Ritter, G. (2019). A methodological approach for the on-site quantification of food losses in primary production: Austrian and German case studies using the example of potato harvest. <i>Waste Management</i> , 86, 106–113. <a href="https://doi.org/10.1016/j.wasman.2019.01.020">https://doi.org/10.1016/j.wasman.2019.01.020</a> | Austria                | potatoes              | H (harvest, on-site field losses); includes under-sized potatoes left in soil and sorted-out potatoes rejected during harvest. | Field measurement methodological case studies.                         | Direct measurement: potential yield determined by pre-harvest excavation of defined areas                                                                                                    |
| 79  | Shee, A., Mayanja, S., Simba, E., Stathers, T., Bechoff, A., & Bennett, B. (2019). Determinants of postharvest losses along smallholder producers maize and sweetpotato value chains: An ordered Probit analysis. <i>Food Security</i> , 11, 1101–1120. <a href="https://doi.org/10.1007/s12571-019-00949-4">https://doi.org/10.1007/s12571-019-00949-4</a>                                                          | Uganda                 | sweetpotato           | Multiple stages                                                                                                                | Cross-sectional survey with stage-wise ordered probit modelling.       | Survey-based elicitation (“bean exercise”) producing ordered loss-category data                                                                                                              |
| 80  | Shoji, K., Schudel, S., Onwude, D., Shrivastava, C., & Defraeye, T. (2022). Mapping the postharvest life of imported fruits from packhouse to retail stores using physics-based digital twins. <i>Resources, Conservation &amp; Recycling</i> , 176, 105914. <a href="https://doi.org/10.1016/j.resconrec.2021.105914">https://doi.org/10.1016/j.resconrec.2021.105914</a>                                           | Spain to Switzerland   | cucumber              | Multiple stages                                                                                                                | Modelling study using sensor datasets                                  | Process modelling (physics-based digital twins using finite-element modelling and kinetic quality model) using time-temperature sensor data                                                  |
| 81  | Spang, E. S., & Stevens, B. D. (2018). Estimating the blue water footprint of in-field crop losses: A case study of U.S.                                                                                                                                                                                                                                                                                             | United States          | potatoes              | Multiple stages                                                                                                                | Modelling study using linked national datasets.                        | Hybrid modelling using multiple datasets: NASS acres planted vs harvested (pre-harvest losses),                                                                                              |



| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                               | Country     | Commodity                                                                                                    | SC Stage                                                                                                                 | Study Design                                                                                         | Quantification Method                                                                                                                                                                                                                                                                |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|--------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     | potato cultivation. Sustainability, 10(8), 2854. <a href="https://doi.org/10.3390/su10082854">https://doi.org/10.3390/su10082854</a>                                                                                                                                                                                                                                                         |             |                                                                                                              |                                                                                                                          |                                                                                                      | RMA crop insurance “cause of loss” drivers to attribute losses by driver, NASS Objective Yield survey for measured harvest losses, and NASS irrigation survey to estimate blue water footprint.                                                                                      |
| 82  | Strecker, K., Bitzer, V., & Kruijssen, F. (2022). Critical stages for post-harvest losses and nutrition outcomes in the value chains of bush beans and nightshade in Uganda. Food Security, 14, 411–426. <a href="https://doi.org/10.1007/s12571-021-01244-x">https://doi.org/10.1007/s12571-021-01244-x</a>                                                                                 | Uganda      | African nightshade                                                                                           | Multiple stages                                                                                                          | Case study with mixed methods                                                                        | Hybrid/multi-method: Informal Food Loss Assessment Method (IFLAM) plus small-scale load tracking                                                                                                                                                                                     |
| 83  | Sugri, I., Abubakari, M., Owusu, R. K., & Bidzakin, J. K. (2021). Postharvest losses and mitigating technologies: Evidence from Upper East Region of Ghana. Sustainable Futures, 3, 100048. <a href="https://doi.org/10.1016/j.sfr.2021.100048">https://doi.org/10.1016/j.sfr.2021.100048</a>                                                                                                | Ghana       | maize, cowpea, Bambara nut, groundnut, millet, rice, sorghum, soybean Survey also reports perishables        | Multiple stages                                                                                                          | Regional mixed-methods assessment plus participatory experimental evaluation and economic appraisal. | Mixed: farmer-declared losses by stage (kg then % of total harvested)                                                                                                                                                                                                                |
| 84  | Tansuchat, R., Pankasemsuk, T., Panmanee, C., Rattanasamakarn, T., & Palason, K. (2023). Analyzing food loss in the fresh longan supply chain: Evidence from field survey measurements. Agriculture, 13, 1951. <a href="https://doi.org/10.3390/agriculture13101951">https://doi.org/10.3390/agriculture13101951</a>                                                                         | Thailand    | Fresh longan                                                                                                 | Multiple stages                                                                                                          | Mixed methods                                                                                        | Hybrid direct measurement and structured field survey aligned with FAO food loss assessment guidance                                                                                                                                                                                 |
| 85  | Tarekegn, K., & Kelem, F. (2022). Assessment of mango post-harvest losses along value chain in the Gamo Zone, Southern Ethiopia. International Journal of Fruit Science, 22(1), 170–182. <a href="https://doi.org/10.1080/15538362.2021.2025194">https://doi.org/10.1080/15538362.2021.2025194</a>                                                                                           | Ethiopia    | mango                                                                                                        | Multiple stages                                                                                                          | Cross-sectional survey with qualitative triangulation                                                | Survey-based estimation with observation, FGDs and KIIs                                                                                                                                                                                                                              |
| 86  | Teferra, T. F. (2022). The cost of postharvest losses in Ethiopia: economic and food security implications. Heliyon, 8(3), e09077. <a href="https://doi.org/10.1016/j.heliyon.2022.e09077">https://doi.org/10.1016/j.heliyon.2022.e09077</a>                                                                                                                                                 | Ethiopia    | barley, maize, wheat, sorghum                                                                                | Unspec upstream (postharvest losses treated as aggregate “after harvest” losses for each crop; stage disaggregation NR). | Modelling/accounting study using secondary data and coefficients.                                    | Coefficients/production statistics: FAOSTAT production and value series combined with crop-specific PHL percentages drawn from literature/FAO reports                                                                                                                                |
| 87  | Thorsen, M., Miroso, M., & Skeaff, S. A. (2021). A quantitative and qualitative study of food loss in glasshouse-grown tomatoes. Horticulturae, 8, 39. <a href="https://doi.org/10.3390/horticulturae8010039">https://doi.org/10.3390/horticulturae8010039</a>                                                                                                                               | New Zealand | Glasshouse-grown tomatoes                                                                                    | Multiple stages                                                                                                          | Mixed methods                                                                                        | Direct measurement: counting unharvested tomatoes and weighing rejects at glasshouse and packhouse                                                                                                                                                                                   |
| 88  | Tonini, P., Muñoz Odina, P., Orsini, F., & Gabarrell Durany, X. (2022). Economic benefit and social impact derived by a food loss prevention strategy in the vegetable sector: A spatial and temporal analysis at the regional level. Frontiers in Sustainable Food Systems, 6, 1043591. <a href="https://doi.org/10.3389/fsufs.2022.1043591">https://doi.org/10.3389/fsufs.2022.1043591</a> | Spain       | cabbage, lettuce, watermelon, pumpkin, zucchini, cucumber, tomato, artichoke, cauliflower, onion, green bean | PH/H (primary production): includes product “ready to harvest” and “not harvested”; explicitly stops before post-        | Case-study modelling/accounting study with spatial–temporal analysis                                 | Hybrid/modelling: (i) coefficients from field measurement studies for Avoidable Loss (AVL) (random soil sampling of commercial and non-commercial crops left in harvested fields), (ii) semi-structured interviews for Possibly Avoidable Loss (PAL) (quality sorting), (iii) single |

| S/N | Full Reference                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Country       | Commodity                                       | SC Stage                                                                                                                                              | Study Design                                                                  | Quantification Method                                                                                                                                                                                                                               |
|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|-------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |               |                                                 | harvest operations.                                                                                                                                   |                                                                               | assumed Unavoidable Loss (UVL) value (5%) based on "optimal production" scenario, (iv) Monte Carlo analysis for uncertainty/sensitivity, (v) spatial-temporal allocation by province and month using harvested-product shares.                      |
| 89  | Vázquez-Rowe, I., Laso, J., Margallo, M., Garcia-Herrero, I., Hoehn, D., Amo-Setién, F., Bala, A., Abajas, R., Sarabia, C., Durá, M. J., Fullana-i-Palmer, P., & Aldaco, R. (2020). Food loss and waste metrics: a proposed nutritional cost footprint linking linear programming and life cycle assessment. <i>The International Journal of Life Cycle Assessment</i> , 25, 1197–1209. <a href="https://doi.org/10.1007/s11367-019-01655-1">https://doi.org/10.1007/s11367-019-01655-1</a> | Spain         | Multiple commodities grouped into 13 categories | Multiple stages                                                                                                                                       | Modelling study                                                               | Hybrid modelling: MFA-based life cycle inventory combined with nutritional profiling (NRF9.3) and economic valuation (EFLW), aggregated through linear programming to create "nutritional cost footprint (NCF)" indicator under an LCA perspective. |
| 90  | Wang, R., Liu, G., Zhou, L., Yang, Z., Tang, Z., Lu, S., Zhao, M., Sun, H., Ma, C., & Cheng, G. (2023). Quantifying food loss along the animal products supply chain in China with large-scale field-survey based primary data. <i>Resources, Conservation &amp; Recycling</i> , 188, 106685. <a href="https://doi.org/10.1016/j.resconrec.2022.106685">https://doi.org/10.1016/j.resconrec.2022.106685</a>                                                                                 | China         | pork                                            | Multiple stages                                                                                                                                       | Large-scale field survey with standardised stage-loss accounting and scaling. | Survey-based estimation with standardised loss-rate calculation (stage loss rates standardised and summed)                                                                                                                                          |
| 91  | Wesana, J., Gellynck, X., Dora, M. K., Pearce, D., & De Steur, H. (2019). Measuring food and nutritional losses through value stream mapping along the dairy value chain in Uganda. <i>Resources, Conservation &amp; Recycling</i> , 150, 104416. <a href="https://doi.org/10.1016/j.resconrec.2019.104416">https://doi.org/10.1016/j.resconrec.2019.104416</a>                                                                                                                             | Uganda        | dairy                                           | Multiple stages                                                                                                                                       | Case study with mixed methods                                                 | Hybrid: Value Stream Mapping (lean waste mapping) combined with FLW Accounting and Reporting Standard                                                                                                                                               |
| 92  | Winans, K., Marvinney, E., Gillman, A., & Spang, E. (2020). An evaluation of on-farm food loss accounting in life-cycle assessment (LCA) of four California specialty crops. <i>Frontiers in Sustainable Food Systems</i> , 4, 10. <a href="https://doi.org/10.3389/fsufs.2020.00010">https://doi.org/10.3389/fsufs.2020.00010</a>                                                                                                                                                          | United States | Processing tomato                               | Unspec upstream within farm-gate boundary: cultivation phase "cradle-to-farm gate" including farm inputs; on-farm losses at production/harvest stage. | Modelling study                                                               | LCA modelling with explicit inclusion of on-farm food loss as a percentage adjustment to the functional unit                                                                                                                                        |
| 93  | Yeshiwas, Y., Alemayehu, M., & Adgo, E. (2023). The rise and fall of onion production; its multiple constraints on pre-harvest and post-harvest management issues along the supply chain in northwest Ethiopia. <i>Heliyon</i> , 9, e15905. <a href="https://doi.org/10.1016/j.heliyon.2023.e15905">https://doi.org/10.1016/j.heliyon.2023.e15905</a>                                                                                                                                       | Ethiopia      | onion                                           | Multiple stages                                                                                                                                       | Cross-sectional supply-chain survey with observational triangulation.         | Survey-based estimation using questionnaires plus direct field/market observations                                                                                                                                                                  |
| 94  | Yigezu, Y. A., Moustafa, M. A., Mohiy, M. M., Ibrahim, S. E., Ghanem, W. M., Niane, A.-A., Abbas, E., Sabry, S. R. S., & Halila, H. (2021). Food losses and wastage along the wheat value chain in Egypt and their implications on food and energy security, natural resources, and the environment.                                                                                                                                                                                        | Egypt         | wheat                                           | Multiple stages                                                                                                                                       | Value-chain case study with mixed methods and national scaling.               | Hybrid: direct measurement (quadrats/plots for pre-harvest and harvest)                                                                                                                                                                             |

| S/N | Full Reference                                                                                                                                                                                                                                                         | Country | Commodity             | SC Stage                                                                        | Study Design                                            | Quantification Method                                          |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|-----------------------|---------------------------------------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------|
|     | Sustainability, 13(18), 10011.<br><a href="https://doi.org/10.3390/su131810011">https://doi.org/10.3390/su131810011</a>                                                                                                                                                |         |                       |                                                                                 |                                                         |                                                                |
| 95  | Zhang, R. J., Lee, B., & Chang, H.-H. (2019). What is missing in food loss and waste analyses? A close look at fruit and vegetable wholesale markets. Sustainability, 11, 7146.<br><a href="https://doi.org/10.3390/su11247146">https://doi.org/10.3390/su11247146</a> | Taiwan  | Fruits and vegetables | W (wholesale market; auction stage with end-of-day disposal of unsold parcels). | Modelling study using administrative observational data | Administrative-record quantification of unsold disposed weight |

## Included Papers in Systematic Literature Review 2

Table A 3: Characteristics of Included Studies (n=102)

| S/N | ID (full reference)                                                                                                                                                                                                                                                       | Country or region                  | Commodity or sector             | Node(s) targeted                                                | Intervention type                                              | Study design and data                                                                                                                                                                                                                                                                    | Outcome indicators                                                                                                                                                                                                                                  | Comparator or baseline                                                                         | Outlet                                      | Year |
|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|---------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|---------------------------------------------|------|
| 1.  | Ahmed, A.R., Aleid, S.M. and Mohammed, M. (2023), "Impact of modified atmosphere packaging conditions on quality of dates: experimental study and predictive analysis using artificial neural networks", <i>Foods</i> , Vol. 12 No. 20, 3811, doi: 10.3390/foods12203811. | Saudi Arabia (Al-Ahsa)             | Dates (Khalas, Sukary)          | Post-harvest storage                                            | Modified-atmosphere packaging (MAP) regimes and predictive ANN | Twelve storage treatments combining packaging (cardboard vs MAP tray), gas (air vs 20% CO <sub>2</sub> + N <sub>2</sub> ), and temperature (24 °C vs 4 °C) for 12 months; MC, aw, TSS, pH, colour (L*, a*, b*, ΔE), and microbiology; ANN trained/tested/validated on the dataset. Ahmed | MAP with 20% CO <sub>2</sub> + N <sub>2</sub> at 4 °C slowed colour change (lower ΔE) and reduced yeast/mould and aerobic counts versus controls; ANN predictivity R <sup>2</sup> ≈ 0.77–0.98 with low RMSE/MAPE (see Tables 2–5; figs. 2–7). Ahmed | Cardboard boxes and MAP with normal air at 24 °C/4 °C. Ahmed                                   | Foods                                       | 2023 |
| 2.  | Akonor, P.T., Osei Tutu, C., Affrifah, N.S., Budu, A.S. and Saalia, F.K. (2023), "Effect of different drying techniques on the functionality and digestibility of                                                                                                         | Ghana (laboratory work at CSIR/UG) | Cassava flour; fufu application | Processing (drying of pre-blanching roots; flour functionality) | Technology comparison: solar vs hot-air oven vs drum drying    | Controlled experiments: single-drum dryer 120 °C; oven 65 °C 7 h; solar tunnel ≈52 °C 40 h. Tests: β-carotene (UV-Vis), in-vitro                                                                                                                                                         | Drum-dried flours showed highest digestibility (≈69.4–79.7%); oven drying best preserved β-carotene (mean ≈2.8 mg kg <sup>-1</sup> )                                                                                                                | Cross-method contrasts among the three drying techniques; no external field comparator. Akonor | Journal of Food Processing and Preservation | 2023 |

|    |                                                                                                                                                                                                                                                                                                                        |                                  |                                                        |                                                            |                                                                                                                   |                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                           |                                                                                                                                                        |                                              |      |
|----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|--------------------------------------------------------|------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------|------|
|    | yellow-fleshed cassava flour and its performance in food application”, <i>Journal of Food Processing and Preservation</i> , Vol. 2023, Article 1775604, doi: 10.1155/2023/1775604.                                                                                                                                     |                                  |                                                        |                                                            |                                                                                                                   | digestibility, hydration (WBC/WSI/SP), pasting (Viscograph), texture of fufu, 25-person sensory panel.                                                                                                             | (Table 1). Drum-dried flour had highest water-binding ( $\approx 829$ – $842\%$ ), instant viscosity and lower breakdown (Tables 2–3; Fig. 3). Fufu from drum-dried flour was softest and most acceptable (Table 5; PCA on page 9). Akonor                |                                                                                                                                                        |                                              |      |
| 3. | Albrecht, A., Ibal, R., Raab, V., Reichstein, W., Haarer, D. and Kreyenschmidt, J. (2020), “Implementation of time–temperature indicators to improve temperature monitoring and support dynamic shelf life in meat supply chains”, <i>Journal of Packaging Technology and Research</i> , Vol. 4 No. 1, pp. 23–32, doi: | Germany (national poultry chain) | Poultry meat (fresh, aerobically packed breast fillet) | Processing → transport → wholesaler → butcher (cold chain) | Intelligent packaging : photochromic TTI (OnVu™) + activation and dynamic predictive models + software deployment | Laboratory validation of TTI kinetics, then 4-week field pilot on 8 boxes (n=480 TTIs) along an actual poultry chain; microbial shelf life by <i>Pseudomonas</i> spp. threshold $7.5 \log_{10} \text{ cfu g}^{-1}$ | High agreement model vs observed ( $R^2 \approx 0.95$ – $0.98$ ; bias $\approx 0.99$ ; accuracy $\approx 1.01$ ); field shelf life TTIs 174–192 h; microbial shelf life mean 162 h (box-level variation), enabling dynamic shelf-life decisions. Albrecht | Isothermal vs dynamic temperature profiles; field comparison of TTI-predicted vs microbiologically estimated shelf life at inspection points. Albrecht | Journal of Packaging Technology and Research | 2020 |

|    |                                                                                                                                                                                                                                                                      |                                                      |                         |                                                       |                                                                                                       |                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                    |                                                           |      |
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|    | 10.1007/s41783-019-00080-x.                                                                                                                                                                                                                                          |                                                      |                         |                                                       |                                                                                                       |                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                    |                                                           |      |
| 4. | Ambler, K., de Brauw, A. and Godlonton, S. (2018), "Measuring postharvest losses at the farm level in Malawi", <i>Australian Journal of Agricultural and Resource Economics</i> , Vol. 62 No. 1, pp. 139–160, doi: 10.1111/1467-8489.12237.                          | Malawi                                               | Maize, groundnuts, soya | Harvest & transport; processing; storage (farm level) | Measurement instrument (PHL survey module)                                                            | Cross-sectional farmer survey ( $\approx 1,118$ households) using detailed PHL module distinguishing damage vs complete loss by activity; comparison with single-question approach. Ambler              | Conditional-on-loss averages $\approx 5\%$ (maize), $12\%$ (groundnuts), $8\%$ (soya); losses concentrated at harvest and processing; detailed module identifies more households with losses than single-question surveys. Ambler                                                        | Comparator is national single-question measure; within-study activity-level accounting. Ambler                                                                                                     | Australian Journal of Agricultural and Resource Economics | 2018 |
| 5. | Argenta, L.C., Wood, R.M., Mattheis, J.P., Thewes, F.R. and Nesi, C.N. (2024), "Impact of storage atmosphere relative humidity on 'Gala' apple fruit quality", <i>Postharvest Biology and Technology</i> , Vol. 217, 113085, doi: 10.1016/j.postharvbio.2024.113085. | Brazil (Fraiburgo, São Joaquim); commercial CA rooms | Apples ('Gala')         | Storage (long-term CA + shelf)                        | Controlled RH regimes in CA (avg 87, 91, 94, $96\% \pm 1$ -MCP; multi-year lab and commercial studies | Six production years; CA $0.5^\circ\text{C}$ , $1.5\text{ kPa O}_2/2.5\text{ kPa CO}_2$ for 240 d + 7 d shelf; factorials for orchard, maturity, year, RH, 1-MCP; n up to 288 batches $\times$ 25 fruit | Lower RH ( $87\text{--}91\%$ ) increased firmness and reduced flesh browning, decay, cracking and wet lenticel breakdown, but increased shrivel beyond $\approx 4\text{--}6\%$ weight loss; suggested compromise at $91\text{--}94\%$ RH ( $\approx 3\text{--}4\%$ weight loss). Argenta | Cross-regime contrasts (four RH levels), with/without 1-MCP and across years, orchards and maturities; regression breakpoints for shrivel risk at $\approx 3.9\text{--}5.1\%$ weight loss. Argenta | Postharvest Biology and Technology                        | 2024 |

|    |                                                                                                                                                                                                                                                                                     |                                                |                                    |                                                                                          |                                                                                                                                                               |                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                           |                                                                                                                                                                 |                               |      |
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| 6. | Arias Bustos, C. and Moors, E.H.M. (2018), "Reducing post-harvest food losses through innovative collaboration: insights from the Colombian and Mexican avocado supply chains", <i>Journal of Cleaner Production</i> , Vol. 199, pp. 1020–1034, doi: 10.1016/j.jclepro.2018.06.187. | Mexico & Colombia (exports to the Netherlands) | Avocados                           | Post-harvest through distribution (processing/packing, storage, transport, coordination) | Governance/collaboration intervention concept (partnerships, information exchange, incentive alignment)                                                       | Two qualitative case studies; 25 semi-structured interviews across supply-chain actors; NVivo thematic analysis                                                                                                                                                                                           | Typology of structural inefficiencies (corporate, cognitive/affective, tangible); drivers/barriers; partnership-based mitigation propositions                                                                                                                                             | Not applicable (qualitative multiple-case; no counterfactual)                                                                                                   | Journal of Cleaner Production | 2018 |
| 7. | Bai, J. (2025). Melons as Lemons: Asymmetric Information, Consumer Learning and Seller Reputation. Review of Economic Studies. <a href="https://doi.org/10.1093/restud/rdaf006">https://doi.org/10.1093/restud/rdaf006</a>                                                          | China, Shijiazhuang                            | Watermelons (retail fruit markets) | Retail sale to households; price–quality signalling at point of sale                     | Signalling technologies: low-cost sticker label vs high-cost laser-engraved label; cross-randomised monetary incentive to subsidise initial quality provision | Field experiment across 60 markets with one seller per market, 8-week intervention during 2014 peak season; randomisation to sticker, laser, or label-free, each crossed with incentive vs none; bi-weekly objective quality checks using a sweetness metre; daily prices, quantities and sales recorded; | Laser labelling induced a genuine quality premium: premium-pile sweetness higher than sticker (e.g., regression differences $\approx$ 0.42–0.71 Brix units depending on specification); sellers with laser achieved 30–40% higher sales profits via higher prices and larger premium-pile | Label-free markets; market-average quality; sticker vs laser head-to-head; within-seller normal vs premium piles; pre vs post removal of the monetary incentive | Review of Economic Studies    | 2025 |

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|  |  |  |  |  |  | <p>675 households kept purchase and satisfaction diaries; baseline sorting ability tests with 30 sellers and 150 consumers; endline and follow-up surveys</p> | <p>quantities; sticker did not outperform baseline and often shifted sales from the normal pile; belief-updating estimates indicate more optimistic priors under laser than sticker and faster learning; counterfactual simulations show a 21% gain in three-season discounted consumer surplus with signalling. Key visuals and tables: seller/consumer sorting and within-seller variation in sweetness (Fig. 1); persistence of differentiation by treatment (Fig. 5); quality effects (Table 2); price, quantity and profit effects (Table 3); incentive</p> |  |  |  |
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|    |                                                                                                                                                                                                                                                     |                            |                    |                            |                                                                                    |                                                                                                                                                                                                                                                       | removal effects (Table 4); learning parameter estimates incl. priors $\lambda_0$ , recovery rate $r$ (Table 7); beliefs over time and consumer surplus implication (Fig. 6). bai                            |                                                                                  |                                     |      |
| 8. | Baoua, I.B., Amadou, L., Ousmane, B., Baributsa, D. and Murdock, L.L. (2014), "PICS bags for post-harvest storage of maize grain in West Africa", <i>Journal of Stored Products Research</i> , Vol. 58, pp. 20–28, doi: 10.1016/j.jspr.2014.03.001. | Benin, Burkina Faso, Ghana | Maize (grain/seed) | Storage                    | Hermetic storage technology (Purdue Improved Crop Storage, triple-layer PICS bags) | Multi-site field storage trials: 3–4 PICS bags and 2 woven-bag controls per site; naturally infested or lightly infested locally purchased maize; $\approx 6.5$ months storage; insect counts, seed moisture, 100-seed weight, germination, aflatoxin | 95–100% insect mortality in PICS; no increase in damaged kernels or loss of 100-seed weight; germination maintained; aflatoxin $\leq 20$ ppb in 55% of PICS vs 34.6% of woven bags (site variability noted) | Woven polypropylene bags as control; baseline (time 0) measurements for each bag | Journal of Stored Products Research | 2014 |
| 9. | Baributsa, D., Bakoye, O.N., Baoua, I. and Murdock, L.L. (2020), "Performance of five postharvest storage methods                                                                                                                                   | Benin (Parakou; Sahel)     | Maize              | Storage (trader warehouse) | Hermetic storage (PICS™, AgroZ®, SuperGrainbag™, EVAL™) vs                         | 7-month field storage (naturally infested maize); gases ( $O_2/CO_2$ ), insect counts, damage, weight loss; $n=4$ per                                                                                                                                 | Hermetic bags: $O_2 \sim 0.5\text{--}2.3\%$ and no additional damage/weight loss; PP woven lost 10.3% and ZeroFly® 6.3%;                                                                                    | PP woven and ZeroFly® served as non-hermetic comparators. Baributsa              | Insects                             | 2020 |

|     |                                                                                                                                                                                                                                                                             |                                                                                        |                              |                                                                     |                                                                                                           |                                                                                                                                                                                                                        |                                                                                                                                                                                                   |                                                                                                                                      |                            |      |
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|     | for maize preservation in northern Benin”, <i>Insects</i> , Vol. 11 No. 8, 541, doi: 10.3390/insects11080541.                                                                                                                                                               |                                                                                        |                              |                                                                     | insecticide-treated woven (ZeroFly®) and PP woven                                                         | treatment; RH/T logged. Baributsa                                                                                                                                                                                      | CO <sub>2</sub> in hermetic 14–16.6% at 7 months (Tables 3–5). Baributsa                                                                                                                          |                                                                                                                                      |                            |      |
| 10. | Barons, M.J., Walsh, L.E., Salakpi, E.E. and Nichols, L. (2024), “A decision support system for sustainable agriculture and food loss reduction under uncertain agricultural policy frameworks”, <i>Agriculture</i> , Vol. 14 No. 3, 458, doi: 10.3390/agriculture14030458. | UK/Ireland casework with EU policy context (lettuce exemplar; EU Green Deal scenarios) | Lettuce (fresh horticulture) | Production                                                          | Decision-support modelling for input reduction and IPM; Bayesian Network with Structured Expert Judgement | Bayesian Network populated with pesticide-usage data and elicited yield-loss distributions; scenario analysis (10–50% pesticide and 5–20% fertiliser reductions; IPM on/off). See Table 3 and Scenarios 1–6, pp. 8–12. | Probabilities of additional food loss categories under each scenario; median yield-loss shifts by scenario (e.g., 50% pesticide and 20% fertiliser reduction categorised “very high” added loss). | Implicit baseline of “typical loss ≈10%” plus scenario-specific reductions of inputs; contrasts with and without IPM.                | Agriculture                | 2024 |
| 11. | Belias, A., Bolten, S., Orsi, R.H. and Wiedmann, M. (2024), “Application of environmental monitoring programs and root cause analysis to identify and implement interventions to reduce or eliminate                                                                        | USA (four apple packing houses)                                                        | Apples (packing)             | Packinghouse environment (drains, waxing line, forklifts, CA rooms) | Governance and sanitation interventions informed by WGS-guided root cause analysis                        | 1,339 environmental sponges; WGS of 280 isolates; longitudinal sampling pre/post interventions; mixed-effects logistic regression                                                                                      | Prevalence reduced significantly in one site post-intervention (e.g., PH-C 27%→5%); monthly forklift cleaning with foamers reduced <i>Listeria</i> on forklifts;                                  | Before–after sampling in same sites/areas (including forklift-only rounds) relative to implemented sanitation/design changes. Belias | Journal of Food Protection | 2024 |

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|     | <i>Listeria</i> populations in apple packinghouses”, <i>Journal of Food Protection</i> , Vol. 87, 100324, doi: 10.1016/j.jfoodprot.2024.100324.                                                                                                                                             |                                             |                          |                                     |                                                                                                                                                                  |                                                                                                                                                          | persistence and common upstream sources identified via WGS clusters. Belias                                                                                                     |                                                          |                                          |      |
| 12. | Bernardi, B., Falcone, G., Stillitano, T., Benalia, S., Strano, A., Bacenetti, J. and De Luca, A.I. (2018), “Harvesting system sustainability in Mediterranean olive cultivation”, <i>Science of the Total Environment</i> , Vol. 625, pp. 1446–1458, doi: 10.1016/j.scitotenv.2018.01.005. | Mediterranean (Italy; Calabria orchards)    | Olives (table/olive oil) | Production/harvesting               | Comparative technology assessment (self-propelled trunk shakers; towed shaker; inverted-umbrella harvester; windrower/ground harvester; small hand-held shakers) | Field productivity measurements; economic costing (Miyata method); Life Cycle Assessment (ReCiPe) with three functional units (per hour, per ha, per kg) | Work capacity 5–18 t/day depending on system; cost per hour and per kg; environmental impacts by FU; quality parameters (free acidity, PV, UV indices) with panel sensory check | Cross-scenario comparisons; no separate external control | Science of the Total Environment         | 2018 |
| 13. | Bhandari, N., Bika, R., Subedi, S. and Pandey, S. (2022), “Essential oils amended coatings in citrus postharvest management”, <i>Journal of Agriculture and</i>                                                                                                                             | Global (synthesis; Nepal context discussed) | Citrus                   | Post-harvest (coatings/day control) | Narrative review of essential-oil-enriched edible coatings                                                                                                       | Literature synthesis of EO types, concentrations, organisms, quality metrics; Nepalese applicability                                                     | Summarises many EO–coating combinations controlling <i>Penicillium</i> spp., reducing weight loss, maintaining quality; calls for                                               | Not applicable (review). Chaomuang                       | Journal of Agriculture and Food Research | 2022 |

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|     | <i>Food Research</i> , Vol. 10, 100375, doi: 10.1016/j.jafr.2022.100375.                                                                                                                                                                                                                                                                  |                                                                 |              |                           |                                                                                                                                       |                                                                                                                                                                                           | commercial-scale validation in Nepal; no primary field trial here. Chaomuang                                                                                                                                                            |                                                                         |                               |      |
| 14. | Both, V., Brackmann, A., Thewes, F.R., Weber, A., Schultz, E.E. and Ludwig, V. (2018), "The influence of temperature and 1-MCP on quality attributes of 'Galaxy' apples stored in controlled atmosphere and dynamic controlled atmosphere", <i>Food Packaging and Shelf Life</i> , Vol. 16, pp. 168–177, doi: 10.1016/j.fpsl.2018.03.010. | Brazil (apples stored under controlled experimental conditions) | Apples       | Storage                   | Dynamic Controlled Atmosphere monitored by Respiratory Quotient (DCA-RQ, RQ≈1.5) at 1.0–2.0°C, with/without 1-MCP, vs conventional CA | 9-month storage + 7-day shelf; factorial comparisons; metabolism (ethylene, ACC oxidase, respiration), disorders (flesh breakdown, mealiness), firmness, acidity, share of healthy fruit. | DCA-RQ reduced ethylene and respiration vs CA, maintained firmness and acidity, and at 2.0°C delivered the highest share of healthy fruit; 1-MCP mainly needed for CA; DCA-RQ controlled fermentative markers within acceptable levels. | Direct CA vs DCA-RQ, temperature contrasts, ±1-MCP. Both                | Food Packaging and Shelf Life | 2018 |
| 15. | Bovi, G.G., Caleb, O.J., Ilte, K., Rauh, C. and Mahajan, P.V. (2018), "Impact of modified atmosphere and humidity packaging on the quality, off-odour development and volatiles of 'Elsanta' strawberries", <i>Food Packaging and Shelf Life</i> , Vol. 16,                                                                               | Germany                                                         | Strawberries | Packaging, storage (5 °C) | Modified-atmosphere-and-humidity packaging (MAHP) using window films (NatureFlex, Xtend, Propafilm)                                   | Ten lidded packs with fixed window areas (33–100%) and film types (2 micro-perforations); 14-day storage; headspace gases, condensation, mass loss, sensory, VOCs. Bovi                   | O <sub>2</sub> 5–14% and CO <sub>2</sub> 8–19% (film-dependent); high-WVTR windows prevented visible condensation but slightly increased mass loss (still <1.5%); control developed                                                     | Sealed control without humidity window; alternative films/windows. Bovi | Food Packaging and Shelf Life | 2018 |

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|     | pp. 204–210, doi: 10.1016/j.fpsl.2018.04.002.                                                                                                                                                                                                                                |                            |                       |                                     |                                                    |                                                                                                                                   | anoxic CO <sub>2</sub> , ethanol/esters and off-odours (Figs. 1–4). Bovi                                                                                                                                                           |                                                                                                       |                |      |
| 16. | Brander, M., Bernauer, T. and Huss, M. (2021), "Improved on-farm storage reduces seasonal food insecurity of smallholder farmer households: evidence from a randomized control trial in Tanzania", <i>Food Policy</i> , Vol. 98, 101891, doi: 10.1016/j.foodpol.2020.101891. | Tanzania (Kilosa & Kondoa) | Maize households      | Storage and food access             | Provision of hermetic storage bags with training   | Matched-pair cluster RCT; quarterly SMS rCSI surveys over 15 months                                                               | Severe food insecurity reduced by 38% in the lean season and by 20% over the full seasonal cycle; probability of reporting any post-harvest loss reduced by 11.1 percentage points; self-reported loss share reduced by 5.1 points | Control clusters without bags                                                                         | Food Policy    | 2021 |
| 17. | Brockelt, J., Dammann, R., Griesse, J., Weiss, A., Fischer, M. and Creydt, M. (2025), "Storage profiling: evaluating the effect of modified atmosphere packaging on metabolomic changes of strawberries", <i>Metabolites</i> , Vol. 15, 330, doi: 10.3390/metabo15030330.    | Germany                    | Strawberries          | Storage (passive MAP vs open trays) | Passive MAP film; multi-omics + NIR + microbiology | 99 samples; FT-NIR, LC-ESI-IM-qTOF-MS, viable counts and water loss over 10 d at 4 °C; regression model for shelf-life prediction | MAP slowed aerobic and yeast/mould growth and halved water loss (~2.27% vs ~6.52% at day 10); NIR-based model estimated $\approx 5 \pm 2$ days shelf-life gain vs control. De Bruno                                                | Open-tray control at same temperature; cross-day comparisons of counts, water loss, spectra. De Bruno | Metabolites    | 2025 |
| 18. | Broeze, J., Guo, X. and Axmann, H.                                                                                                                                                                                                                                           | Multiple (Kenya,           | Multiple (milk, beef, | Production, processing,             | Scenario analyses                                  | Generic LCA-lite tool with default                                                                                                | Most FLW-reducing                                                                                                                                                                                                                  | Baseline chains vs intervention                                                                       | Sustainability | 2023 |

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|     | (2023), "Trade-off analyses of food loss and waste reduction and greenhouse gas emissions in food supply chains", <i>Sustainability</i> , Vol. 15 No. 11, 8531, doi: 10.3390/su15118531.                                                                                                        | Netherlands, Honduras–UK, India, Vietnam–EU) | cut veg, melons, tomatoes, dragon fruit) | storage, transport, retail (case dependent) | with ACE GHG calculator for FLW-reduction options (cooling, temperature set-points, MAP, variety choice, supply chain redesign) | loss and emission factors; case studies quantify net GHG per kg food sold under baseline vs intervention scenarios.                                    | interventions lowered total GHG per unit sold (e.g., milk cooling in Kenya, melon MAP); some did not (e.g., lowering temperature for cut vegetables increased energy-related GHG more than FLW-GHG saved).                                  | scenarios for each case.                                           |                                  |      |
| 19. | Butkevičiūtė, A., Viškelis, J., Liaudanskas, M., Viškelis, P. and Janulis, V. (2022), "Impact of storage controlled atmosphere on the apple phenolic acids, flavonoids, and anthocyanins and antioxidant activity <i>in vitro</i> ", <i>Plants</i> , Vol. 11, 201, doi: 10.3390/plants11020201. | Lithuania (multi-cultivar)                   | Apples                                   | Controlled-atmosphere storage               | CA variants (low O <sub>2</sub> /high CO <sub>2</sub> ) over 8 months; phenolics and DPPH                                       | Ten cultivars stored in eight CA variants; HPLC quantification of phenolics; in-vitro antioxidant assays; before-versus-after comparison. Butkeviciute | Chlorogenic acid and several flavan-3-ols/flavonols increased under specific CA variants; antioxidant activity trends cultivar- and variant-dependent (e.g., 'Auksis' chlorogenic acid to 2265.7 µg/g in one variant; Fig. 1). Butkeviciute | Pre-storage baseline and across CA variants (I–VIII). Butkeviciute | Plants                           | 2022 |
| 20. | Channa, H., Ricker-Gilbert, J., Feleke, S. and Abdoulaye, T. (2022), "Overcoming                                                                                                                                                                                                                | Tanzania, Mbeya Region                       | Maize                                    | Storage; finance at harvest                 | Provision of two 100 kg hermetic bags;                                                                                          | RCT with three arms at VICOPA cluster level, baseline and endline surveys;                                                                             | Credit offer increased maize inventory by 223 kg and net sales by 233 kg;                                                                                                                                                                   | Control clusters; within-study pre-intervention values             | Journal of Development Economics | 2022 |

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|     | smallholder farmers' post-harvest constraints through harvest loans and storage technology: insights from a randomized controlled trial in Tanzania", <i>Journal of Development Economics</i> , Vol. 157, 102851, doi: 10.1016/j.jdeveco.2022.102851.                                                          |                                               |                                              |                                                    | harvest loan collateralised by maize                                               | n≈1,238 at endline; ANCOVA and quarter-wise analyses                                                                           | storage-only arm effects smaller and not significant; loan uptake 81%                                                                                                   |                                                                                                                                       |                                             |      |
| 21. | Chaomuang, N., Laguerre, O., Supapvanich, S., Flick, D. and Duret, S. (2024), "Evaporative cooling with a wet fabric blanket for non-refrigerated horticultural produce transport: an experimental study", <i>Journal of Agriculture and Food Research</i> , Vol. 18, 101339, doi: 10.1016/j.jafr.2024.101339. | Thailand (tropical test room)                 | Vegetables (model loads; lettuce case study) | Transport/storage (non-refrigerated cargo chamber) | Passive evaporative cooling using a water-sodden acrylic felt blanket over pallets | Full-scale cargo mock-up with axial-fan airflow; air/load temperatures and RH logged; lettuce mass-loss and defects after 20 h | Air temp reduced by ~3–4 °C (towards WBT ≈25.5 °C); RH near 100% above loads; lettuce mass loss <6% inside cargo vs 8–10% outside; simple model errors ≤1.2%. Chaomuang | Compared positions/air velocities; lettuce inside cargo vs outside; shade/charcoal cooler used as benchmarks in discussion. Chaomuang | Journal of Agriculture and Food Research    | 2024 |
| 22. | Chen, S.-P. and Chen, C.-Y. (2021), "Dynamic markdown decisions based on a quality loss function in on-site                                                                                                                                                                                                    | Taiwan (context for retailers); generalizable | Perishable foods (general)                   | Retail (pricing/markdown); supply coordination     | Analytical policy design: dynamic markdown with quality-                           | Analytical model with propositions; numerical studies; explicit comparison to                                                  | Optimal markdown timing, profit function properties; sensitivity to markdown rate                                                                                       | "No-promotion" scenario within the same model; no empirical baseline                                                                  | Journal of the Operational Research Society | 2021 |

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|     | direct-sale supply chains for perishable food”, <i>Journal of the Operational Research Society</i> , Vol. 72 No. 4, pp. 822–836, doi: 10.1080/01605682.2019.1700814.                                                                                                                       |                                                  |                                  |                                              | loss function                                                                        | no-promotion case                                                                                                                                                               | and processing costs; comparison with no-promotion profits                                                                                                                                                      |                                                            |                                       |      |
| 23. | Ciliberti, S., Frascarelli, A. and Martino, G. (2023), “Matching ecological transition and food security in the cereal sector: the role of farmers’ preferences on production contracts”, <i>Frontiers in Sustainable Food Systems</i> , Vol. 7, 1114590, doi: 10.3389/fsufs.2023.1114590. | Italy                                            | Durum wheat                      | Production contracting and on-farm practices | Governance design of production contracts and clauses                                | Discrete choice experiment with 163 producers; mixed logit; six attributes across pricing, payment timing, techniques, quality thresholds, sustainability, technical assistance | Strong preference for guaranteed minimum price; aversion to techniques imposed unilaterally; positive valuation of technical assistance and decision-support; weak preference for costly sustainability clauses | Not applicable; preference space, not a causal trial       | Frontiers in Sustainable Food Systems | 2023 |
| 24. | Davalo, K.M., Yuba, A.N. and Pinto, J.O.P. (2023), “Implementation and performance evaluation of a community-scale adobe evaporative cooling chamber for vegetable preservation”,                                                                                                          | Brazil (prototype intended for hot-dry contexts) | Vegetables (storage environment) | Storage facility (zero-energy cooling)       | Community-scale evaporative cooler using stabilised adobe double walls with wet sand | 1:1 prototype build; instrumented performance tests under varying watering regimes                                                                                              | Internal temperature reduction up to 13.24 °C; high internal RH; saturation efficiency reported; build cost ≈ US\$292 for 8 m <sup>3</sup> chamber; feasible for                                                | Ambient conditions as comparator; no produce-quality trial | Buildings                             | 2023 |



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|     | <i>Buildings</i> , Vol. 13 No. 6, 1401, doi: 10.3390/buildings13061401.                                                                                                                                                                                                                    |                             |                      |                                                                |                                                                                                    |                                                                                                                      | remote communities (see methods and Figures 3–5)                                                                                                                                             |                                                                                                           |                               |      |
| 25. | De Bruno, A., Gattuso, A., Ritorto, D., Piscopo, A. and Poiana, M. (2023), “Effect of edible coating enriched with natural antioxidant extract and bergamot essential oil on the shelf life of strawberries”, <i>Foods</i> , Vol. 12, 488, doi: 10.3390/foods12030488.                     | Italy                       | Strawberries         | Post-harvest (coatings)                                        | Edible coatings based on gum arabic + bergamot pomace extract (AE) or bergamot essential oil (BEO) | Refrigerated storage 14 d at 4 °C; 6 coating formulations + control; physicochemical, microbiology, texture, sensory | Best performers: AE 2.5% and BEO 0.1% reduced weight loss (e.g., ≈12–13% at day 14 vs ≈25% control), lowered decay (27–36% vs 100% control), maintained firmness and acceptability. De Bruno | Untreated control and alternative AE/BEO concentrations; repeated measures across 1,3,7,10,14 d. De Bruno | Foods                         | 2023 |
| 26. | de Hooge, I.E., van Dulm, E. and van Trijp, H. (2018), “Cosmetic specifications in the food waste issue: supply chain considerations and practices concerning suboptimal food products”, <i>Journal of Cleaner Production</i> , Vol. 183, pp. 698–709, doi: 10.1016/j.jclepro.2018.02.226. | Germany and the Netherlands | Fruit and vegetables | Production, initial handling, processing, distribution, retail | Diagnostic study of cosmetic standards and handling of suboptimal produce                          | 33 semi-structured interviews across producers, producer organisations, and retailers; MOA framework analysis        | Reported rejection rates commonly around 20% in Germany, lower at Dutch retail; documented pathways for suboptimal flows to processing, animal feed, donation, landfill                      | Not applicable; no intervention evaluated                                                                 | Journal of Cleaner Production | 2018 |

|     |                                                                                                                                                                                                                                                                                            |                                    |                                          |                                        |                                                                                       |                                                                                                                         |                                                                                                                                                                                                                                                      |                                                   |                   |      |
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| 27. | Dong, C-D., Tsai, M-L., Nargotra, P., Kour, B., Chen, C-W., Sun, P-P. and Sharma, V. (2023), "Bioprocess development for the production of xylooligosaccharide prebiotics from agro-industrial lignocellulosic waste", <i>Heliyon</i> , Vol. 9, e18316, doi:10.1016/j.heliyon.2023.e18316. | Global                             | Biorefinery using agro-industrial wastes | Processing                             | Synthesis review and process strategies ; reports experimental yields from literature | Narrative synthesis with tables of pretreatment conditions and yields for XOS from various biomasses                    | Reported XOS yields for specific methods, for example citric-acid pretreatment 52.3% from xylan residue, xylonic-acid pretreatment 44.5% from bagasse, and 120 g XOS/kg biomass in a furoic-acid co-production scheme; no supply-chain loss outcomes | Not applicable                                    | Heliyon           | 2023 |
| 28. | Dsouza, A., Mishra, A.K. and Webster, S. (2023), "Vertical coordination and post-harvest losses: implications on food loss", <i>Applied Economic Perspectives and Policy</i> , Vol. 45 No. 1, pp. 460–486, doi:10.1002/aepp.13210.                                                         | India (Karnataka: Belgaur, Mysore) | Okra                                     | Post-harvest handling, transport, sale | Contract/governance (production contracts; marketing contracts)                       | Cross-sectional survey of 638 growers; endogenous switching regression (two ESRs by district) (see Fig. 1; Tables 1–2). | Farm profits (₹/acre); PHL (kg/acre); treatment effects (ATT/ATU)                                                                                                                                                                                    | Independent growers (counterfactual via ESR)      | AEPP (Wiley/AAEA) | 2023 |
| 29. | Eichenauer, H., Huss, M., Brander, M., Bernauer, T. and Ehlert, U. (2023), "Effects of improved on-farm crop storage on                                                                                                                                                                    | Kenya, Kakamega County             | Maize households                         | Storage                                | Hermetic storage bag programme with training; SMS-                                    | Matched-pair cluster RCT; monthly SMS PSS-4 surveys of pregnant women, n=1,591 over 11 months                           | Higher perceived coping among treated women in multiple months including May,                                                                                                                                                                        | Control clusters without the storage intervention | PLOS ONE          | 2023 |

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|     | perceived stress and perceived coping in pregnant women: evidence from a cluster-randomized controlled trial in Kenya”, <i>PLOS ONE</i> , Vol. 18 No. 7, e0288446, doi:10.1371/journal.pone.0288446.                                                            |                                                      |                             |                     | based mental-health follow-up                                         |                                                                                                                      | September and December; higher perceived stress early in the lean season with attenuation later                                                                                |                                                                                       |                                    |      |
| 30. | Fabi, C., Cachia, F., Conforti, P., English, A. and Rosero Moncayo, J. (2021), “Improving data on food losses and waste: from theory to practice”, <i>Food Policy</i> , Vol. 98, 101934, doi:10.1016/j.foodpol.2020.101934.                                     | Global, emphasizes on low- and middle-income regions | Multiple commodities        | Multiple stages     | Measurement frameworks and meta-analysis                              | Machine-learning text-mining of publications and datasets; compilation of loss estimates and methodological guidance | Median losses: fruits and vegetables around 6.4%, cereals 2.7–3.8%; higher losses in low- and middle-income regions; substantial evidence gaps identified                      | Not applicable                                                                        | Food Policy                        | 2020 |
| 31. | Fadiji, T., Coetzee, C., Chen, L., Chukwu, O. and Opara, U.L. (2016), “Susceptibility of apples to bruising inside ventilated corrugated paperboard packages during simulated transport damage”, <i>Postharvest Biology and Technology</i> , Vol. 118, pp. 111– | South Africa                                         | Apples (‘Golden Delicious’) | Transport/packaging | Simulated vibration of two ventilated corrugated designs (MK4 vs MK6) | Electrodynamic shaker: 9, 12, 15 Hz; 0.9 g; 4 h; accelerometers; bruise area/volume by tray layer. khalil            | Packaging transmissibility 100–250%; larger bruising in MK6 (lower L/H ratio); top layers most affected; 50–74% of apples bruised under tested conditions (Figs. 6–10). khalil | Cross-package and cross-frequency comparisons; no-vibration baseline not used. khalil | Postharvest Biology and Technology | 2016 |

|     |                                                                                                                                                                                                                                                                                                         |                     |                                 |                                         |                                                                                                                     |                                                                                                                     |                                                                                                                                                                                                                             |                                                                                                                     |                                   |      |
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|     | 119,<br>doi:10.1016/j.posth<br>arvbio.2016.03.010.                                                                                                                                                                                                                                                      |                     |                                 |                                         |                                                                                                                     |                                                                                                                     |                                                                                                                                                                                                                             |                                                                                                                     |                                   |      |
| 32. | Feng, L., Zhang, M., Bhandari, B. and Guo, Z. (2018), "Determination of postharvest quality of cucumbers using nuclear magnetic resonance and electronic nose combined with chemometric methods", <i>Food and Bioprocess Technology</i> , Vol. 11 No. 12, pp. 2142–2152, doi:10.1007/s11947-018-2171-9. | China (Wuxi)        | Cucumbers                       | Post-harvest storage/quality monitoring | Method development (NMR & e-nose + PLS/SVM)                                                                         | Experimental storage study (n=90 fruit across 25 days): quality measures, NMR T2, e-nose, PCA/PLS/SVM               | Decline in firmness/SSC, $\Delta E/pH$ shifts; SVM with e-nose predicted quality with $R_p^2 \approx 0.92-0.95$ and $RPD \approx 3.3-4.0$                                                                                   | Not applicable (no external comparator beyond model variants)                                                       | Food and Bioprocess Technology    | 2018 |
| 33. | Flaherty, E.J., DeEll, J.R., Shelp, B.J. and Bozzo, G.G. (2018), "1-Methylcyclopropene affects the shelf-life quality of controlled atmosphere stored 'Cold Snap' pears", <i>Canadian Journal of Plant Science</i> , Vol. 98 No. 6, pp. 1365–1375, doi:10.1139/cjps-2018-0136.                          | Canada              | Pears ('Cold Snap™')            | Storage (CA) + shelf                    | 1-MCP + CA regimens (2.5 vs 18 kPa O <sub>2</sub> ; 2 kPa CO <sub>2</sub> ) with pre-storage conditioning (0/3/7 d) | Two harvest years; 111 d at 0 °C under CA then 14 d shelf; ethylene, peel colour, firmness; disorder incidence; PCA | 1-MCP consistently reduced ethylene, peel yellowing and softening; in 2.5 kPa O <sub>2</sub> , senescent scald incidence was lower; internal breakdown/cavities responses varied by year and factor interactions. Goransson | Factorial contrasts: 1-MCP vs none; low vs high O <sub>2</sub> ; 0/3/7 d conditioning; shelf days 1/7/14. Goransson | Canadian Journal of Plant Science | 2018 |
| 34. | Galford, G.L., Peña, O., Sullivan, A.K., Nash, J.,                                                                                                                                                                                                                                                      | 12 countries across | Multiple value chains including | Production, harvesting, processing,     | Bundled development                                                                                                 | Mixed methods across 13 USAID FtF                                                                                   | Project-reported changes in food loss                                                                                                                                                                                       | Business-as-usual (pre-project) FLW                                                                                 | Science of the Total              | 2020 |

|     |                                                                                                                                                                                                                                                                                 |                                               |                                                                       |                         |                                                                                                                                                                 |                                                                                                                                                                                                                                                                                               |                                                                                                                                                                                                                                                                        |                                                                                                          |                                     |      |
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|     | Gurwick, N., Pirolli, G., Richards, M., White, J. and Wollenberg, E. (2020), "Agricultural development addresses food loss and waste while reducing greenhouse gas emissions", <i>Science of the Total Environment</i> , Vol. 699, 134318, doi:10.1016/j.scitotenv.2019.134318. | Africa, Asia, Latin America and the Caribbean | dairy, maize, rice, vegetables, fruit, legumes, coffee, sesame, wheat | storage, transportation | interventions: capacity building, improved harvesting and post-harvest practices, storage technologies including hermetic bags, cooling, logistics improvements | projects: document review, questionnaires and semi-structured interviews with implementers; project monitoring data assembled to estimate FLW and GHG pathways                                                                                                                                | percentages by commodity and stage; changes in effective yield and emission intensity using EX-ACT estimates; tabulated BAU vs with-project FLW and yields                                                                                                             | levels and yields for each value chain and project                                                       | Environment                         |      |
| 35. | García-Lara, S., García-Jaimes, E. and Ortiz-Islas, S. (2020), "Field effectiveness of improved hermetic storage technologies on maize grain quality in Central Mexico", <i>Journal of Stored Products Research</i> , Vol. 87, 101585, doi:10.1016/j.jspr.2020.101585.          | Central Mexico highlands (≈2300 m a.s.l.)     | Maize                                                                 | Storage (on-farm)       | Hermetic plastic bag (sBag) and hermetic plastic silo (Bioxilo) vs traditional woven polypropylene sack                                                         | On-farm trial with three farmers over 12 months; sampling at 0, 4, 8, 12 months; logged O <sub>2</sub> , temperature and RH; additional artificial infestation bioassay inside each storage device; multiple maize quality assays, including aflatoxin ELISA and industrial quality tests for | Under natural infestation: total damaged kernels ≈51–60% at 8–12 months in traditional sacks vs <10% in sBag and Bioxilo; aflatoxin rose from ~45 to ~85 ppb in traditional sacks; physical and nutritional traits remained stable in hermetic systems; oxygen fell to | Traditional woven polypropylene sacks under identical on-farm conditions; time-zero samples as baseline. | Journal of Stored Products Research | 2020 |

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|     |                                                                                                                                                                                                                                                                         |             |                      |                                                                |                                                                                                                                                            | tortillas and seed.                                                                                                                                       | ~3% in sBag at 4 months. Under artificial infestation at 12 months: weight loss 72.5% (traditional) vs 6.1% (sBag) and 13.8% (Bioxilo); insects 152.9 vs 19.5 and 27.7 per unit bioassay. |                                                                                           |                                    |      |
| 36. | Gautam, R., Singh, A., Karthik, K., Pandey, S., Scrimgeour, F. and Tiwari, M.K. (2017), "Traceability using RFID and its formulation for a kiwifruit supply chain", <i>Computers &amp; Industrial Engineering</i> , Vol. 103, pp. 46–58, doi:10.1016/j.cie.2016.09.007. | New Zealand | Kiwifruit            | Distribution, packing, cool-store storage, transport to export | Digital traceability and network optimisation: RFID compared to barcodes; multi-objective MOINLP solved with a new Plant Pollinator Optimisation heuristic | Modelling study using supply chain data for ~2700 growers, 71 pack-houses and 92 cool-stores; comparative scenarios with RFID vs barcodes; no field trial | Objective values: total transport cost, liability cost when contamination occurs; allocation decisions for pack-houses and cool-stores                                                    | Alternative scenario with barcodes and without RFID; no empirical before–after comparator | Computers & Industrial Engineering | 2017 |
| 37. | Ghani, L.A., Mahmood, N.Z., Ismail, R., Sa'at, S.A., Ali, N. and Mohd Zakuan, S.A. (2022), "Scenario modelling of proxy                                                                                                                                                 | Malaysia    | National food system | Production, trade, consumption, waste, wastewater              | Material Flow Analysis with scenarios                                                                                                                      | MFA integrating national statistics across five subsystems; scenario analysis with                                                                        | Quantified flows including 2,533 Mt annual food flow and 383 Mt outflow to the environment; identified                                                                                    | Not applicable                                                                            | Heliyon                            | 2022 |

|     |                                                                                                                                                                                                                                                                      |                                     |                                                     |                                  |                                                                                                                                              |                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                      |                |      |
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|     | system in the context of Malaysian food flow management”, <i>Heliyon</i> , Vol. 8, e12309, doi:10.1016/j.heliyon.2022.e12309.                                                                                                                                        |                                     |                                                     |                                  |                                                                                                                                              | uncertainty intervals                                                                                                                                                                                                                                                                                      | hotspots at waste and wastewater stages; scenario levers to reduce leakages                                                                                                                                                                                                                         |                                                                                                                                                                      |                |      |
| 38. | Gillespie, J., da Costa, T.P., Cama-Moncunill, X., Cadden, T., Condell, J., Cowderoy, T. <i>et al.</i> (2023), “Real-time anomaly detection in cold chain transportation using IoT technology”, <i>Sustainability</i> , Vol. 15 No. 3, 2255, doi:10.3390/su15032255. | Northern Ireland, UK (Belfast area) | Perishable and frozen foods in grocery distribution | Refrigerated last-mile transport | LTE-M cellular IoT logger with two temperature probes, humidity, GPS and accelerometer; trip-detection and SMS/email alerting; web dashboard | Field deployment in 3 delivery vans for 6 months: 3154 journeys, 49,839 datapoints; decision rules for alerts after 35-minute cool-down; bench battery test without trip detection for comparison. Architecture and algorithms specified, with figures and pseudo-code; cooldown plots provided. Gillespie | Intelligent alerts avoided false alarms when stationary; battery life with trip detection $\approx$ 179 days vs $\approx$ 68 days estimated without, a 62% improvement; cool-down to targets: freezer about 35 min, fridge about 5 min; system power-efficient and operable in real time. Gillespie | Same hardware without trip detection and continuous 5-minute uploads in bench test; historical manual monitoring practices discussed in literature review. Gillespie | Sustainability | 2023 |
| 39. | Gitonga, Z.M., De Groote, H., Kassie, M. and Tefera, T. (2013), “Impact of metal silos on households’ maize storage, storage losses and food security: an application of                                                                                             | Kenya (national maize zones)        | Maize                                               | Storage                          | Hermetically sealed household metal silos                                                                                                    | Household survey with PSM; 116 adopters matched to non-adopters                                                                                                                                                                                                                                            | Near-elimination of storage insect losses saving $\approx$ 150–200 kg grain; storage extended by 1.8–2.4 months; storage insecticide cost fell; period of                                                                                                                                           | Non-adopters using traditional storage (cribs, PP bags)                                                                                                              | Food Policy    | 2013 |

|     |                                                                                                                                                                                                                                                              |                          |                                        |                                              |                                                                     |                                                                                                                           |                                                                                                                                                                                      |                                             |                                |      |
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|     | propensity score matching”, <i>Food Policy</i> , Vol. 43, pp. 44–55, doi:10.1016/j.foodpol.2013.08.005.                                                                                                                                                      |                          |                                        |                                              |                                                                     |                                                                                                                           | inadequate food provision reduced by >1 month                                                                                                                                        |                                             |                                |      |
| 40. | Gomez, M. and Grady, C. (2023), “A balancing act: the interplay of food supply chain resilience and environmental sustainability in American cities”, <i>Environmental Research Letters</i> , Vol. 18 No. 12, 124022, doi:10.1088/1748-9326/ad0608.          | United States, 69 cities | Urban food consumption systems         | Supply networks and sourcing                 | Analytical framework linking footprinting with network resilience   | FAF4 commodity flows, county production data, environmental coefficients; supply-chain diversity as resilience metric     | Supply-chain resilience and environmental footprints are not inherently in conflict; identified cities with high resilience and moderate or low impacts; regional patterns by domain | Not applicable                              | Environmental Research Letters | 2023 |
| 41. | Göransson, M., Nilsson, F. and Jevinger, Å. (2018), “Temperature performance and food shelf-life accuracy in cold food supply chains: insights from multiple field studies”, <i>Food Control</i> , Vol. 86, pp. 332–341, doi:10.1016/j.foodcont.2017.10.029. | Sweden                   | Meat (smoked ham) & fish (cod)         | Distribution; retail display                 | Digital monitoring + dynamic shelf-life modelling (DPSL vs printed) | 25 field tests from production to retail; pallet-level and display-level sensors; modelled DPSL (Fig. 3–6; Tables 1,3–5). | Loss of DPSL vs SSL; hotspots by stage; effect of display design                                                                                                                     | Printed shelf life; static temp assumptions | Food Control                   | 2018 |
| 42. | Heising, J.K., Claassen, G.D.H. and Dekker, M. (2017), “Options for                                                                                                                                                                                          | Global (concept +        | Perishables with heterogeneous quality | Logistics (routing, stock, chain conditions) | Intelligent packaging with dynamic                                  | Conceptual framework; mixed-integer programming                                                                           | % waste reduction vs standard FIFO/FED;                                                                                                                                              | “Standard” fixed expiry date, single-       | Food Additives & Contaminants  | 2017 |



|     |                                                                                                                                                                                                                                                  |                 |                     |                                          |                                                                                                                                            |                                                                                                                                                          |                                                                                                                                                                                        |                                                                                      |                                    |      |
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|     | reducing food waste by quality-controlled logistics using intelligent packaging along the supply chain”, <i>Food Additives &amp; Contaminants: Part A</i> , Vol. 34 No. 10, pp. 1672–1680, doi:10.1080/19440049.2017.1315776.                    | simulations)    |                     |                                          | expiry dates (IP-DED) + QCL                                                                                                                | scenarios; three quality distributions; multi-temp routes (Figs. 4–6; Table 2).                                                                          | trade-offs with cooling costs                                                                                                                                                          | temperature transport                                                                | ants: Part A                       |      |
| 43. | Hoffmann, V. and Jones, K.M. (2021), “Improving food safety on the farm: experimental evidence from Kenya on incentives and subsidies for technology adoption”, <i>World Development</i> , Vol. 143, 105406, doi:10.1016/j.worlddev.2021.105406. | Kenya           | Maize (food safety) | Post-harvest drying and storage          | Farmer training; free plastic drying sheets; randomised access prices for mobile dryer and hermetic bags; premium for aflatoxin-safe maize | Randomised field experiment: village-level assignment to technology package and price-premium arm; adoption outcomes linked to public-health simulations | Training plus sheets most cost-effective; subsidies and price premium increased adoption; simulated reductions in aflatoxin-related disease burden; detailed adoption effects reported | Status quo practices in control villages; within-study price and incentive contrasts | World Development                  | 2021 |
| 44. | Hou, D., Wang, C., Yang, Y., Jing, S. and Chen, M. (2024), “Effects of transport vibration on storage quality and expression of genes related to cell wall metabolism of                                                                         | China (Shaanxi) | Winter jujube       | Simulated transport and subsequent shelf | Simulated vibration at 0.25 g, 0.5 g, 0.75 g (10 Hz, 40 min)                                                                               | Vibration then 12-day shelf at ~25 °C; decay, weight loss, firmness, colour, respiration; PG/PME/Cx activities; ZjPG/ZjPME/ZjC                           | Vibration accelerated decay (up to 46%), weight loss and softening (hardness –45% at 0.75 g); higher PG/PME/Cx                                                                         | No-vibration control; comparisons among accelerations. khera                         | Postharvest Biology and Technology | 2024 |

|     |                                                                                                                                                                                                                                                                                                                                                                                     |                       |                 |                                         |                                                                                                          |                                                                                                                                                                      |                                                                                                                                                                                                                  |                                                                    |                                                             |      |
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|     | winter jujube”,<br><i>Postharvest Biology and Technology</i> , Vol. 209, 112729, doi:10.1016/j.posth<br>arvbio.2023.112729<br>.                                                                                                                                                                                                                                                     |                       |                 |                                         |                                                                                                          | x expression;<br>microscopy.<br>khera                                                                                                                                | activities and<br>upregulated<br>genes;<br>microstructural<br>cracking vs<br>control (Figs. 1–<br>5; 6).<br>khera                                                                                                |                                                                    |                                                             |      |
| 45. | Isvand, A.,<br>Karimaei, S. and<br>Amini, M. (2024),<br>“Assessment of<br>chitosan coating<br>enriched with <i>Citrus<br/>limon</i> essential oil<br>on the quality<br>characteristics and<br>shelf life of beef<br>meat during cold<br>storage”,<br><i>International<br/>Journal of Food<br/>Microbiology</i> , Vol.<br>423, 110825,<br>doi:10.1016/j.ijfood<br>micro.2024.110825. | Iran                  | Beef            | Post-harvest<br>storage                 | Edible<br>coating:<br>chitosan<br>nano-<br>emulsion<br>with<br>lemon<br>essential<br>oil at 2%<br>and 4% | Lab storage at 4<br>°C for 16 days;<br>repeated<br>measures of<br>TVB-N, TBARS,<br>carbonyls,<br>microbiology,<br>sensory;<br>treatment set<br>defined in Table<br>1 | Lower TVB-N;<br>TBARS at day<br>16 $\approx$ 0.68–1.01<br>mg MDA kg <sup>-1</sup> for<br>2–4% groups;<br>reduced<br>Enterobacteriac<br>eae, LAB,<br>psychrotrophs,<br>mesophiles;<br>better sensory<br>retention | Water control;<br>chitosan without<br>oil; time-zero<br>values     | Internatio<br>nal<br>Journal of<br>Food<br>Microbiolo<br>gy | 2024 |
| 46. | Jagtap, S. and<br>Rahimifard, S.<br>(2019), “The<br>digitisation of food<br>manufacturing to<br>reduce waste: case<br>study of a ready-<br>meal factory”,<br><i>Waste<br/>Management</i> , Vol.<br>87, pp. 387–397,<br>doi:10.1016/j.wasm<br>an.2019.01.030.                                                                                                                        | United<br>Kingdo<br>m | Ready-<br>meals | Processing<br>and in-plant<br>logistics | IoT<br>waste-<br>tracking<br>system<br>with load-<br>cell<br>scales,<br>app and<br>dashboar<br>ds        | Industrial<br>before–after<br>case; 9 months<br>of real-time<br>factory data                                                                                         | Total factory<br>food waste<br>reduced by<br>60.7%; trim<br>waste reduced<br>by 89%;<br>financial saving<br>$\approx$ £306,873 vs<br>prior year                                                                  | Paper-based<br>manual logging<br>period and<br>January<br>baseline | Waste<br>Managem<br>ent                                     | 2019 |

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| 47. | Jarolmasjed, S., Zúñiga Espinoza, C., Sankaran, S. and Khot, L.R. (2016), "Postharvest bitter pit detection and progression evaluation in 'Honeycrisp' apples using computed tomography images", <i>Postharvest Biology and Technology</i> , Vol. 118, pp. 35–42, doi:10.1016/j.postharvbio.2016.03.007. | USA (Washington State)     | Apples ('Honeycrisp')             | Post-harvest inspection/sorting; storage   | Method development (X-ray CT imaging + image analysis) | Two field sites; 40 H/40 BP apples; storage 63 d; pit-ratio metric; logistic regression classification (Figs. 3–6; Table 2). | Classification accuracy (site-1 overall 96%); pit progression; pit distribution (calyx-end dominant)                                                             | Healthy vs bitter-pit labelled fruit; site differences                                     | Postharvest Biology & Technology | 2016 |
| 48. | Jia, X., Schneider, F., Ning, M. and Ding, J. (2025), "Aesthetic grading causes food losses without financially benefiting farmers: micro-level evidence from China's fresh apple supply chain", <i>Waste Management &amp; Research</i> , Vol. 43 No. 6, pp. 957–968, doi:10.1177/0734242X241280097.     | China (Shandong & Shaanxi) | Fresh apples                      | On-farm grading; marketing to supermarkets | Governance/standards (aesthetic grading vs size-only)  | Cross-sectional farm and transaction survey; n=351 farms; OLS and fixed-effects regressions                                  | Mean on-farm post-harvest loss due to aesthetic grading ≈17.1% of harvest; aesthetic grading reduces farm-gate price; regional and chain-type effects quantified | Within-study contrasts: aesthetic+size vs size-only; direct vs indirect supermarket supply | Waste Management & Research      | 2025 |
| 49. | Jiang, S., Chen, H., Shan, P. and Wang, X. (2024), "Efficacy of                                                                                                                                                                                                                                          | China (Quzhou)             | Food service (hotpot restaurants) | Consumption (restaurant)                   | Behavioural information                                | 11-week RCT; N=1303 diners; direct weighing; PSM analyses;                                                                   | Change in total plate waste; category-specific waste;                                                                                                            | Baseline 5-week no-info control; within-study no-                                          | Journal of Cleaner Production    | 2024 |

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|     | informational intervention on food waste: evidence from a randomized controlled trial”, <i>Journal of Cleaner Production</i> , Vol. 443, 141106, doi:10.1016/j.jclepro.2024.141106.                                                                                          | Zhejiang )                     |                                    |                                                  | prompts (instructional, guilt-based, coupled)                           | multi-phase intervention (see poster examples on page 3).                                                                      | spillover to ordering; subgroup effects                                                                                                                                                      | intervention phase                                                      |                               |      |
| 50. | Kariuki, I.M. and Loy, J.-P. (2016), “Contractual farming arrangements, quality control, incentives, and distribution failure in Kenya’s smallholder horticulture: a multivariate probit analysis”, <i>Agribusiness</i> , Vol. 32 No. 4, pp. 547–562, doi:10.1002/agr.21462. | Kenya (Mwea Tebere, Kirinyaga) | French beans (export horticulture) | Production/quality control; collection/logistics | Contracting, certification/audits, forward price, collection governance | Farmer survey n=249; multivariate probit with marginal success probabilities                                                   | Signs and significance of drivers for written contracts, audits, rejections, price expectation at planting, uncollected produce; e.g., farm size, extension, producer groups, seller density | No experimental counterfactual; model-based contrasts across covariates | Agribusiness                  | 2016 |
| 51. | Kessler, S.J., Cooksey, K., Pometto III, A.L., Hurley, A. and Bridges, W. (2023), “Shelf-life extension of fresh strawberries packaged in vented clamshells through an in-package widget designed to                                                                         | USA                            | Strawberries                       | Post-harvest packaging and distribution          | ClO <sub>2</sub> sachet vs sachet in gas-distribution widget            | Storage at 4 °C to 21 days; temperature-abuse factors 30 °C for 2 h on day 0 and/or 6; quality, colour, weight loss, volatiles | Lower visible mould; better firmness; widget mitigated localised bleaching seen with sachet alone; weight-loss effect depended on abuse scenario                                             | Untreated control and sachet-only; abuse vs no-abuse                    | ACS Food Science & Technology | 2023 |

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|     | promote chlorine dioxide gas distribution”, <i>ACS Food Science &amp; Technology</i> , Vol. 3 No. 3, pp. 394–403, doi: 10.1021/acsfoodsci tech.2c00225.                                                                                                                                                                                 |                                     |                                            |                          |                                                                  |                                                                                                                                                                              |                                                                                                                                                                                                                                     |                                                                                   |                          |      |
| 52. | Khalil, U., Rajwana, I.A., Razzaq, K., Singh, S., Sarkhosh, A. and Brecht, J.K. (2024), “Evaluation of modified atmosphere packaging system developed through breathable technology to extend postharvest life of fresh muscadine berries”, <i>Food Science &amp; Nutrition</i> , Vol. 12 No. 5, pp. 3663–3673, doi: 10.1002/fsn3.4037. | USA (Florida; Georgia fruit source) | Muscadine grapes (‘Granny Val’, ‘Supreme’) | Packaging/storage (4 °C) | Active MAP using BreatheWay® patch (target ~6% CO <sub>2</sub> ) | Clamshell trays sealed with impermeable film; patch over 4-mm hole; 42-day storage; headspace gases, firmness, decay, colour, TSS/TA, antioxidants, phenolics, anthocyanins. | MAP maintained ~4–6% CO <sub>2</sub> and reduced O <sub>2</sub> to ~10–15%; significantly reduced decay and better firmness retention up to 28 days; minimal effects on TSS; cultivar-specific colour effects (Figs. 1–6; Table 1). | Control packages with identical hole but no breathable patch (air exchange only). | Food Science & Nutrition | 2024 |
| 53. | Khera, K., Büchele, F., Wood, R.M., Thewes, F.R., Wagner, R., Hagemann, M.H. and Neuwald, D.A. (2024), “Impact of different storage conditions with combined use of ethylene blocker on                                                                                                                                                 | Germany (Lake Constance)            | Apples (‘Shalimar’)                        | Cold storage and shelf   | RA, CA (1 or 3 °C), and DCA-CD (~2.5 °C) ± 1-MCP                 | 7 months storage + 7-day shelf; firmness, TA, TSS, colour; respiration and ethylene; GC-MS VOCs; PCA.                                                                        | CA and DCA maintained firmness/TA and suppressed ethylene/respiration vs RA; DCA without 1-MCP better preserved fruity esters; CA at 1 °C efficient long-term                                                                       | RA at 1 and 3 °C; ±1-MCP comparators.                                             | Scientific Reports       | 2024 |

|     |                                                                                                                                                                                                                                                                                                                                                                                                    |                                                         |                      |                                            |                                                                                       |                                                                                                                        |                                                                                                                                                                    |                                                                                                         |                                          |      |
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|     | 'Shalimar' apple variety", <i>Scientific Reports</i> , Vol. 14, 8485, doi: 10.1038/s41598-024-57688-6.                                                                                                                                                                                                                                                                                             |                                                         |                      |                                            |                                                                                       |                                                                                                                        | storage; 1-MCP further enhanced firmness but reduced volatiles (Figs. 2–5).                                                                                        |                                                                                                         |                                          |      |
| 54. | Klein, B., Ribeiro, Q.M., Thewes, F.R., Wagner, R., de Oliveira, S.J., Neuwald, D.A. and Brackmann, A. (2021), "The isolated or combined effects of dynamic controlled atmosphere and 1-MCP on the chemical composition of cuticular wax and metabolism of 'Maxi Gala' apples after long-term storage", <i>Food Research International</i> , Vol. 140, 109900, doi: 10.1016/j.foodres.2020.109900. | Brazil                                                  | Apples ('Maxi Gala') | Storage (CA, DCA-CF, DCA-RQ)               | Low O <sub>2</sub> regimes with and without 1-MCP                                     | Nine-month storage at 2 °C plus 7 days shelf; wax profiling; ethylene and respiration; multivariate analysis           | DCA reduced metabolism; 1-MCP further lowered ethylene; total wax not changed; 1-MCP in DCA increased mass loss; treatment differences detailed in Table 3 and PCA | Internal comparisons across storage atmospheres and 1-MCP                                               | Food Research International              | 2021 |
| 55. | La Scalia, G., Settanni, L., Micale, R. and Enea, M. (2016), "Predictive shelf-life model based on RF technology for improving the management of                                                                                                                                                                                                                                                   | Italy (University of Palermo ; refrigerated cell tests) | Strawberries         | Logistics and transport quality monitoring | Smart Logistic Unit with sensors for VOCs, temperature, RH and CO <sub>2</sub> ; VOC- | Validation of the VOC sensor against GC/MS during 8 days at ambient conditions; simulated transport: vibration at 9 Hz | VOC trends tracked GC/MS; shelf-life computed from VOCs had small errors versus the microbiological model: at t <sub>0</sub>                                       | Microbiological shelf-life model and measured bacterial counts; sensor vs GC/MS for VOC quantification. | International Journal of RF Technologies | 2016 |

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|     | food supply chain: a case study”, <i>International Journal of RF Technologies</i> , Vol. 7 No. 1, pp. 31–42, doi: 10.3233/RFT-150073.                                                                                                                           |         |                  |                          | based shelf-life model; RF/3G data pipeline                                              | for 48 h at 4 °C; derived linear primary model and VOC-based shelf-life estimator; comparison to microbiological shelf-life model. | error $\approx$ 1.68–8.89%, at $t^*$ error $\approx$ 4.23–6.44% across tests; framework provides real-time residual shelf-life estimates for operational decisions.                               |                                                        |                                             |      |
| 56. | Leavens, L., Bauchet, J. and Ricker-Gilbert, J. (2021), “After the project is over: measuring longer-term impacts of a food safety intervention in Senegal”, <i>World Development</i> , Vol. 141, 105414, doi: 10.1016/j.worlddev.2021.105414.                  | Senegal | Maize households | Harvest, drying, storage | Previous RCT bundle: training, moisture meter, tarp, hermetic bag; longer-term follow-up | Follow-up of $\approx$ 2,000 households two years post-intervention; aflatoxin tests and surveys                                   | Training+hygro meter+tarp reduced probability of aflatoxin >20 ppb by $\sim$ 7 percentage points; tarp was the key marginal driver; hermetic not significant two years later due to access issues | Control villages from original RCT; intention-to-treat | World Development                           | 2021 |
| 57. | Lee, Y.-C., Wei, Z.-W., Yu, M.-C., Tsay, J.-S., Hsu, M.-C., Huang, P.-H. and Liang, Y.-S. (2024), “Effects of delayed precooling on the postharvest quality and anthracnose incidence of ‘Irwin’ mangoes”, <i>Journal of Food Processing and Preservation</i> , | Taiwan  | Mango (‘Irwin’)  | Field-to-cool chain      | Forced-air precooling at 3, 6, 12, 24 h postharvest; storage at 5 °C                     | Experimental storage 30 days at 5 °C plus 3 days at 20 °C; anthracnose, respiration, ethylene, firmness, TSS, TA, over-ripening    | Precooling within 3–6 h cut anthracnose and over-ripening, reduced respiration and weight loss, maintained firmness vs 12–24 h delay                                                              | Between-group delays as comparators                    | Journal of Food Processing and Preservation | 2024 |

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|     | Vol. 2024, Article 4004963, doi: 10.1155/2024/4004963.                                                                                                                                                                                                                                              |                                                      |                       |                                              |                                                                                                                         |                                                                                             |                                                                                                                                                                                                                                    |                                                                           |                                                    |      |
| 58. | Likhayo, P., Bruce, A.Y., Tefera, T. and Mueke, J. (2018), "Maize grain stored in hermetic bags: effect of moisture and pest infestation on grain quality", <i>Journal of Food Quality</i> , Vol. 2018, Article 2515698, doi: 10.1155/2018/2515698.                                                 | Kenya (barn storage, 180 days)                       | Maize                 | Storage                                      | Technology comparison: hermetic bags vs open-weave polypropylene bags at 12–18% initial moisture with <i>S. zeamais</i> | Experimental storage study, 180 days; periodic gas, insect, damage and weight measurements  | Weight loss 1.2% (hermetic) vs 35.8% (polypropylene) at 12% MC; insect densities up to 1273 adults kg <sup>-1</sup> in PP vs 7 kg <sup>-1</sup> in hermetic at 18% MC; lower O <sub>2</sub> and higher CO <sub>2</sub> in hermetic | Conventional woven bags as control; time-0 condition as baseline          | Journal of Food Quality                            | 2018 |
| 59. | Lin, Y.-C., Chen, S.-H., Lin, S.-B. and Chen, H.-H. (2025), "Field verification of food quality monitoring in the cold chain by using a laccase time–temperature indicator label", <i>International Journal of Food Science &amp; Technology</i> , Vol. 60 No. 1, vvae053, doi: 10.1111/ijfs.16945. | Taiwan (field logistics via DC to retail simulation) | Fresh-cut cucumber    | Cold-chain logistics; retail display         | Enzymatic laccase time–temperature indicator label (LTTIL) affixed to packs                                             | Field verification study: microbial TPC vs TTI colour change under temperature fluctuations | Critical point of TTI colouration at ~132.8 h vs microbiological deterioration ~139.2 h; prediction error ≈ 4.6% (Ea and k calibrated isothermally)                                                                                | Microbiological threshold (TPC 6 log CFU/g) used as ground truth baseline | International Journal of Food Science & Technology | 2025 |
| 60. | Loisel, J., Cornuéjols, A., Laguerre, O., Tardet, M.,                                                                                                                                                                                                                                               | France (lab pallet set-up)                           | Apples (pallet-level) | Cold-chain monitoring (distribution/storage) | Digital/AI monitoring (NN models;                                                                                       | 10 inlet-air scenarios × 16 pallet zones; experimental vs                                   | RMSE of core-temperature prediction; best with sensor at                                                                                                                                                                           | Explicit comparisons: sensor position;                                    | Journal of Food Engineering                        | 2022 |



|     |                                                                                                                                                                                                                                                                                                        |                                                                                      |                    |                                     |                                                                                                                                                                |                                                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                                            |                                                                                                                                          |                              |      |
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|     | Cagnon, D., Duchesne de Lamotte, O. and Duret, S. (2022), "Machine learning for temperature prediction in food pallet along a cold chain: comparison between synthetic and experimental training dataset", <i>Journal of Food Engineering</i> , Vol. 335, 111156, doi: 10.1016/j.jfoodeng.2022.111156. |                                                                                      |                    |                                     | sensor placement)                                                                                                                                              | synthetic training; LOO cross-validation                                                                                                                                                                                       | back; experimental data improves performance by ~20–40% vs synthetic; synthetic alone can overestimate by up to 150%                                                                                                                                                                                       | training set type; added scenarios                                                                                                       |                              |      |
| 61. | Mack, M., Dittmer, P., Veigt, M., Kus, M., Nehmiz, U. and Kreyenschmidt, J. (2014), "Quality tracing in meat supply chains", <i>Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences</i> , Vol. 372 No. 2017, 20130308, doi: 10.1098/rsta.2013.0308.     | Ireland to Germany cross-docking network (field trial); model development in Germany | Vacuum-packed lamb | Cold-chain distribution and storage | Temperature-based quality control model using a sensory quality index with Arrhenius temperature dependence; wireless sensor network and decision-support tool | Three-step study: develop sensory-based QI model at 2, 7, 15, 20 °C; derive Arrhenius parameters; process analysis of LTL cross-docking; implement model in hardware and software; field test of sensor network and data flow. | Predicted use-by at 2 °C ≈ 696 h with QI limit 4.0; quality decay accelerates with temperature; scenario analysis shows shelf-life reduction ≈168 h under optimal handling by retailer stage vs ≈292 h under abusive temperatures; field trial demonstrated real-time data transfer and practicability for | Comparison of optimal versus abusive temperature histories across logistics stages; practice-as-usual monitoring as contextual baseline. | Philosophical Transactions A | 2014 |

|     |                                                                                                                                                                                                                                                                                                |                            |                                                  |                                                                  |                                                                                               |                                                                                                                                                     |                                                                                                                                                                                                                                                                                                     |                                                                                           |                               |      |
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|     |                                                                                                                                                                                                                                                                                                |                            |                                                  |                                                                  |                                                                                               |                                                                                                                                                     | quality-driven routing.                                                                                                                                                                                                                                                                             |                                                                                           |                               |      |
| 62. | Manouchehri, F., Nookabadi, A.S. and Kadivar, M. (2020), "Production routing in perishable and quality degradable supply chains", <i>Heliyon</i> , Vol. 6 No. 2, e03376, doi: 10.1016/j.heliyon.2020.e03376.                                                                                   | Iran (case: chicken chain) | Poultry (chicken meat, parts)                    | Production, inventory, storage-temperature, distribution routing | Integrated PRP with quality decay; hybrid VNS+SA heuristic                                    | Mixed-integer model; 18 test instances vs CPLEX; industrial case                                                                                    | Cost objective; average gap ~0.52% vs CPLEX on small/medium sets; case: total 5-period cost 128,959,370 Rials; optimal temperatures, routes and inventories                                                                                                                                         | Comparisons: heuristic vs CPLEX; pre- vs post-optimization routes/temps                   | Heliyon                       | 2020 |
| 63. | May, N. and Guenther, E. (2020), "Shared benefit by material flow cost accounting in the food supply chain: the case of berry pomace as upcycled by-product of a black currant juice production", <i>Journal of Cleaner Production</i> , Vol. 245, 118946, doi: 10.1016/j.jclepro.2019.118946. | Germany                    | Black-currant juice processing; pomace upcycling | Processing; end-of-life scenarios                                | MFCA combined with carbon footprinting; scenario analysis of pomace upcycling vs incineration | MFCA model for one season of production (~520k 1-L bottles), with cost matrix (Table 5) and GWP matrix (Table 6); scenario and uncertainty analyses | Baseline total GWP ≈ 64,156 kg CO <sub>2</sub> -eq (~0.12 kg CO <sub>2</sub> -eq/L). Upcycling scenarios substantially cut net GWP (Alternative I ≈ 25,830 kg; Alternative II negative due to credits). Economic profits lower than baseline due to added investment/energy for cooling and drying. | Baseline: incineration of pomace; scenarios: upcycling to powder (and with apple pomace). | Journal of Cleaner Production | 2020 |
| 64. | Messner, R., Johnson, H. and Richards, C. (2021), "From surplus-to-waste: a                                                                                                                                                                                                                    | Australia                  | Horticulture (fruit & vegetables)                | Production; harvesting; handling; storage; selling               | Diagnostic/qualitative systems analysis                                                       | 29 semi-structured, face-to-face interviews across the                                                                                              | Identified "surplus-to-waste lock-ins" and four themes;                                                                                                                                                                                                                                             | Not applicable (no trial; no before-after)                                                | Journal of Cleaner Production | 2021 |

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|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|------------------|------------------------------------|----------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|---------------------------|------|
|     | study of systemic overproduction, surplus and food waste in horticultural supply chains”, <i>Journal of Cleaner Production</i> , Vol. 278, 123952, doi: 10.1016/j.jclepro.2020.123952.                                                                   |                   |                  | (producer–retailer interface)      | of “lock-ins” (no tested intervention)                                                                         | Australian horticulture chain; thematic analysis                                                             | provides recommendations; no quantitative loss reductions                                                                                    |                                                             |                           |      |
| 65. | Mlambo, S., Mvumi, B.M., Stathers, T. and Mubayiwa, M. (2017), “Field efficacy of hermetic and other maize grain storage options under smallholder farmer management”, <i>Crop Protection</i> , Vol. 98, pp. 198–210, doi: 10.1016/j.cropro.2017.04.001. | Zimbabwe (Hwedza) | Maize            | Storage                            | Hermetic options (PICS, GrainPro SGB, metal silos) vs pesticide dusts, botanicals, ZeroFly and farmer practice | Two on-farm seasons, randomised blocks, 8–40 weeks; insect counts, damage, weight loss, moisture             | Hermetic options consistently kept insect damage and weight loss far lower than controls; efficacy drops when hermetic liners are perforated | Woven polypropylene bags ± local dusts; botanicals; ZeroFly | Crop Protection           | 2017 |
| 66. | Moradi, M., Shabanali Fami, H., Barati, A.A., Schneider, F., Salehi Mohammadi, R. and Aramyan, L. (2025), “Leveraging contract farming to reduce leafy vegetable waste: a system dynamics approach from Kermanshah province of Iran”,                    | Iran (Kermanshah) | Leafy vegetables | Production, marketing, consumption | Contract farming scenarios as market-based coordination                                                        | System dynamics model calibrated with surveys of 728 actors and 60 specialists; scenario simulations to 2072 | Baseline waste ≈39% of demand; contract-farming scenario reduces total waste to about 16,000 t per year in model runs                        | Business-as-usual simulated baseline                        | Cogent Food & Agriculture | 2025 |

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|     | <i>Cogent Food &amp; Agriculture</i> , Vol. 11 No. 1, 2443270, doi: 10.1080/23311932.2024.2443270.                                                                                                                                                                                        |                            |            |                                                    |                                                                                                         |                                                                                                           |                                                                                                                                                                                                                                           |                                                                                                                                                           |                                                |      |
| 67. | Mubayiwa, M., Mvumi, B.M., Stathers, T. and Nyabako, T. (2021), "Field evaluation of hermetic and synthetic pesticide-based technologies in smallholder sorghum grain storage in hot and arid climates", <i>Scientific Reports</i> , Vol. 11, 3692, doi: 10.1038/s41598-021-83086-3.      | Zimbabwe (Mbire; hot arid) | Sorghum    | Storage                                            | Hermetic containers (PICS, GrainPro SGB, metal silos) vs Shumba Super dust, Actellic Gold dust, ZeroFly | Two seasons; 32-week storage; randomised blocks; insect damage, weight loss, insect populations, moisture | Hermetic kept weight loss below ~3% and damage low over 32 weeks; pesticide treatments performed less well, particularly later in storage                                                                                                 | Untreated woven bag controls and pesticide treatments                                                                                                     | Scientific Reports                             | 2021 |
| 68. | Ndambi, O.A., Kilelu, C., van Knippenberg, C. and van der Lee, J. (2023), "Estimating public and private costs and benefits of implementing a milk quality assurance system in Kenya: a case study", <i>NJAS: Impact in Agricultural and Life Sciences</i> , Vol. 95 No. 1, 2194258, doi: | Kenya                      | Dairy milk | Farm, collection, cooperative, processor, consumer | Quality-based milk payment system (QBMPS) with testing, grading and bonuses                             | Mixed case study: interviews, FGDs; private partial budget; DALY-based public health costing              | Private: farmers' net +2.31 KES/kg at Grade A; cooperatives and processor net losses at onset due to testing and staffing; Public: avoided health costs up to 13 KES/kg if 15% of milk passes through QBMPS; disease burden ≈53,000 DALYs | Implicit baseline without QBMPS; comparisons of costs and benefits per kg for each actor; health cost reductions modelled at different coverage scenarios | NJAS: Impact in Agricultural and Life Sciences | 2023 |

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|     | 10.1080/27685241.2023.2194258.                                                                                                                                                                                                                                                                         |                           |                                |                                    |                                                         |                                                                                                                                                         | annually from milk-related infections                                                                                                                                                                |                                                                 |                                   |      |
| 69. | Ndegwa, M.K., De Groote, H., Gitonga, Z.M. and Bruce, A.Y. (2016), "Effectiveness and economics of hermetic bags for maize storage: results of a randomized controlled trial in Kenya", <i>Crop Protection</i> , Vol. 90, pp. 17–26, doi: 10.1016/j.cropro.2016.08.007.                                | Kenya                     | Maize                          | Storage                            | Technology intervention: hermetic bags (SuperGrainBag™) | RCT with 300 treatment and 300 control farmers; grain sampling at 2 and 4 months; entomological counts, damage and weight loss; economic partial budget | After 4 months: grain damage 14% (control) vs 4% (treatment); weight loss 1.7% (control) vs 0.4% (treatment). Profitability if stored $\geq 4$ months per season with bags lasting $\geq 4$ seasons. | Farmer practice using woven PP bags (with/without insecticide). | Crop Protection                   | 2016 |
| 70. | Negede, B.M., De Groote, H., Minten, B. and Voors, M. (2024), "Does access to improved grain storage technology increase farmers' welfare? Experimental evidence from maize farming in Ethiopia", <i>Journal of Agricultural Economics</i> , Vol. 75 No. 1, pp. 137–152, doi: 10.1111/1477-9552.12546. | Ethiopia (Western region) | Maize                          | Storage                            | Provision of hermetic bags (improved storage)           | Randomised controlled trial; welfare, sales timing, storage duration                                                                                    | No measurable welfare gains; access to hermetic bags increased storage period for maize intended for sale by ~2 weeks; lean-season price $\approx 36\%$ higher than post-harvest                     | Control group without access; pre-specified welfare indicators  | Journal of Agricultural Economics | 2024 |
| 71. | Negi, S. and Anand, N. (2014), "Supply chain                                                                                                                                                                                                                                                           | India                     | Fruits & vegetables (sectoral) | Whole chain (production to retail) | Critical review/diagnostic                              | Narrative review; secondary data                                                                                                                        | Reported stylized figures (e.g., 30–40%                                                                                                                                                              | Not applicable (no tested intervention)                         | Journal of Operations &           | 2014 |

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|     | efficiency: an insight from fruits and vegetables sector in India”, <i>Journal of Operations &amp; Supply Chain Management</i> , Vol. 7 No. 2, pp. 154–167, doi: 10.12660/joscmv7n2p154-167.                                                                            |                                     |       |                        | (cold chain, logistics, standards )                                             | (e.g., cold storage gaps, losses)                                                                                      | losses; cold-storage gap by state); no intervention outcomes                                                                                                       |                                                                                   | Supply Chain Management |      |
| 72. | Nepali, D.K. and Maharjan, K.L. (2025), “Assessing the impact of hermetic storage technology on storage quantity and post-harvest storage losses among smallholding maize farmers in Nepal”, <i>Agriculture</i> , Vol. 15 No. 2, 151, doi: 10.3390/agriculture15020151. | Nepal (Lumbini Province, mid-hills) | Maize | Storage                | Randomised encouragement design: up to three PICS bags with 100% vs 50% subsidy | IV (encouragement ) design; n = 692; storage quantity and PHL outcomes                                                 | 100% subsidy: +42.84 kg stored, –10 kg PHL ( $\approx$ –33%); 50% subsidy: +39.2 kg stored, no significant PHL reduction vs control                                | Non-encouraged control; within-study 100% vs 50% subsidy contrasts                | Agriculture (MDPI)      | 2025 |
| 73. | Ng’ang’a, J., Mutungi, C., Imathiu, S.M. and Affognon, H. (2016), “Low permeability triple-layer plastic bags prevent losses of maize caused by insects in rural on-farm stores”, <i>Food Security</i> , Vol. 8 No.                                                     | Eastern Kenya (Makueni County)      | Maize | Storage (on-farm bags) | Hermetic PICS triple-layer bags vs woven polypropylene and jute                 | Participatory on-farm trial, 33 farmers, 35 weeks; periodic gas, moisture, insect counts, grain damage and weight loss | PICS: weight loss below 1 percent; no live insects after baseline; PP and jute at 35 weeks: grain damage 77.6 and 82.3 percent; weight loss 41.2 and 48.5 percent; | Baseline sample; woven polypropylene and jute bags under the same farm conditions | Food Security           | 2016 |

|     |                                                                                                                                                                                                                                                                                                          |                                                     |                  |                                              |                                                                                                              |                                                                                                                                                                                     |                                                                                                                                                                                    |                                                                                                                            |                                       |      |
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|     | 3, pp. 621–633, doi: 10.1007/s12571-016-0567-9.                                                                                                                                                                                                                                                          |                                                     |                  |                                              |                                                                                                              |                                                                                                                                                                                     | PICS maintained moisture; O <sub>2</sub> fell to ≈5 percent then rose to ≈10 percent; CO <sub>2</sub> ≈10 percent stable                                                           |                                                                                                                            |                                       |      |
| 74. | Ngubane, S., Tesfay, S.Z., Magwaza, L.S. and Mditshwa, A. (2024), “The effect of composite edible coatings on the postharvest quality of ‘Hass’ avocado fruit treated at different harvest maturities”, <i>Frontiers in Sustainable Food Systems</i> , Vol. 8, 1473731, doi: 10.3389/fsufs.2024.1473731. | South Africa (post-harvest lab storage)             | Avocado (“Hass”) | Post-harvest handling (quality preservation) | Edible coatings: moringa leaf extract (8%/16%) + 5% carboxymethyl cellulose (CMC)                            | Controlled storage: 28 days at 5.5 °C then 7 days at 23 °C; weekly quality assays                                                                                                   | Coatings preserved phenolics/flavonoids/antioxidant activity; significantly reduced weight loss and firmness decline; delayed colour change and sugar depletion                    | Uncoated fruit (water-washed control)                                                                                      | Frontiers in Sustainable Food Systems | 2024 |
| 75. | Nwaubani, S.I., Otitodun, G.O., Ajao, S.K., Opit, G.P., Ala, A.A., Omobowale, M.O., <i>et al.</i> (2020), “Assessing efficacies of insect pest management methods for stored bagged maize preservation in storehouses located in Nigerian                                                                | Nigeria, market storehouses in Oyo and Kwara States | Maize            | Storage in market warehouses                 | Botanical (Piper guineense), diatomaceous earth, permethrin powder, ZeroFly deltamethrin bags, PICS hermetic | RCBD across four storehouses for 11 months; monthly sampling of six 100 kg bags per treatment (PICS destructively sampled quarterly); insect densities, % insect damaged kernels, % | Order of effectiveness: PICS > Permethrin > ZeroFly > DE > Botanical > control. Examples at December: S. zeamais per 700 g, control 18.9 vs PICS 0.2; %WL control 0.4 vs PICS 0.0; | Untreated polypropylene bags, and each alternative treatment as comparators; pre-treatment fumigation described separately | Journal of Stored Products Research   | 2020 |

|     |                                                                                                                                                                                                                                                                                |                                                            |       |                                    |                                                                     |                                                                                                                                                                |                                                                                                                                                                                                                                                                                                                                                                       |                                                                                     |                                     |      |
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|     | markets”, <i>Journal of Stored Products Research</i> , Vol. 86, 101566, doi: 10.1016/j.jspr.2019.101566.                                                                                                                                                                       |                                                            |       |                                    | bags, and untreated control                                         | weight loss, % discolouration, germination, aflatoxin                                                                                                          | psocids absent in PICS throughout; aflatoxin remained low across treatments and months measured                                                                                                                                                                                                                                                                       |                                                                                     |                                     |      |
| 76. | Nyarko, S.K., Akyereko, Y.G., Akowuah, J.O. and Wireko-Manu, F.D. (2021), “Comparative studies on grain quality and pesticide residues in maize stored in hermetic and polypropylene storage bags”, <i>Agriculture</i> , Vol. 11 No. 8, 772, doi: 10.3390/agriculture11080772. | Ghana (Ashanti Region: Ejura, Abofour, Asante-Akyem Agogo) | Maize | Storage (warehouse bags, one year) | Naturalistic comparison: hermetic bags vs traditional polypropylene | Field sampling after one year; grain quality grading; aflatoxin by lateral flow; multi-residue pesticide screening (QuEChERS; GC-ECD/PFPD; GC-MS confirmation) | Hermetic bags had significantly fewer total defective grains ( $\approx 9.6$ percent) than polypropylene ( $\approx 30.5$ percent). Aflatoxin: hermetic 0.9–2.6 ppb vs polypropylene 13.9–20 ppb. Lambda-cyhalothrin detected in all polypropylene samples above EU MRL 0.02 mg kg <sup>-1</sup> ; deltamethrin in hermetic samples below MRL 2.0 mg kg <sup>-1</sup> | Between-bag comparison across sites; no experimental counterfactual beyond bag type | Agriculture                         | 2021 |
| 77. | Odjo, S., Burgueño, J., Rivers, A. and Verhulst, N. (2020), “Hermetic storage technologies reduce maize pest                                                                                                                                                                   | Mexico (109 locations across agro-ecologic                 | Maize | Storage                            | Field comparisons: hermetic metal silos,                            | Multi-site trials under “controlled” (researcher-managed) and “non-controlled”                                                                                 | After 6 months: insect-damaged grain $\sim 39.4\%$ (PP bag) in lowlands vs 2.9–3.8% with                                                                                                                                                                                                                                                                              | Conventional polypropylene bag ( $\pm$ insecticide) practices; initial              | Journal of Stored Products Research | 2020 |



|     |                                                                                                                                                                                                                                                                                                                  |                                       |                        |                                            |                                                                                                  |                                                                                                                                                       |                                                                                                                                                                                                                      |                                                                              |                                     |      |
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|     | damage in smallholder farming systems in Mexico”, <i>Journal of Stored Products Research</i> , Vol. 88, 101664, doi: 10.1016/j.jspr.2020.101664.                                                                                                                                                                 | al zones)                             |                        |                                            | hermetic bags, recycled hermetic containers, plastic silage bags, inert dusts vs local practices | (on-farm) conditions, 1–12 months                                                                                                                     | hermetic; highlands PP $\approx 4.1\%$ vs hermetic $\approx 3.8\%$ ; recycled hermetic containers comparable to silos                                                                                                | infestation and climate recorded                                             |                                     |      |
| 78. | Odjo, S., González-Regalado, J., Saldivia Tejeda, A., Guera, M. and Verhulst, N. (2025), “Hermetic bags remain effective in minimising storage loss after four successive cycles of reuse in Mexican highlands”, <i>Journal of Stored Products Research</i> , Vol. 110, 102480, doi: 10.1016/j.jspr.2024.102480. | Mexico highlands                      | Maize and common beans | Storage                                    | Hermetic bags reused and repaired vs polypropylene and silage plastic bags                       | Four successive 3-month storage cycles; repeated measurements of holes, moisture, insect damage, weight loss                                          | Despite perforations and repair, hermetic bags kept insect damage $<5\%$ and weight loss $<2\%$ across cycles; polypropylene reached 15.6% damage in cycle 2; silage bags most perforated and replaced after cycle 2 | Conventional woven polypropylene; silage plastic bags; bag integrity tracked | Journal of Stored Products Research | 2025 |
| 79. | Omotilewa, O.J., Ricker-Gilbert, J., Ainembabazi, J.H. and Shively, G.E. (2018), “Does improved storage technology promote modern input use and food security? Evidence from a randomized trial in                                                                                                               | Uganda (national ly stratified sites) | Maize smallholders     | Storage, and subsequent production choices | Offer of one PICS hermetic bag to treated households; village demonstrations                     | Cluster RCT, $\approx 1,200$ households, baseline 2014, intervention 2015, follow-up 2016; ITT, DiD, FE; storage and planting outcomes, chemical use, | Treated households were $\approx 10$ percentage points more likely to plant improved maize; stored $\approx 3$ weeks longer for consumption and $\approx 0.6-0.7$                                                    | Control households without bags; pre-intervention values                     | Journal of Development Economics    | 2018 |

|     |                                                                                                                                                                                                                                                    |                              |                          |                                |                                                                                                |                                                                                                        |                                                                                                                                                                                                                             |                                                                    |                                     |      |
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|     | Uganda”, <i>Journal of Development Economics</i> , Vol. 135, pp. 176–198, doi: 10.1016/j.jdeveco.2018.07.006.                                                                                                                                      |                              |                          |                                |                                                                                                | self-reported losses                                                                                   | weeks longer for sale; storage chemical use reduced by $\approx 4$ percentage points; self-reported storage losses reduced by $\approx 2.2$ – $2.5$ percentage points                                                       |                                                                    |                                     |      |
| 80. | Opoku, B., Osekre, E.A., Opit, G., Bosomtwe, A. and Bingham, G.V. (2023), “Evaluation of hermetic storage bags for the preservation of yellow maize in poultry farms in Ghana”, <i>Insects</i> , Vol. 14 No. 2, 141, doi: 10.3390/insects14020141. | Ghana (Dormaa Ahenkro)       | Yellow maize for poultry | Storage                        | Hermetic bags: ZeroFly Hermetic and PICS vs polypropylene                                      | Randomised complete block design across three poultry farms; monthly destructive sampling for 6 months | Insects: PP 161 vs PICS 7 vs ZFH 4.5 per 500 g at month 6; weight loss far lower in hermetic; aflatoxin and fumonisin remained below recommended thresholds in all bags; proximate composition better preserved in hermetic | Polypropylene bags as farmer practice                              | Insects                             | 2023 |
| 81. | Pretari, A., Hoffmann, V. and Tian, L. (2019), “Post-harvest practices for aflatoxin control: Evidence from Kenya”, <i>Journal of Stored Products Research</i> , Vol. 82, pp. 31–39, doi: 10.1016/j.jspr.2019.03.001.                              | Kenya (Meru & Tharaka-Nithi) | Maize                    | Post-harvest (drying, storage) | Training + free plastic sheets; lottery for dryer and hermetic bags (free/discount/full price) | Randomised trial at village level with household follow-up sampling of stored maize                    | Aflatoxin contamination reduced by $>50\%$ overall; most of the reduction attributable to training and sheet use                                                                                                            | Control villages with basic ToT only; internal price-arm contrasts | Journal of Stored Products Research | 2019 |

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| 82. | Rao, M. and Shenoy, A. (2023), "Got (clean) milk? Organization, incentives, and management in Indian dairy cooperatives", <i>Journal of Economic Behavior &amp; Organization</i> , Vol. 212, pp. 708–722, doi: 10.1016/j.jebo.2023.06.002.                                                | India (Karnataka) | Dairy milk            | Producer–cooperative interface; cleanliness at collection and handling | Team-level financial incentives ; private vs public disclosure of payments           | Cluster RCT in 51 cooperatives; SPC and MBRT measures; difference-in-differences and ANCOVA | Cleanliness improved up to 0.64 SD in the private-information arm; SPC decreased by $\approx 0.42$ log cfu ml <sup>-1</sup> and MBRT rose $\approx 0.4$ h; one third of managers opted out when payments were public | Testing-only control; within-study private vs public disclosure         | Journal of Economic Behavior & Organization | 2023 |
| 83. | Raut, R.D., Gardas, B.B., Narwane, V.S. and Narkhede, B.E. (2019), "Improvement in the food losses in fruits and vegetable supply chain: a perspective of cold third-party logistics approach", <i>Operations Research Perspectives</i> , Vol. 6, 100119, doi: 10.1016/j.orp.2019.100119. | India             | Fruits and vegetables | Cold-chain logistics                                                   | Multi-criteria decision method to select cold-third-party logistics (CTPL) providers | Fuzzy-DEMATEL to prioritise criteria and sub-criteria; fuzzy-AHP to rank CTPLs              | Key selection drivers: 'refrigeration and loading capacity' and 'knowledge and IT management'. Study proposes CTPL selection to reduce losses; no direct before–after loss metric.                                   | Not applicable (MCDM evaluation framework).                             | Operations Research Perspectives            | 2019 |
| 84. | Rux, G., Mahajan, P.V., Geyer, M., Linke, M., Pant, A., Saengerlaub, S. and Caleb, O.J. (2015), "Application of humidity-regulating tray for                                                                                                                                              | Germany           | Button mushrooms      | Packaging humidity control                                             | NaCl-based humidity-regulating tray vs PP tray                                       | 250 g per tray; 7 °C, 85% RH for 6 days; headspace RH, water absorption, transmission and   | Humidity tray stabilised headspace at $\sim 93\%$ RH and absorbed $\sim 4.1$ g water in 6 days; improved visual quality vs                                                                                           | Control polypropylene tray under identical film and conditions. SAENGER | Postharvest Biology and Technology          | 2015 |

|     |                                                                                                                                                                                                                                                               |                         |                             |                                                                      |                                                               |                                                                                                                 |                                                                                                                                                                                                |                                                                                                                     |                                            |      |
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|     | packaging of mushrooms”, <i>Postharvest Biology and Technology</i> , Vol. 108, pp. 102–110, doi: 10.1016/j.postharvbio.2015.06.010.                                                                                                                           |                         |                             |                                                                      |                                                               | condensation; visual quality. SAENGER                                                                           | control, though condensation not fully prevented (Figs. 6–8). SAENGER                                                                                                                          |                                                                                                                     |                                            |      |
| 85. | Saenger, C., Torero, M. and Qaim, M. (2014), “Impact of third-party contract enforcement in agricultural markets: A field experiment in Vietnam”, <i>American Journal of Agricultural Economics</i> , Vol. 96 No. 4, pp. 1220–1238, doi: 10.1093/ajae/aau021. | Vietnam (HCMC region)   | Dairy (quality-graded milk) | Producer–buyer interface (governance)                                | Third-party quality verification (voucher-enabled lab checks) | Randomised field experiment: 102 treatment, 100 control; 12 months; company weekly output data + surveys. Fadji | Treated farmers increased concentrate use per cow (~+0.83 kg/day, ≈12%); total milk fat and total solids produced and dairy revenues rose (heterogeneous by collection centre; Table 2). Fadji | Original contract without third-party verification. Fadji                                                           | American Journal of Agricultural Economics | 2014 |
| 86. | Safo, N.K., Al-Hassan, R.M., Somuah, H.A., Boakye, A.A. and Egyir, I.S. (2023), “Warehouse receipt system: A shift to improve maize marketing in Ghana”, <i>Ghana Journal of Agricultural Science</i> , Vol. 58 No. 1, pp. 60–76, doi:                        | Ghana (Northern Region) | Maize                       | Storage to market access (WRS nodes: deposit, grading, sale, credit) | Participation in warehouse receipt system (WRS)               | Cross-sectional survey of 400 farmers; Endogenous Switching Regression plus PSM; determinants and ATT           | ESRM: participants sold more produce by ~3%; counterfactual shows non-participants would gain ~48% sales if they joined; PSM ATT: +11.89 bags sold and +GH¢34.39 per 110 kg bag;               | Non-participants; pre-treatment “baseline” months; internal counterfactuals (ESRM) and matched controls (PSM). Safo | Ghana Journal of Agricultural Science      | 2023 |

|     |                                                                                                                                                                                                                                                                                                                                                      |                                    |                                |                                            |                                                                                                             |                                                                                                                                                                                                              |                                                                                                                                                                                                                                                                                                                                               |                                                                            |                                    |      |
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|     | 10.4314/gjas.v58i1.6.                                                                                                                                                                                                                                                                                                                                |                                    |                                |                                            |                                                                                                             |                                                                                                                                                                                                              | participation driven by loans, output, established buyers, FBO membership. See Tables 3–5 and the seasonal price chart (Fig. 2). Safo                                                                                                                                                                                                         |                                                                            |                                    |      |
| 87. | Saidi, L., Duanis-Assaf, D., Galsarker, O., Maurer, D., Alkan, N. and Poverenov, E. (2021), "Elicitation of fruit defence response by active edible coatings embedded with phenylalanine to improve quality and storability of avocado fruit", <i>Postharvest Biology and Technology</i> , Vol. 174, 111442, doi: 10.1016/j.postharvbio.2020.111442. | Israel (lab and cold-store trials) | Avocado ('Fuerte', 'Ettinger') | Post-harvest storage, quality preservation | Chitosan or CMC+stearic-acid coatings with phenylalanine (Phe); comparisons to water control and prochloraz | Controlled storage at 22 °C and cold storage at 5 °C/2 °C; decay severity indices (SER and side rot), weight loss, firmness, respiration volatiles; sensory; qPCR of cold- and phenylpropanoid-pathway genes | Phe-coatings reduced SER and side rot vs controls; reduced pitting and chilling injury, especially chitosan+Phe at 2 °C; gene expression indicated induction of LOX/HSP/FAD and phenylpropanoid genes with Phe; sensory flavour improved vs controls. See Fig. 2 (physiology), Fig. 3 (decay panels), Fig. 4 (chilling), Fig. 6 (qPCR). Saidi | Water-dipped control and prochloraz fungicide; coatings without Phe. Saidi | Postharvest Biology and Technology | 2021 |
| 88. | Singano, C.D., Mvumi, B.M. and Stathers, T.E.                                                                                                                                                                                                                                                                                                        | Malawi (Thyolo &                   | Maize                          | Storage                                    | Comparative field trials of                                                                                 | On-farm randomised complete block                                                                                                                                                                            | Hermetic bags (PICS, SGB) consistently kept                                                                                                                                                                                                                                                                                                   | Direct comparisons among seven                                             | Journal of Stored                  | 2019 |

|     |                                                                                                                                                                                                                                                                                 |                          |                         |                                                   |                                                                                                                                                   |                                                                                                                                   |                                                                                                                                                                                                             |                                                                                                   |                              |      |
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|     | (2019), "Effectiveness of grain storage facilities and protectants in controlling stored-maize insect pests in a climate-risk prone area of Shire Valley, Southern Malawi", <i>Journal of Stored Products Research</i> , Vol. 83, pp. 130–147, doi: 10.1016/j.jspr.2019.06.001. | Chikwa wa; two seasons ) |                         |                                                   | storage technologies and protectants: PICS, Super Grain Bag, metal silo, ZeroFly bag, Actellic Super Dust, neem leaf powder, and untreated PP bag | trials over 32 weeks × two seasons; insect counts, % damaged grain, % weight loss, moisture, temperature/RH, germination. Singano | damage and weight loss very low (<~2% loss), while PP, neem and in some cases metal silo/ZeroFly showed higher damage and loss; hermetic storage led to very low germination after 40 weeks (<15%). Singano | treatments and across storage periods and sites; early vs late storage stages contrasted. Singano | Products Research            |      |
| 89. | Soethoudt, H. and Castelein, B. (2021), "Food loss-reducing intervention strategies for potato smallholders in Kenya: a positive business case with reduced greenhouse gas emissions", <i>Agronomy</i> , Vol. 11 No. 9, 1857, doi: 10.3390/agronomy11091857.                    | Kenya                    | Potatoes (smallholders) | Production; harvest; storage; transport to market | Scenario-based intervention modelling: certified/clean seed, mechanised ploughing/harvest, improved NPK, intensified crop protection              | Backward-flow calculation from marketable 1 t; yield/loss and GHG modelling for four scenarios                                    | Modelled increases in yield and reductions in losses and GHG; positive profit per tonne for improved scenarios; no field RCT                                                                                | Baseline: "standard practice" (home-saved seed, manual operations, low DAP) vs scenarios 2–4      | Agronomy                     | 2021 |
| 90. | Springael, J., Paternoster, A. and Braet, J. (2018), "Reducing postharvest losses                                                                                                                                                                                               | Belgium                  | Apples                  | Transport                                         | Algorithmic routing intervention to avoid                                                                                                         | Vibration measurements on Belgian roads; network simulations                                                                      | Profit increase per transport (e.g., ~€27 mean in one scenario) and                                                                                                                                         | Baseline: shortest-path by travel cost only                                                       | Computers and Electronics in | 2018 |

|     |                                                                                                                                                                                                                                                   |                           |                                                 |                        |                                                                                                                        |                                                                                                                  |                                                                                                                                                                                                                              |                                                                                               |                                    |      |
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|     | of apples: optimal transport routing (while minimising total costs)", <i>Computers and Electronics in Agriculture</i> , Vol. 146, pp. 136–144, doi: 10.1016/j.compag.2018.02.007.                                                                 |                           |                                                 |                        | high-vibration road segments                                                                                           | (1,000 routes) combining travel cost + vibration-induced damage                                                  | loss-rate reductions (~10.7% average reduction in the illustrated case); industry-level savings estimated €250k–€1.5m                                                                                                        |                                                                                               | Agriculture                        |      |
| 91. | Tesfaye, W. and Tirivayi, N. (2018), "The impacts of postharvest storage innovations on food security and welfare in Ethiopia", <i>Food Policy</i> , Vol. 75, pp. 52–67, doi: 10.1016/j.foodpol.2018.01.004.                                      | Ethiopia (national panel) | Food crops (cereals, pulses, roots, vegetables) | Storage (on-farm)      | Adoption of improved storage technologies (metal silos, airtight drums, improved stores)                               | Endogenous switching regression on nationally representative survey; multiple food-security and welfare outcomes | Use of improved storage increases dietary diversity, reduces child malnutrition and self-reported food insecurity; effects for non-users under counterfactual adoption estimated                                             | Non-users' counterfactual via ESR; no experimental control arm                                | Food Policy                        | 2018 |
| 92. | Thewes, F.R., Brackmann, A., Both, V., Weber, A., Anese, R.O., Ferrão, T.S. and Wagner, R. (2017), "The different impacts of dynamic controlled atmosphere and controlled atmosphere storage in the quality attributes of 'Fuji Suprema' apples", | Brazil                    | Apples (Fuji Suprema)                           | Cold storage and shelf | Dynamic controlled atmosphere monitored by chlorophyll fluorescence and by respiratory quotient (RQ 1.5; RQ 2.0) vs CA | 9-month storage at –0.5 °C plus 7-day shelf; multi-year factorial trials with 1-MCP factors                      | DCA lowered ethylene and respiration, maintained firmness; DCA-RQ 2.0 reduced decay when established immediately and delivered higher concentrations of key Fuji esters; CA stored fruit had higher butyl and hexyl acetates | Cross-regime contrasts: CA vs DCA-CF vs DCA-RQ; immediate vs delayed atmosphere establishment | Postharvest Biology and Technology | 2017 |

|     |                                                                                                                                                                                                                                                                                                                                                                               |                                    |                                                                                       |                                                                                                |                                                                                                                   |                                                                                                                                                                         |                                                                                                                                                                                                                    |                                                                                                             |                                            |      |
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|     | <i>Postharvest Biology and Technology</i> , Vol. 130, pp. 7–20, doi: 10.1016/j.postharvbio.2017.01.002.                                                                                                                                                                                                                                                                       |                                    |                                                                                       |                                                                                                |                                                                                                                   |                                                                                                                                                                         | but more quality disorders                                                                                                                                                                                         |                                                                                                             |                                            |      |
| 93. | Totobesola, M., Delve, R., Nkundimana, J.d'A., Cini, L., Gianfelici, F., Mvumi, B., Gaiani, S., Pani, A., Safa Barraza, A. and Rolle, R.S. (2022), "A holistic approach to food loss reduction in Africa: food loss analysis, integrated capacity development and policy implications", <i>Food Security</i> , Vol. 14 No. 6, pp. 1401–1415, doi: 10.1007/s12571-021-01243-y. | Burkina Faso; DRC; Uganda          | Staple grains and legumes (e.g., maize, sorghum, cowpea, rice; also sunflower, beans) | Harvesting; drying; shelling/threshing; on-farm storage; transport; wholesale storage          | FAO Food Loss Analysis with capacity development and pilot activities                                             | Country case applications of FAO FLA methodology; stakeholder training; policy process; load-tracking measurements                                                      | Indicative loss magnitudes at critical points (e.g., harvesting 3–12%, shelling 0.6–11%, on-farm storage up to 10%; aflatoxin exceedances noted). Policy outputs and pilot upscaling are documented (see Table 2). | Stage-by-stage baselines within supply chains; no randomised comparator                                     | Food Security                              | 2022 |
| 94. | Treurniet, M. (2021), "The potency of quality incentives: evidence from the Indonesian dairy value chain", <i>American Journal of Agricultural Economics</i> , Vol. 103 No. 5, pp. 1661–1678, doi:                                                                                                                                                                            | Indonesia (peri-urban cooperative) | Dairy milk                                                                            | Post-harvest aggregation and payment at milk collection points; handling and storage practices | Governance and pricing: introduction of individual quality incentives combined with MCP facility upgrades, farmer | Quasi-experimental evaluation using coarsened exact matching and synthetic controls: baseline farmer survey, panel administrative records on compositional quality, and | Compositional quality: total solids +0.410 to +0.453 percentage points ( $\approx$ 3.5–3.8% over control mean) and freezing-point violations near zero after upgrade. Hygienic quality:                            | Matched farmers at non-upgraded MCPs and pre-upgrade periods; prior group-based incentive regime. TREURNIET | American Journal of Agricultural Economics | 2021 |



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|     | 10.1111/ajae.12176                                                                                                                                                                                                                                                                                                                            |                          |                   |                                 | training, and improved testing; bonuses and penalties tied to solids and hygiene | endline individual hygienic tests (Bactoscan/TPC ). Effects estimated as ITT with matched controls; robustness checks reported. T REURNIET | TPC reduced by about 0.41 million cfu mL <sup>-1</sup> and log-TPC by 0.29–0.32; share meeting the ≤1,000,000 cfu mL <sup>-1</sup> standard increased by 0.135–0.139. Hygienic gains attenuated over time as practices decayed. T REURNIET |                                                          |                        |      |
| 95. | Vélez Rivera, N., Gómez-Sanchis, J., Chanona-Pérez, J., Carrasco, J.J., Millan-Giraldo, M., Lorente, D., Cubero, S. and Blasco, J. (2014), “Early detection of mechanical damage in mango using NIR hyperspectral images and machine learning”, <i>Biosystems Engineering</i> , Vol. 122, pp. 91–98, doi: 10.1016/j.biosystemseng.2014.03.009 | Mexico (Manila cultivar) | Mangos            | Post-harvest quality inspection | Method development for nondestructive detection (classification models)          | Hyperspectral imaging (650–1080 nm) on 10 mangos over 7 days; feature selection + k-NN/LDA/NBC/D T/ELM                                     | Pixel-level accuracy: up to 97.9% (k-NN, full spectra) on day 3; ~91.4% using selected bands; no loss reduction measured                                                                                                                   | Comparator: all wavelengths vs selected-band classifiers | Biosystems Engineering | 2014 |
| 96. | Waldhans, C., Albrecht, A., Ibal, D.                                                                                                                                                                                                                                                                                                          | Germany; pilots          | Raw pork sausage; | Transport, loading/unloading    | Photochromic                                                                     | Mixed methods: survey of 45                                                                                                                | Survey: TTIs scarcely used,                                                                                                                                                                                                                | Practice as usual: visual                                | Journal of Packaging   | 2024 |

|     |                                                                                                                                                                                                                                                                                                                                                                                                   |                                                     |                                        |                                                                                |                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                                                          |                           |      |
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|     | R., Wollenweber, D., Sy, S.-J. and Kreyenschmidt, J. (2024), "Temperature control and data exchange in food supply chains: current situation and the applicability of a digitalised system of time-temperature-indicators to optimise temperature monitoring in different cold chains", <i>Journal of Packaging Technology and Research</i> , Vol. 8, pp. 79–93, doi: 10.1007/s41783-024-00165-2. | in German supply chains                             | MA-packed fish; mixed e-commerce boxes | ding, storage, retail display, last-mile e-commerce                            | OnVu™ TTI labels with smartphone app read-out and cloud logging; status-quo survey of companies | firms across production, logistics, wholesale, retail and e-commerce; three real-chain pilots with data loggers and TTI app vs colourimeter on B2C sausage pallet flow, B2B fish boxes, and B2C e-commerce boxes; additional lab storage at set temperatures. App metrics SVRcGcBc cross-checked with colourimeter SVLAB. Figures and temperature traces reported across pages 82–90. Waldhans | controls are mostly visual or static; limited digital data exchange. Pilots: app TTI closely tracked logger temperatures on pallet and box levels; unloading interruptions detected in B2B fish; e-commerce inside-box means $\approx 2.0 \pm 1.3$ to $4.6 \pm 1.1$ °C during transport; TTI placement close to sensitive product recommended; lab tests showed stronger discolouration at 10 °C than 4 °C as expected. Waldhans | checks, vehicle recorders and best-before dates; external box labels vs internal placements; bench comparison at 4 °C vs 10 °C. Waldhans | g Technology and Research |      |
| 97. | Waldhans, C., Albrecht, A., Ibal, R., Wollenweber, D., & Kreyenschmidt, J. 2024. Implementation of an app-based Time-Temperature-                                                                                                                                                                                                                                                                 | German y (pilot in a German raw pork sausage chain) | Meat, raw pork sausage                 | Processing, transport, transshipment, storage at consumer-simulated conditions | App-based digital read-out of OnVu™ TTI integrated with                                         | Two parts: (i) laboratory development of kinetic shelf-life model for MA-packed raw pork sausages at 2, 4, 7, 10, 15 °C plus two                                                                                                                                                                                                                                                               | Agreement of app-predicted vs measured TTI colour in pilot: Bf 1.00–1.01, Af 1.02–1.03, R <sup>2</sup> 0.93–0.99; laboratory dynamic TTI                                                                                                                                                                                                                                                                                         | Cross-validation against laboratory microbiology and sensory shelf-life, and against reference colorimeter                               | Food Control              | 2025 |

|  |                                                                                                                            |  |  |  |                                 |                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                                                                                                           |  |  |
|--|----------------------------------------------------------------------------------------------------------------------------|--|--|--|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|--|--|
|  | Indicator system for the real-time shelf-life prediction in a pork sausage supply chain. <i>Food Control</i> , 168, 110935 |  |  |  | predictive shelf-life modelling | dynamic scenarios; identification of LAB as SSO; development and laboratory validation of a dynamic TTI model; (ii) pilot study with 384 TTI-tagged packs charged at 1500 ms, transported on a real route, then stored at 2, 4, 7, 10 °C; app and colorimeter colour measurements, microbial counts (TVC, LAB) and sensory scoring collected at defined points. | validation: Bf 1.00–1.02, Af 1.02–1.03, observed TTI shelf-life 98–140 h vs predicted 69–109 h depending on charging time; laboratory dynamic product model bias/accuracy: Bf 0.95 (S1) and 0.96 (S2), Af 1.07 and 1.06, observed product shelf-life 299 h (S1) and 262 h (S2) vs predicted 285 h; pilot total shelf-life after transport and storage (h): microbial 496, 300, 184, 130 at 2, 4, 7, 10 °C; app-predicted TTI 256, 154, 87 at 4, 7, 10 °C; TTI based on app measurements 501, 242, 127, 103 at 2, 4, 7, 10 °C. | measurements; constant-temperature vs dynamic-temperature scenarios; comparison of app-predicted TTI vs observed TTI and vs product microbial shelf-life. |  |  |
|--|----------------------------------------------------------------------------------------------------------------------------|--|--|--|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|--|--|

|     |                                                                                                                                                                                                                                                                                                                    |                     |                                 |                                                      |                                                                    |                                                                                                                                                        |                                                                                                                                                                                                                                                                                  |                                                                                        |                                    |      |
|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|---------------------------------|------------------------------------------------------|--------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------------------|------|
| 98. | Willersinn, C., Mack, G., Mouron, P., Siegrist, M. and Hartmann, M. (2015), "Quantity and quality of food losses along the Swiss potato supply chain: stepwise investigation and the influence of quality standards on losses", <i>Waste Management</i> , Vol. 46, pp. 120–132, doi: 10.1016/j.wasman.2015.08.033. | Switzerland         | Potatoes (table and processing) | Production, wholesale, processing, retail, household | Systematic loss assessment; scenario analysis on quality standards | Mixed methods: field trials, stakeholder interviews, delivery controls, consumer diaries                                                               | Total losses: fresh potatoes ~53–55% of initial production; processing ~41–46%. About half of losses due to quality standards; of these, 25–34% are food-safety driven; scenario with "lower" specs reduces losses at farm by ~3–11% depending on line (pp.1–3, 6–8). Willersinn | Comparisons across baseline vs. "lower specification" scenarios; cross-stage contrasts | Waste Management                   | 2015 |
| 99. | Wittkamp, T., Defraeye, T., Yegon, R. and Onwude, D. (2025), "Enhancing postharvest storage in low- and middle-income countries: evaluation of a passive evaporative cooling blanket", <i>Energy for Sustainable Development</i> , Vol. 88, 101787, doi: 10.1016/j.esd.2024.101787.                                | Kenya (Embu County) | Vegetables and tomatoes         | Storage/cooling                                      | Passive evaporative "cooling blanket" vs charcoal cooler and shade | Full-scale outdoor field experiments on tomatoes, kale, zucchini, peas; sensors for T/RH; quality assessments; farmer/vendor interviews; cost analysis | Blanket reduced air and fruit temperature by 3–5 °C on average, up to 10 °C at peak; maintained ~95% RH; daytime cooling efficiency ~70% (Fig. 5b); reduced postharvest losses up to 45% and weight loss by 50–60%; payback < 3 months; performance                              | Shade storage and stationary charcoal cooler as benchmarks. Wittkamp                   | Energy for Sustainable Development | 2025 |

|      |                                                                                                                                                                                                                                                                                         |                                               |       |                                     |                                                                                                                            |                                                                                                                                                                               |                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                   |                                     |      |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|-------|-------------------------------------|----------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-------------------------------------|------|
|      |                                                                                                                                                                                                                                                                                         |                                               |       |                                     |                                                                                                                            |                                                                                                                                                                               | comparable to large charcoal cooler (Fig. 4, Fig. 7–10). Wittkamp                                                                                                                                                                                                                                                                                                                                                                  |                                                                                   |                                     |      |
| 100. | Worku, A.F., Kalsa, K.K., Abera, M., Tenagashaw, M.W. and Habtu, N.G. (2022), "Evaluation of various maize storage techniques on total aflatoxins prevalence and nutrient preservation", <i>Journal of Stored Products Research</i> , Vol. 95, 101913, doi: 10.1016/j.jspr.2021.101913. | Ethiopia (laboratory-controlled ambient room) | Maize | Storage (12-month extended storage) | Six techniques: PICS, Super GrainPro, metal silo, filter-cake admixed in PP bag, Triplex admixed in PP bag, and PP control | Completely randomised design, three replications each; measurements at 0, 6 and 12 months: moisture, water activity, aflatoxins, kernel mould infection, protein, oil, starch | After 12 months, aflatoxins increased significantly in PP control, Triplex and metal silo; remained statistically unchanged and low in PICS and Super GrainPro; filter-cake also contained aflatoxins effectively. Kernel mould infection 0 percent in PICS, Super GrainPro and filter-cake at 12 months; protein and oil losses smallest in PICS, Super GrainPro and filter-cake; moisture remained stable in hermetic containers | Baseline maize at 11.1 percent moisture; direct comparison across storage methods | Journal of Stored Products Research | 2022 |
| 101. | Yewle, N.R., Stroshine, R.L., Ambrose, R.K. and Baributsa, D.                                                                                                                                                                                                                           | USA (lab study; implications)                 | Maize | Storage during wet-season drying    | Short-term hermetic storage of                                                                                             | 1-L jar trials at 25 °C and 80% RH for 7/14/21 days; O <sub>2</sub> /CO <sub>2</sub> ,                                                                                        | At 18–21% m.c., germination remained ≥90% up to 14 days; at                                                                                                                                                                                                                                                                                                                                                                        | Non-hermetic jars; initial germination and                                        | Foods                               | 2023 |

|      |                                                                                                                                                                                                                                                                                    |                        |                           |                      |                                                                                                                               |                                                                                                                 |                                                                                                                                                                                                                                                                                        |                                                                                           |                             |      |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|---------------------------|----------------------|-------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------|------|
|      | (2023), "Short-term hermetic storage of wet maize and its effect on quality", <i>Foods</i> , Vol. 12 No. 4, 891, doi: 10.3390/foods12040891.                                                                                                                                       | ons for humid tropics) |                           |                      | wet grain (18%, 21%, 24% m.c.) vs non-hermetic                                                                                | pH, visible mould; germination, shoot/root length                                                               | 24% m.c., germination collapsed by 21 days; hermetic jars suppressed visible mould vs non-hermetic but showed lactic fermentation (pH drop) at $\geq 21\%$ m.c.; rapid O <sub>2</sub> depletion and CO <sub>2</sub> rise in hermetic jars (Fig. 2), mould photos in Fig. 3. Yewle      | m.c. at day 0. Yewle                                                                      |                             |      |
| 102. | Zhang, W., Lin, M., Feng, X., Zhang, X., Liang, K., Lin, H. and Zhang, J. (2022), "Effect of lemon essential oil-enriched coating on the postharvest storage quality of citrus fruits", <i>Food Science and Technology (Campinas)</i> , Vol. 42, e125421, doi: 10.1590/fst.125421. | China                  | Citrus (Satsuma mandarin) | Post-harvest storage | Experimental preservative intervention: coatings with lemon essential oil (LEO) $\pm$ chitosan, CaCl <sub>2</sub> , natamycin | Laboratory storage trial (20 $\pm$ 2 °C; 75 $\pm$ 5% RH; 60 days); pathogen assays; quality/biochemical indices | Best treatment (LEO+chitosan+CaCl <sub>2</sub> +natamycin) halved decay vs control at 60 d (~7% vs 14%), and cut weight loss (14.33% vs 20.56%); higher TSS/TA/Vit C; elevated SOD/POD activities; lower MDA and relative conductivity (pp.4–6, figs.1–4; table on respiration). Zhang | Water-dipped control (CK) and simpler coating arms (LEO; LEO+chitosan+CaCl <sub>2</sub> ) | Food Science and Technology | 2022 |



### 9.3 Appendix 3: 1<sup>st</sup> Conceptual Framework for Food Loss Interventions

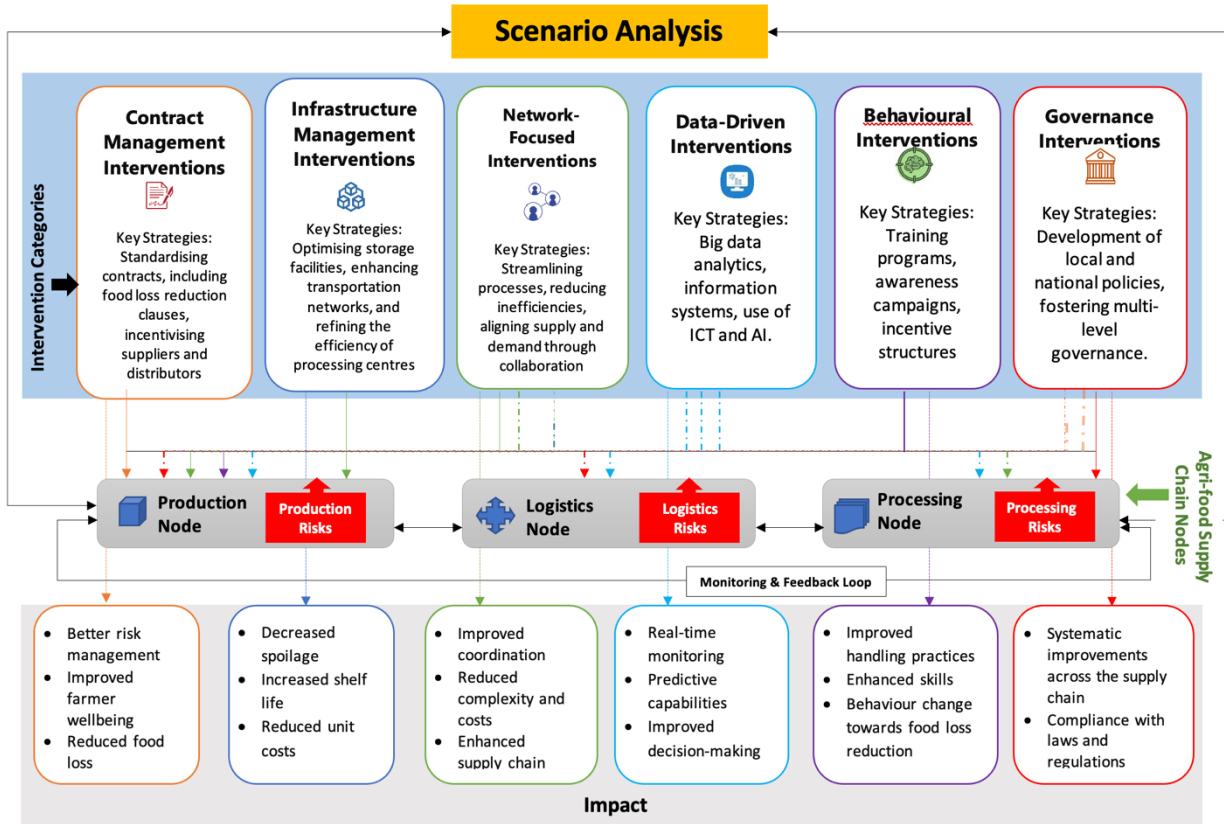


Fig. A 1: Old Conceptual Framework



## 9.4 Appendix 4: Stacking and Multiplier Losses

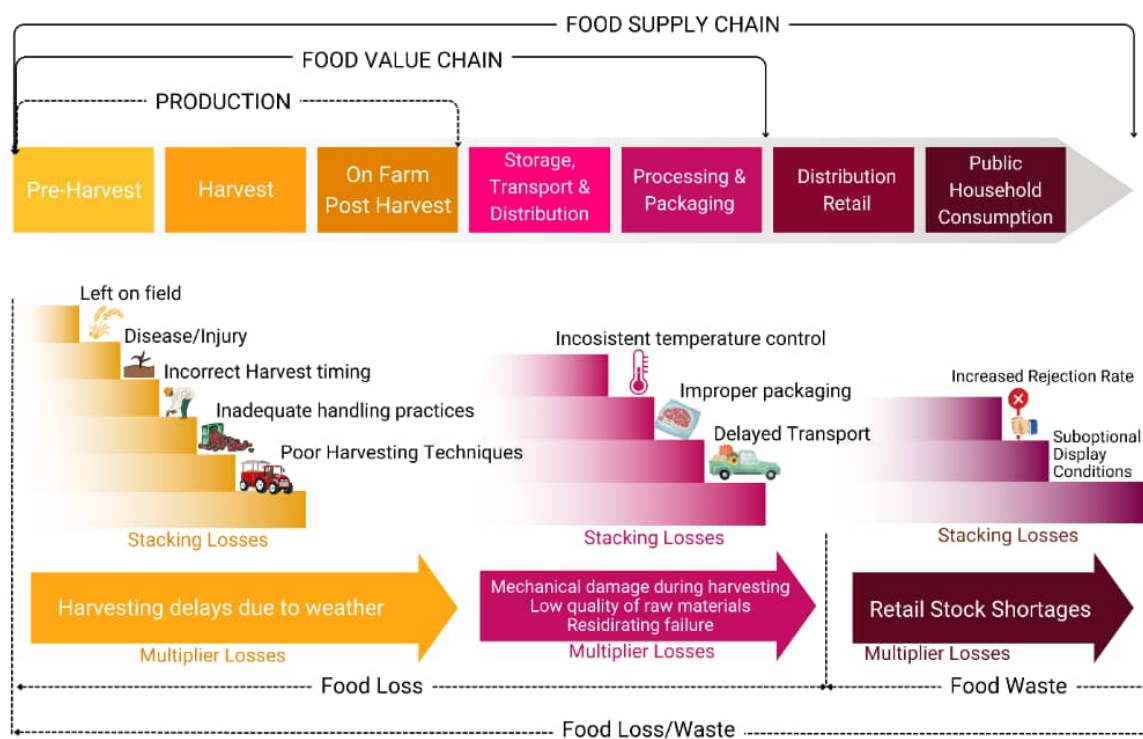


Fig. A 2: Stacking and Multiplier Losses

## **9.5 Appendix 5: Archival Data Sources and Policy Documents**

### **Key Federal Policy Documents and Legislative Acts Analysed**

The archival review identified over 30 critical national policies, regulations, and legislative frameworks shaping Nigeria's approach to digital transformation in fresh produce supply chains, food waste management, and agricultural innovation. These include:

- i. National Agricultural Technology and Innovation Policy (NATIP) 2022–2027 – Aims to integrate technology-driven solutions to enhance agricultural productivity and post-harvest food loss mitigation.
- ii. National Digital Economy Policy and Strategy (NDEPS) 2020–2030 – Establishes a roadmap for digital transformation across sectors, including agriculture, emphasizing smart farming, AI-driven analytics, and supply chain digitization.
- iii. National Broadband Plan 2020–2025 – Targets rural broadband expansion to support digital platforms in agriculture, including e-commerce marketplaces, digital financing, and blockchain-enabled food traceability systems.
- iv. National Policy on Food Safety and Its Implementation Strategy (NPFSIS) 2014 – Outlines traceability measures, regulatory requirements, and digital solutions for ensuring food safety in fresh produce markets.
- v. National Policy on Solid Waste Management 2020 – Addresses organic waste recycling and proposes policy incentives for technology-enabled waste-to-energy initiatives in food systems.
- vi. National Industrial Revolution Plan (NIRP) 2014 – Promotes agri-processing industrialization and digital innovations for food preservation and quality control in perishable goods.
- vii. National Climate Change Policy 2021 – Encourages climate-smart agricultural practices, advocating for sensor-based precision farming to optimize resource use and minimize post-harvest losses.
- viii. Smart Agriculture Policy Framework 2019 – Designed by FMSTI to accelerate IoT-enabled farming, blockchain for agri-transactions, and AI-driven decision support systems in agriculture.
- ix. Agricultural Promotion Policy (APP) 2016–2020 – Focuses on reducing post-harvest losses through strategic investments in logistics, cold-chain infrastructure, and digital marketplace connectivity.
- x. National Artificial Intelligence Policy (2023 Draft) – Highlights the role of AI in agricultural automation, risk assessment, and data-driven optimization in food production.

- xi. Nigerian Data Protection Act 2023 – Regulates digital data governance, influencing the adoption of smart supply chain platforms and food traceability applications.
- xii. National IoT Strategy 2021 – Provides guidelines for the deployment of sensor technologies in agriculture, including soil monitoring, climate adaptation, and logistics optimization.
- xiii. Blockchain Policy for Digital Transactions (2022) – Regulates blockchain-based smart contracts and digital payments in agricultural markets.
- xiv. National Transport Policy (2019) – Guides infrastructural investments in logistics and cold-chain networks essential for reducing food spoilage in Nigeria’s perishable supply chains.
- xv. National Financial Inclusion Strategy (Revised 2020) – Governs mobile-based payment systems and digital lending platforms that facilitate financial access for smallholder farmers.
- xvi. Nigerian Startup Act 2022 – Provides incentives for agritech startups pioneering digital supply chain solutions, logistics innovations, and AI-powered market intelligence platforms.

#### State and Local Policies in Archival Review

In addition to national policies, this study reviewed relevant state-level policies across key agricultural regions, particularly in:

- i. Kaduna State Agricultural Development Policy – Promotes public-private partnerships in agricultural innovation and outlines digital extension service strategies for smallholder farmers.
- ii. Katsina Agricultural Digitalization Initiative – Provides government incentives for adopting satellite-based monitoring systems in tomato production.
- iii. Lagos State Food Security Initiative – Encourages digitized market linkages, food waste reduction programs, and AI-powered logistics optimization platforms.
- iv. Kano State Agricultural Development Framework – Prioritizes precision agriculture, farmer aggregation platforms, and digital lending schemes.

Table A 4: Policy Framework Table

| Policy/Regulation Name                                                 | Year of Implementation | Governing Body/Institution                                                      | Focus Area                                                                                     |
|------------------------------------------------------------------------|------------------------|---------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| National Tomato Policy (2017)                                          | 2017                   | Federal Ministry of Agriculture and Rural Development (FMARD)                   | Boosting local tomato production, reducing import dependency, post-harvest technology adoption |
| Tomato Sector Development Plan (2020 to 2025)                          | 2020                   | FMARD                                                                           | Technological innovation, AI-driven yield forecasting, precision agriculture                   |
| Presidential Fertilizer Initiative (2016 to 2022)                      | 2016                   | Presidency of Nigeria                                                           | Fertilizer distribution and optimization for improved soil health                              |
| Nigeria Agricultural Transformation Agenda (2011 to 2020)              | 2011                   | FMARD                                                                           | Food value chain efficiency, e-wallet programs, geospatial analytics                           |
| National Agricultural Seed Policy (2019)                               | 2019                   | National Agricultural Seeds Council (NASC)                                      | Seed certification and blockchain-enabled traceability                                         |
| National Agribusiness Investment Policy (2021)                         | 2021                   | FMARD                                                                           | Agribusiness investments in digital supply chain management                                    |
| National Horticultural Research and Innovation Strategy (2022 to 2027) | 2022                   | FMARD                                                                           | Horticultural advancements, AI-enabled disease detection                                       |
| National Food Safety Policy (2014)                                     | 2014                   | FMARD and National Agency for Food and Drug Administration and Control (NAFDAC) | Food handling, safety, traceability, logistics                                                 |
| Kaduna State Tomato Processing and Export Initiative                   | Ongoing                | Kaduna State Government                                                         | Processing investments, cold-chain logistics, quality standards                                |
| Kano State Tomato Innovation Fund (2021)                               | 2021                   | Kano State Government                                                           | Digital farming incentives, cooperative blockchain traceability                                |
| Katsina Smart Greenhouse Project                                       | Ongoing                | Katsina State Government                                                        | Smart greenhouse technology, AI-driven irrigation                                              |
| Lagos State Smart Food Market Project                                  | Ongoing                | Lagos State Government                                                          | E-commerce, RFID-based inventory tracking, smart food markets                                  |
| National Horticultural Research Institute (NIHORT) Regulations         | Ongoing                | NIHORT                                                                          | Horticulture research, IoT-based pest monitoring                                               |
| Nigeria Export Promotion Council (NEPC) Guidelines                     | Ongoing                | NEPC                                                                            | Export regulatory frameworks, quality assurance                                                |
| Nigerian Stored Products Research Institute (NSPRI) Regulations        | Ongoing                | NSPRI                                                                           | Stored product monitoring, cold storage regulations                                            |

|                                                                                  |         |                                                      |                                                                |
|----------------------------------------------------------------------------------|---------|------------------------------------------------------|----------------------------------------------------------------|
| Nigeria Agricultural Quarantine Service (NAQS) Phytosanitary Regulations         | Ongoing | NAQS                                                 | Phytosanitary standards, blockchain-based traceability         |
| The Tomato Value Chain Digitization Project (2022)                               | 2022    | FMARD and Private Sector Partnerships                | AI-driven analytics for tomato supply chain                    |
| Nigeria's Cold-Chain Logistics Expansion Project (2021)                          | 2021    | African Development Bank (AfDB) and Private Sector   | Solar-powered cold-chain logistics, IoT temperature monitoring |
| Nigeria Smart Farming Accelerator (2023)                                         | 2023    | Federal Government of Nigeria and Agri-Tech Startups | IoT, AI, blockchain-led agricultural innovation                |
| Jos Tomato Market Regulations and Development Framework                          | Ongoing | Plateau State Government and Jos Market Authorities  | Market structure and regulations for tomato trade              |
| Federal Ministry of Agriculture and Rural Development Digital Farming Guidelines | Ongoing | FMARD                                                | Digital transformation in farming, smart farming guidelines    |
| National Communications Commission (NCC) IoT Regulations for Agri-Tech           | Ongoing | National Communications Commission (NCC)             | IoT policies for agricultural digitalization                   |
| Nigerian Custom and Trade Policies for Perishable Goods (2020)                   | 2020    | Nigerian Customs Service                             | Customs and tariffs for perishable goods trade                 |
| Central Bank of Nigeria (CBN) Agricultural Finance Regulations                   | Ongoing | Central Bank of Nigeria (CBN)                        | Agricultural finance policies, digital payment solutions       |

## 9.6 Appendix 6: Research protocol and data collection instruments

This appendix suite is structured as a controlled “process architecture” for Chapter Four. It separates core methodological logic (kept in the chapter body) from execution-level artefacts (located in appendices), ensuring auditability, replicability, and clean examiner navigation. Appendix 6.1 functions as the operational protocol pack for fieldwork delivery, whilst Appendix 6.2 functions as the analytical controls pack governing coding, reliability, and evidence traceability.

### 9.6.1 Appendix 6.1: Full research protocol and data collection instruments

This appendix contains the complete set of fieldwork instruments and control documents required to reproduce the study's data generation process with fidelity. It is organised by research phase to demonstrate explicit alignment between the study's methodological design, research questions, and data collection procedures. The appendix includes stakeholder-specific interview guides, focus group schedules, participant information sheets, consent forms, and the full fieldwork protocol. The organisation by phase provides instrument-level transparency by documenting question routing, actor-specific modules, sequencing logic, and procedural safeguards for ethical and culturally appropriate implementation.

#### 9.6.1.1 Overview: Phase-to-Instrument Mapping

Table A5 provides an overview of how the research instruments align with each phase of the study, linking data collection activities to research questions and objectives.

Table A 5:Phase-to-Instrument Alignment Overview

| Phase     | Primary Focus                                | Instruments                                    | Linked RQ(s) | Linked Objective(s) |
|-----------|----------------------------------------------|------------------------------------------------|--------------|---------------------|
| Pilot     | Instrument validation and refinement         | Draft interview guides; pilot protocol         | All          | Construct validity  |
| Phase One | Exploratory mechanism mapping                | Interview Guides 1A-1E; Focus Group Protocol 1 | RQ1          | Objectives 1, 2     |
| Phase Two | Governance and contractual mechanism probing | Interview Guides 2A-2D; Focus Group Protocol 2 | RQ1, RQ2     | Objectives 2, 3, 4  |
| Archival  | Documentary and policy analysis              | Document extraction protocol                   | RQ2          | Objective 4         |

### 9.6.1.2 Pilot Study Protocol and Refinements

The pilot study was conducted prior to full-scale fieldwork to test the feasibility, clarity, and theoretical sensitivity of the research instruments. Table A6 summarises the pilot study components and their contribution to instrument development.

Table A 6: Pilot Study Components

| Element                             | Description                                                                                                                                   | Contribution                              |
|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|
| Pilot Interview Guide (Version 1.0) | Initial semi-structured protocol tested with 15 participants across actor categories                                                          | Baseline instrument for validation        |
| Pilot Sample                        | 15 participants (approximately 16% of final corpus) purposively selected from supply chain actors with direct digital intervention experience | Representative testing across actor types |
| Translation Workflow Trial          | Multilingual engagement procedures tested to verify retention of key governance constructs across languages                                   | Cross-linguistic validity                 |
| Pilot Refinement Log                | Systematic documentation of four material changes resulting from pilot analysis                                                               | Audit trail for instrument evolution      |
| Final Interview Guide (Version 2.0) | Revised protocol incorporating all pilot findings, forming basis for Phase One and Phase Two instruments                                      | Enhanced construct validity               |

### 9.6.1.3 Summary of Pilot Refinements

The pilot study produced four material refinements that strengthened instrument quality and analytical fit:

1. Questions were reworded to reduce normative framing and to encourage respondents to describe specific episodes of implementation and decision-making, thereby supporting later retroductive inference.
2. Targeted probes were added to explicitly capture contractual and platform governance mechanisms, including data access, payment terms, dispute resolution, and enforcement practices.
3. The protocol was modularised into actor-specific versions to preserve cross-actor comparability whilst avoiding irrelevant prompts and reducing the risk of leading questions.
4. Consent and briefing scripts were simplified and standardised across languages, and additional prompts were introduced to minimise social desirability bias when discussing sensitive issues such as price formation, exclusion, and informal payments

#### 9.6.1.4 Phase One Instruments: Exploratory Mechanism Mapping

Phase One involved exploratory semi-structured interviews with a diverse set of supply chain actors, designed to map the key constraints and paradoxes shaping digital transformation. This phase addressed RQ1 and contributed primarily to Objectives 1 and 2. Table A7 details the Phase One instruments and their specific applications.

Table A 7: Phase One Instrument Matrix

| Instrument             | Actor Group         | Linked RQ | Linked Objective | Thematic Focus                                                          |
|------------------------|---------------------|-----------|------------------|-------------------------------------------------------------------------|
| Interview Guide 1A     | Farmers/Producers   | RQ1       | Objective 1      | Technology adoption; efficiency perceptions; infrastructure constraints |
| Interview Guide 1B     | Logistics Actors    | RQ1       | Objective 1      | Transport coordination; cold chain challenges; digital tracking         |
| Interview Guide 1C     | Processors          | RQ1       | Objective 1      | Processing technology; quality management; supplier relationships       |
| Interview Guide 1D     | Platform Operators  | RQ1       | Objectives 1, 2  | Platform design; user engagement; governance rules; data practices      |
| Interview Guide 1E     | Cooperative Leaders | RQ1       | Objectives 1, 2  | Collective action; member coordination; institutional support           |
| Focus Group Protocol 1 | Mixed actor groups  | RQ1       | Objective 1      | Cross-actor dynamics; shared constraints; divergent perspectives        |

#### 9.6.1.5 Phase One Thematic Areas and Sample Questions

The Phase One interview protocol focused on three broad thematic areas:

Table A 8: Phase One Interview Themes and Sample Questions

| Thematic Area                                          | Sample Questions                                                                                                                                                                                                                                                                                                                                                                         |
|--------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Digital Technology Adoption and Efficiency Perceptions | "What digital tools or technologies have you integrated into your operations?"<br>"How have these technologies affected efficiency, costs, and waste management in your business?"<br>"Have the promised benefits of these digital tools been realised in practice?"                                                                                                                     |
| Institutional and Market Constraints                   | "What are the main barriers to adopting and using digital technologies in your work?"<br>"Do government regulations, policy incentives, or institutional support play a role in shaping your engagement with digital tools?"<br>"How do market conditions, such as pricing, contracts, and buyer expectations, affect your ability to adopt and sustain digital transformation efforts?" |
| Supply Chain and Food Loss Dynamics                    | "To what extent does digital technology help in reducing food loss and waste in your operations?"                                                                                                                                                                                                                                                                                        |



| Thematic Area | Sample Questions                                                                                                                                                              |
|---------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|               | "What other factors, beyond technology, contribute to food waste in your supply chain?"<br>"What strategies have been most effective in reducing food waste in your context?" |

#### 9.6.1.6 Phase Two Instruments: Governance and Contractual Mechanism Probing

Phase Two was designed to interrogate contractual logics and governance constraints explicitly, following insights from Phase One analysis that identified contractual governance structures as central to digital transformation trajectories. This phase addressed both RQ1 and RQ2 and contributed primarily to Objectives 2, 3, and 4. Phase Two included follow-up interviews with selected respondents from Phase One, ensuring continuity and deeper exploration of emerging themes. Table A9 details the Phase Two instruments.

Table A 9: Phase Two Instrument Matrix

| Instrument             | Actor Group                    | Linked RQ | Linked Objective   | Thematic Focus                                                                   |
|------------------------|--------------------------------|-----------|--------------------|----------------------------------------------------------------------------------|
| Interview Guide 2A     | Farmers (follow-up)            | RQ1, RQ2  | Objectives 2, 3    | Contract terms; price determination; dispute experiences; platform rules         |
| Interview Guide 2B     | Platform Operators (follow-up) | RQ1, RQ2  | Objectives 2, 3, 4 | Governance design; enforcement mechanisms; data ownership; algorithmic decisions |
| Interview Guide 2C     | Aggregators/Traders            | RQ1, RQ2  | Objectives 2, 3    | Intermediation roles; contract renegotiation; information asymmetries            |
| Interview Guide 2D     | Financial Service Providers    | RQ2       | Objectives 3, 4    | Digital finance; credit access; risk assessment; platform integration            |
| Focus Group Protocol 2 | Governance-focused (mixed)     | RQ2       | Objectives 3, 4    | Power dynamics; collective bargaining; governance preferences                    |

#### 9.6.1.7 Phase Two Additional Questions

Building on Phase One findings, the following additional questions were introduced in Phase Two to probe governance mechanisms explicitly:

Table A 10: Phase Two Additional Interview Questions

| Governance Dimension                      | Sample Questions                                                                                                                                                                                                             |
|-------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Contractual Terms and Price Determination | "How are prices determined in your contracts with buyers or platforms?"<br>"Who sets the terms, and how much room is there for negotiation?"<br>"Have you experienced situations where contract terms changed unexpectedly?" |
| Dispute Resolution and Enforcement        | "What happens when there is a dispute over quality, delivery, or payment?"                                                                                                                                                   |

| Governance Dimension                                | Sample Questions                                                                                                                                                                                                                              |
|-----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                     | "How are disagreements typically resolved? Through formal or informal means?"<br>"Have you ever felt unable to challenge a decision made by a platform or buyer?"                                                                             |
| Data Access and Control                             | "Who has access to the data generated through digital platforms, and how is it used?"<br>"Do you have visibility into how your data influences pricing or ranking?"<br>"Have you ever felt that information was used against your interests?" |
| Residual Rights and Incomplete Contracts            | "How are decisions made when contracts do not specify what should happen?"<br>"Who bears the risk when unexpected problems arise?"<br>"What happens to produce that does not meet quality standards?"                                         |
| Platform Governance and Algorithmic Decision-Making | "How do platforms decide which farmers or traders to prioritise?"<br>"Do you understand how the platform's ranking or matching system works?"<br>"Have platform rules ever changed in ways that affected your business?"                      |

#### 9.6.1.8 Archival and Documentary Protocol

Archival data collection complemented the interview and focus group data by providing documentary evidence on formal governance structures, policy frameworks, and institutional arrangements. This component primarily addressed RQ2 and Objective 4. Table A11 details the archival data sources and their analytical purpose.

Table A 11: Archival Data Sources and Linkages

| Document Type             | Source                                      | Linked RQ | Linked Objective | Analytical Purpose                                     |
|---------------------------|---------------------------------------------|-----------|------------------|--------------------------------------------------------|
| Policy documents          | FMARD; State agricultural agencies          | RQ2       | Objective 4      | Formal governance frameworks; stated policy intentions |
| Platform terms of service | Digital platforms operating in tomato chain | RQ1, RQ2  | Objectives 2, 3  | Formal platform rules; contractual provisions          |
| Cooperative bylaws        | Farmer cooperatives                         | RQ1       | Objective 2      | Collective governance structures; member obligations   |
| Regulatory frameworks     | NAFDAC; SON; FMARD                          | RQ2       | Objective 4      | Formal regulatory requirements; enforcement provisions |
| Industry reports          | FAO; World Bank; IFPRI                      | RQ1, RQ2  | Objectives 1, 4  | Contextual data; sector-level trends                   |

#### 9.6.1.9 Ethical Documentation

The following ethical documentation was prepared and used across all phases of data collection:

- Participant Information Sheet (English version)
- Participant Information Sheet (Hausa translation)
- Informed Consent Form (with provisions for verbal consent where literacy constraints applied)
- Data Management Protocol (detailing anonymisation, storage, and access procedures)

- Aston University Ethics Approval Documentation

#### 9.6.1.10 Consolidated Phase-Instrument-Objective Mapping

Table A6.8 provides a consolidated view of the complete instrument set, demonstrating transparent alignment between research phases, instruments, research questions, and study objectives.

Table A 12: Consolidated Phase-Instrument-Objective Mapping

| Phase    | Instrument                 | Actor Group(s)                                          | RQ     | Obj.    | n              |
|----------|----------------------------|---------------------------------------------------------|--------|---------|----------------|
| Pilot    | Draft Interview Guide v1.0 | Mixed (representative sample)                           | All    | Valid.  | 15 interviews  |
| Phase 1  | Interview Guides 1A-1E     | Farmers; Logistics; Processors; Platforms; Cooperatives | RQ1    | 1, 2    | 38 interviews  |
| Phase 1  | Focus Group Protocol 1     | Mixed actor groups                                      | RQ1    | 1       | 4 focus groups |
| Phase 2  | Interview Guides 2A-2D     | Farmers; Platforms; Aggregators; Finance                | RQ1, 2 | 2, 3, 4 | 26 interviews  |
| Phase 2  | Focus Group Protocol 2     | Governance-focused (mixed)                              | RQ2    | 3, 4    | 2 focus groups |
| Archival | Document Protocol          | N/A (documentary sources)                               | RQ2    | 4       | 47 documents   |



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18<sup>th</sup> June 2024

|              |                                                                                                                                                     |
|--------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| Study title: | Towards a Constrained Efficiency Framework for the Digital Transformation of Agri-food Supply Chains: A Case of the Tomato Supply Chain in Nigeria. |
| REC ID:      | BSS21164                                                                                                                                            |

### Confirmation of Ethical Opinion

Dear Clement,

On behalf of the College of Business and Social Sciences Research Ethics Committee, I am pleased to confirm a favourable opinion for the above research on the basis described in the application form and supporting documentation listed below.

Please note that as Principal Investigator you are responsible for ensuring that (where applicable) all the necessary legal and regulatory requirements to conduct the research are met, and the necessary licenses and approvals have been obtained prior to commencing your research. You are also responsible for reporting any ethics-related issues that occur during the course of the research, or arising from the research, to the Research Ethics Officer at [bss\\_ethics@aston.ac.uk](mailto:bss_ethics@aston.ac.uk) (e.g. unforeseen ethical issues, complaints about the conduct of the research, adverse reactions such as extreme distress).

#### Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

| <b>Document</b>                      | <b>Version</b> | <b>Date</b> |
|--------------------------------------|----------------|-------------|
| Application form                     | 1              | 03/06/2024  |
| Consent form Pidgin English          | 3              | 03/06/2024  |
| Consent form Hausa                   | 3              | 03/06/2024  |
| Consent form English                 | 3              | 03/06/2024  |
| Participant information sheet        | 3              | 03/06/2024  |
| Participant information sheet Hausa  | 3              | 03/06/2024  |
| Participant information sheet Pidgin | 3              | 03/06/2024  |

With the Committee's best wishes for the success of this project.

Fig. A 3: Ethics Approval Stating Documents Used

## 9.6.2 Appendix 6.2 : Coding modes, coding manual, and reliability procedure

Appendix 6.2 contains the detailed analytical operating model underpinning the study's qualitative inference. It includes the full coding procedure, covering first- and second-order coding modes; the evolving codebook; double-coding procedures; disagreement-resolution rules; documentation of decision thresholds; and, where feasible, the calculation approach used for chance-corrected agreement checks. The appendix functions as a quality assurance and governance mechanism for analysis, providing an auditable trail from raw data to conceptual categories and cross-case claims.

### 9.6.2.1 Framework Overview

#### Purpose

This section provides standardised procedures for coding 79 semi-structured interview transcripts into a four-level hierarchical thematic framework. It ensures analytical consistency, transparency, and replicability.

#### Analytical Structure

The framework comprises four hierarchical levels, from specific empirical observations to theoretical abstractions:

Table A 13: Levels of Abstraction

| LEVEL 4               | LEVEL 3                      | LEVEL 2                | LEVEL 1                   |
|-----------------------|------------------------------|------------------------|---------------------------|
| Conceptual Categories | Higher Analytical Categories | Second-Order Codes     | First-Order Code Elements |
| 6 theoretical themes  | 12 interpretive constructs   | 12 abstract categories | 48 empirical phenomena    |

Table A 14: Core Principles

| Principle                     | Application                                                              |
|-------------------------------|--------------------------------------------------------------------------|
| <b>Fixed Framework</b>        | No new codes may be created. All quotations must map to existing codes.  |
| <b>Verbatim Extraction</b>    | Quotations must be exact transcriptions. No paraphrasing permitted.      |
| <b>Hierarchical Integrity</b> | Each first-order element maps to only one pathway through the hierarchy. |
| <b>British English</b>        | All outputs use British spelling (organisation, minimise, analyse).      |

#### Complete Hierarchical Mapping

The following table presents the fixed mapping structure. This mapping is immutable and must be followed precisely.

Table A 15: Hierarchical Mapping

| First-Order Code Elements                                                                                                  | Second-Order Code         | Higher Analytical Category       | Conceptual Category | Category Short Title                                     |
|----------------------------------------------------------------------------------------------------------------------------|---------------------------|----------------------------------|---------------------|----------------------------------------------------------|
| Soil monitoring devices;<br>Environmental sensors; Digital pest identification; Weather monitoring tools                   | Technology Integration    | Technology-enabled Systems       | 1                   | Technological Absorption and Infrastructure Constraints  |
| Storage facility limitations;<br>Transport infrastructure gaps;<br>Power supply inconsistency;<br>Water access constraints | Infrastructure Management | Resource Coordination            |                     |                                                          |
| Smartphone adoption barriers;<br>Internet connectivity issues;<br>Device cost constraints; Digital literacy gaps           | Digital Access            | Digital Access                   | 2                   | Digital Access and Knowledge Fragmentation               |
| Extension service contacts;<br>Peer learning groups;<br>WhatsApp networks; Farmer associations                             | Network Stewardship       | Institutional Knowledge Networks |                     |                                                          |
| Demonstration plots; Field trials; Training workshops;<br>Extension materials                                              | Knowledge Transfer        | Knowledge Governance             | 3                   | Regulatory Control and Market Coordination Failures      |
| Policy implementation gaps;<br>Regulatory frameworks;<br>Enforcement mechanisms;<br>Compliance systems                     | Governance                | Institutional Reconfiguration    |                     |                                                          |
| Cold storage inadequacy;<br>Temperature control issues;<br>Transport refrigeration gaps;<br>Preservation system limits     | Cold Chain Logistics      | Algorithmic Supply Chain Control | 4                   | Algorithmic Supply Chain Control and Power Asymmetries   |
| Data privacy concerns;<br>Cybersecurity issues;<br>Information control worries;<br>Digital payment fears                   | Data Trust                | Institutional Knowledge Networks |                     |                                                          |
| Online registration systems;<br>Mobile banking platforms; E-commerce integration; Digital payment systems                  | Digital Service Delivery  | Digital Financial Integration    | 5                   | Contract Enforcement Rigidity and Financial Lock-ins     |
| Group loan arrangements;<br>Cooperative savings; Shared resources; Joint purchasing                                        | Collective Access         | Risk Management Infrastructure   |                     |                                                          |
| Traditional preservation methods; Local cooling techniques; Cultural farming practices; Community adaptations              | Indigenous Knowledge      | Knowledge Hybridization          | 6                   | Path Dependency and Indigenous Knowledge Marginalization |
| Chemical usage tracking;<br>Product traceability; Quality certification; Standards compliance                              | Transparency Systems      | Trust-based Governance           |                     |                                                          |

### Operational Code Definitions

Each code is defined with: (a) scope statement, (b) inclusion criteria, (c) exclusion criteria, and (d) indicative keywords.

Table A 16: Technology Integration Scope

|                 |                                                                                                                                                            |
|-----------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Technologies for monitoring, assessment, and management of agricultural production                                                                         |
| <b>Include</b>  | Digital/electronic monitoring devices; apps for farm management; sensor-based systems; precision agriculture tools; GPS/satellite technologies for farming |
| <b>Exclude</b>  | Basic mechanical equipment without digital components; general farming tools; post-harvest processing equipment; transportation technologies               |
| <b>Keywords</b> | sensor, app, GPS, satellite, monitor, digital, smart farming, precision, weather app, soil test, pest detection, forecast                                  |

Table A 17: Technology Integration Operational Definition

| Element                     | Operational Definition                                                                                                                                                                                   |
|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Soil monitoring devices     | Any technology measuring soil properties (pH, moisture, nutrients, temperature). Includes handheld meters, in-ground sensors, and laboratory testing equipment linked to digital reporting.              |
| Environmental sensors       | Devices measuring ambient conditions (humidity, temperature, light intensity, atmospheric pressure). Excludes weather forecasting services (see Weather monitoring tools).                               |
| Digital pest identification | Image recognition apps, diagnostic tools, or digital databases used to identify pests, diseases, or crop health issues. Includes AI-based diagnostics and remote expert consultation via digital images. |
| Weather monitoring tools    | Apps, devices, or services providing weather data/forecasts. Includes radio weather reports accessed via phones, SMS weather alerts, and dedicated weather stations.                                     |

Table A 18: Infrastructure Management Scope

|                 |                                                                                                                                                                                       |
|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Physical and systemic infrastructure required for value chain operations                                                                                                              |
| <b>Include</b>  | Warehouses, roads, electricity supply, irrigation systems, water sources, storage facilities, transport networks affecting agricultural operations                                    |
| <b>Exclude</b>  | Cold chain infrastructure (see Cold Chain Logistics); digital infrastructure like internet connectivity (see Digital Access); financial infrastructure (see Digital Service Delivery) |
| <b>Keywords</b> | storage, warehouse, road, transport, electricity, power, NEPA, light, water, irrigation, borehole, infrastructure, facility                                                           |

Table A 19: Infrastructure Management Definition

| Element                       | Operational Definition                                                                                                                                                              |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Storage facility limitations  | Inadequate capacity, inaccessibility, or absence of non-refrigerated storage. Includes warehouses, silos, and temporary storage structures. Excludes cold storage (see Cold Chain). |
| Transport infrastructure gaps | Poor road conditions, vehicle unavailability, distance to markets, or transport network deficiencies. Excludes refrigerated transport (see Cold Chain).                             |
| Power supply inconsistency    | Unreliable grid electricity, generator dependence, fuel costs, or power outages affecting agricultural operations. Code here when power affects general operations.                 |
| Water access constraints      | Irrigation limitations, borehole problems, seasonal water scarcity, or water quality issues affecting production. Excludes water for cooling purposes (see Indigenous Knowledge).   |

Table A 20: Digital Access Scope

|                 |                                                                                                                                                           |
|-----------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Barriers to and enablers of digital technology access among value chain actors                                                                            |
| <b>Include</b>  | Phone ownership barriers, network coverage problems, data/airtime costs, ability to use digital tools, internet access issues                             |
| <b>Exclude</b>  | Specific apps or platforms (code by function); trust issues with digital systems (see Data Trust); digital payment systems (see Digital Service Delivery) |
| <b>Keywords</b> | phone, smartphone, network, internet, data, airtime, coverage, literacy, education, afford, expensive, access, connectivity                               |

Table A 21: Digital Access Definitions

| Element                      | Operational Definition                                                                                                                                                   |
|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Smartphone adoption barriers | Factors preventing smartphone ownership/use: cost, availability, perceived need, cultural factors. Includes feature phone use as alternative and USSD-based workarounds. |
| Internet connectivity issues | Network coverage gaps, signal strength problems, data costs, connectivity reliability. Code references to 'no network', 'poor signal', 'expensive data' here.            |
| Device cost constraints      | Affordability of digital devices relative to income. Includes references to device prices, saving for phones, sharing devices due to cost.                               |
| Digital literacy gaps        | Inability to operate digital devices/apps effectively. Includes education levels, age-related difficulties, need for assistance, language barriers in app interfaces.    |

Table A 22: Network Stewardship Scope

|                 |                                                                                                                                            |
|-----------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Formal and informal networks facilitating knowledge and resource flow                                                                      |
| <b>Include</b>  | Extension agent relationships, farmer-to-farmer learning, messaging groups, cooperative structures, professional networks                  |
| <b>Exclude</b>  | Formal training events (see Knowledge Transfer); purely financial cooperatives (see Collective Access); regulatory bodies (see Governance) |
| <b>Keywords</b> | extension, agent, WhatsApp, group, association, cooperative, network, farmer group, share information, learn from, contact                 |

Table A 23: Network Stewardship Definition

| Element                    | Operational Definition                                                                                                                                                    |
|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Extension service contacts | Relationships with government/private extension agents, frequency of contact, quality of interaction. Includes both presence and absence of extension support.            |
| Peer learning groups       | Informal farmer-to-farmer knowledge exchange. Includes neighbourhood learning, copying successful farmers, informal mentorship arrangements.                              |
| WhatsApp networks          | Use of WhatsApp or similar messaging platforms (Telegram, SMS groups) for agricultural information sharing. Includes market price sharing, weather alerts, pest warnings. |
| Farmer associations        | Formal cooperative structures, unions, producer organisations. Focus on organisational function and information sharing, not financial aspects (see Collective Access).   |

Table A 24: Knowledge Transfer Scope

|                |                                                                                                                       |
|----------------|-----------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>   | Mechanisms for disseminating agricultural knowledge and best practices                                                |
| <b>Include</b> | Demonstration activities, organised training, experimental plots, educational materials, capacity building programmes |



|                 |                                                                                                                                                                     |
|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Exclude</b>  | Informal peer learning (see Network Stewardship); indigenous knowledge transmission (see Indigenous Knowledge); regulatory training for compliance (see Governance) |
| <b>Keywords</b> | training, workshop, demonstration, demo plot, field day, trial, experiment, teach, learn, material, manual, capacity building                                       |

Table A 25: Knowledge Transfer Definition

| <b>Element</b>      | <b>Operational Definition</b>                                                                                                                         |
|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| Demonstration plots | Designated areas showing new techniques, varieties, or technologies. Includes model farms, lead farmer plots, and organisational demonstration sites. |
| Field trials        | Experimental testing under local conditions. Includes variety trials, input testing, technology pilots, and participatory research activities.        |
| Training workshops  | Organised educational sessions for skill/knowledge transfer. Includes seminars, field days, farmer schools, and structured learning events.           |
| Extension materials | Educational resources: printed guides, videos, radio programmes, posters, mobile content designed for agricultural learning.                          |

Table A 26: Governance Scope

|                 |                                                                                                                                       |
|-----------------|---------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Formal regulatory and policy mechanisms affecting the value chain                                                                     |
| <b>Include</b>  | Government policies, regulations, enforcement activities, standards requirements, institutional roles                                 |
| <b>Exclude</b>  | Quality standards for export (see Transparency Systems); private sector governance; informal community rules; organisational policies |
| <b>Keywords</b> | government, policy, regulation, law, ministry, enforce, compliance, standard, official, inspection, permit, licence                   |

Table A 27: Governance Definition

| <b>Element</b>             | <b>Operational Definition</b>                                                                                                                             |
|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Policy implementation gaps | Discrepancies between stated policies and ground-level implementation. Includes unfunded mandates, capacity constraints, and policy-practice disconnects. |
| Regulatory frameworks      | Existing laws, regulations, and formal rules. Code mentions of specific regulations, ministries' roles, and legal requirements here.                      |
| Enforcement mechanisms     | Systems for ensuring regulatory compliance: inspections, penalties, monitoring activities. Includes both presence and absence of enforcement.             |
| Compliance systems         | Procedures and requirements for meeting regulations. Includes licensing, permits, registration requirements, and compliance costs.                        |

Table A 28: Cold Chain Logistics Scope

|                 |                                                                                                                                                                       |
|-----------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Temperature-controlled supply chain infrastructure and processes                                                                                                      |
| <b>Include</b>  | Cold rooms, refrigerated transport, cold storage facilities, modern preservation technologies, temperature monitoring                                                 |
| <b>Exclude</b>  | Traditional/non-mechanical cooling methods (see Indigenous Knowledge); general storage without temperature control (see Infrastructure); food processing technologies |
| <b>Keywords</b> | cold room, cold storage, refrigerator, freezer, cold chain, temperature, cooling, refrigerated truck, preservation, chill                                             |

Table A 29: Cold Chain Logistics Definition

| Element                      | Operational Definition                                                                                                                                         |
|------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Cold storage inadequacy      | Insufficient capacity, accessibility, or availability of refrigerated storage. Includes cost barriers to cold storage access and geographic distribution gaps. |
| Temperature control issues   | Challenges maintaining appropriate temperatures: power failures affecting cold chains, temperature fluctuations, inadequate monitoring.                        |
| Transport refrigeration gaps | Absence or inadequacy of refrigerated vehicles. Includes high costs of reefer trucks, lack of availability, long distances without cooling.                    |
| Preservation system limits   | Constraints in modern shelf-life extension technologies. Excludes traditional methods. Includes packaging technologies, controlled atmosphere storage.         |

Table A 30: Data Trust Scope

|                 |                                                                                                                                                  |
|-----------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Concerns regarding data security, privacy, and control within digital systems                                                                    |
| <b>Include</b>  | Privacy worries, fraud fears, data misuse concerns, digital security issues, trust in electronic systems                                         |
| <b>Exclude</b>  | General technology adoption barriers (see Digital Access); positive experiences with digital systems; technical failures without trust dimension |
| <b>Keywords</b> | trust, fraud, scam, privacy, data, security, fear, worry, safe, hack, steal, information, control                                                |

Table A 31: Data Trust Definition

| Element                     | Operational Definition                                                                                                                                         |
|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Data privacy concerns       | Worries about how personal/business data is collected, stored, and used by platforms or organisations. Includes concerns about data sharing without consent.   |
| Cybersecurity issues        | Concerns about digital security threats: hacking, account breaches, system vulnerabilities. Includes experiences of or fears about cyber attacks.              |
| Information control worries | Concerns about who controls access to data and information. Includes power asymmetries in data ownership and platform control over farmer data.                |
| Digital payment fears       | Anxieties about electronic payment security and reliability. Includes fears of losing money through digital transactions, fraud concerns, preference for cash. |

Table A 32: Digital Service Delivery Scope

|                 |                                                                                                                                                             |
|-----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Digital platforms and systems for delivering services to value chain actors                                                                                 |
| <b>Include</b>  | Farmer registration platforms, mobile money, e-commerce, digital payments, online marketplaces, fintech services                                            |
| <b>Exclude</b>  | Apps for farm management (see Technology Integration); informal digital communication (see Network Stewardship); fears about these systems (see Data Trust) |
| <b>Keywords</b> | register, registration, mobile money, bank transfer, e-commerce, online, platform, app, payment, digital payment, fintech                                   |

Table A 33: Digital Service Delivery Definition

| Element                     | Operational Definition                                                                                                                                  |
|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|
| Online registration systems | Digital platforms for registering farmers, products, or businesses. Includes government farmer databases, input subsidy registration, scheme enrolment. |
| Mobile banking platforms    | Financial services via mobile: mobile money (OPay, PalmPay), bank apps, USSD banking. Focus on service delivery, not fears (see Data Trust).            |
| E-commerce integration      | Online marketplaces, digital sales channels, platform-mediated transactions. Includes produce aggregation platforms and B2B digital trading.            |

|                         |                                                                                                                               |
|-------------------------|-------------------------------------------------------------------------------------------------------------------------------|
| Digital payment systems | Electronic payment methods: POS, transfers, mobile payments. Code actual use or description of systems, not fears about them. |
|-------------------------|-------------------------------------------------------------------------------------------------------------------------------|

Table A 34: Collective Access Scope

|                 |                                                                                                                                                      |
|-----------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Shared resources and collective economic arrangements                                                                                                |
| <b>Include</b>  | Group lending, savings cooperatives, equipment sharing, bulk purchasing, collective bargaining, resource pooling                                     |
| <b>Exclude</b>  | Information sharing networks (see Network Stewardship); formal financial institutions (see Digital Service Delivery); individual credit arrangements |
| <b>Keywords</b> | group, cooperative, together, share, collective, pool, joint, bulk, contribution, esusu, ajo, savings group                                          |

Table A 35: Collective Access Definition

| Element                 | Operational Definition                                                                                                                         |
|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| Group loan arrangements | Collective borrowing with shared repayment responsibility. Includes group guarantees, cluster lending, and joint liability schemes.            |
| Cooperative savings     | Communal saving arrangements: rotating credit (esusu/ajo), savings groups, contribution schemes. Focus on informal/semi-formal arrangements.   |
| Shared resources        | Collective equipment use, shared facilities, communal assets. Includes shared tractors, processing equipment, storage facilities used jointly. |
| Joint purchasing        | Collective input procurement for economies of scale. Includes bulk buying of seeds, fertilisers, agrochemicals through groups.                 |

Table A 36: Indigenous Knowledge Scope

|                 |                                                                                                                                              |
|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Traditional practices and locally developed knowledge systems                                                                                |
| <b>Include</b>  | Traditional techniques, inherited practices, local innovations, non-mechanical preservation, cultural approaches to farming                  |
| <b>Exclude</b>  | Modern cold chain technologies (see Cold Chain); formally trained practices; commercially developed techniques; technology-based innovations |
| <b>Keywords</b> | traditional, local, grandfather, ancestor, our way, before, old method, shade, evaporative, charcoal, pot-in-pot, cultural                   |

Table A 37: Indigenous Knowledge Definition

| Element                          | Operational Definition                                                                                                                                            |
|----------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Traditional preservation methods | Indigenous post-harvest techniques: sun drying, smoking, salting, fermentation. Includes traditional tomato paste making and local preservation recipes.          |
| Local cooling techniques         | Non-mechanical temperature reduction: pot-in-pot/zeer pot, evaporative cooling, shade structures, charcoal-based cooling, wet cloth wrapping.                     |
| Cultural farming practices       | Agricultural methods rooted in tradition: intercropping patterns, planting calendars based on local knowledge, traditional pest management, seed saving.          |
| Community adaptations            | Locally developed modifications to standard practices: hybrid techniques combining traditional and modern, community-specific innovations, local problem-solving. |

Table A 38: Transparency Systems Scope

|                 |                                                                                                                                                                              |
|-----------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Scope</b>    | Mechanisms ensuring accountability and traceability within the value chain                                                                                                   |
| <b>Include</b>  | Chemical records, traceability systems, quality verification, certification processes, standards compliance, product tracking                                                |
| <b>Exclude</b>  | Government regulatory frameworks (see Governance); technology for monitoring farm conditions (see Technology Integration); price transparency (see Digital Service Delivery) |
| <b>Keywords</b> | trace, track, record, certificate, certify, quality, standard, chemical, spray, residue, test, safe, organic                                                                 |

Table A 39: Transparency Systems Definition

| <b>Element</b>          | <b>Operational Definition</b>                                                                                                                                        |
|-------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Chemical usage tracking | Recording and monitoring agrochemical applications: spray records, input registers, residue testing. Includes both presence and absence of such systems.             |
| Product traceability    | Mechanisms for tracking products through supply chain: batch coding, origin labelling, blockchain traceability, QR codes, documentation trails.                      |
| Quality certification   | Verification processes: NAFDAC registration, organic certification, GlobalGAP, export certifications, third-party quality verification.                              |
| Standards compliance    | Adherence to established standards: food safety protocols, quality grades, market standards, buyer requirements. Focus on meeting criteria, not regulatory mandates. |

## 9.6.2.2 Participant Classification

## Identification System

Format: [3-letter code] [2-digit number] : Example: FRM05, AGR11, TEC03

Table A 40: Code Definition for Participants

| Code       | Category      | Roles Included                                                                                                          | n         |
|------------|---------------|-------------------------------------------------------------------------------------------------------------------------|-----------|
| <b>FRM</b> | Farmers       | Smallholders, medium-scale farmers, traditional farmers, soilless farming experts, farm owners/supervisors/managers     | 19        |
| <b>AGR</b> | Agronomists   | Aggregators, market connectors, agronomists, consultants, agripreneurs, greenhouse supervisors, sustainability trainers | 11        |
| <b>TEC</b> | Technology    | Tech entrepreneurs, agri-tech product managers, digital farming specialists, cloud engineers, software developers       | 9         |
| <b>EXT</b> | Extension     | Extension officers, field agents, technical advisors, agricultural consultants, private extension CEOs                  | 9         |
| <b>PRJ</b> | Projects      | Project leads, programme coordinators, strategic partnership heads, agricultural development officers                   | 5         |
| <b>FIN</b> | Finance       | Microfinance managers, agricultural credit managers, insurance branch managers                                          | 5         |
| <b>SCM</b> | Supply Chain  | Supply chain experts, seed company CEOs, general managers, agricultural support specialists                             | 4         |
| <b>ORG</b> | Organisations | National/state secretaries of farmer associations, perishable goods association chairs                                  | 4         |
| <b>RSR</b> | Research      | Research officers, senior scientists, academic researchers, agricultural consultants                                    | 4         |
| <b>REG</b> | Regulatory    | Policy analysts, technical advisors, digital infrastructure directors                                                   | 4         |
| <b>LOG</b> | Logistics     | Logistics experts, assistant logistics officers                                                                         | 2         |
| <b>RTL</b> | Retail        | Market tomato sellers                                                                                                   | 2         |
| <b>PRC</b> | Processing    | Tomato processing firm CEOs                                                                                             | 1         |
|            | <b>TOTAL</b>  |                                                                                                                         | <b>79</b> |

## 9.6.2.3 Case Structure

Table A 41: Hub Classifications

| Hub Type                                               | Definition                                                                                       | Key Characteristics                                                                                                      |
|--------------------------------------------------------|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| <b>Primary Production and emerging production Hubs</b> | Established tomato production regions with traditional practices and mature market relationships | Long production history; traditional methods predominate; established trading relationships; limited technology adoption |
|                                                        | Developing areas experiencing technological and market transitions                               | Recent production expansion; active adoption of new techniques; evolving markets; higher innovation receptivity          |
| <b>Commercial Innovation Hubs</b>                      | Centres with advanced technology integration and commercial sophistication                       | High technology adoption; formal market integration; commercial-scale operations; advanced infrastructure                |

#### Assignment Decision Rules

1. Determine the primary location of participant's described activities
2. Identify dominant characteristics of their operational context
3. Assess the technology and institutional arrangements described
4. If the participant operates across contexts, assign based on majority content
5. Document any ambiguous cases for supervisory review

### **9.7 Appendix 7: Semi-Structured Interview and Focus Group Discussion Questions**

#### **9.7.1 Semi- Structured Interview Questions**

##### **Introductory Questions for All Participants**

1. Brief introduction of the participant. Position/role and primary responsibilities.
2. What is the technology(ies) that you use on your farm and food business?
3. How has your organisation/Farm integrated technology into its operations, and how has this impacted efficiency, competitiveness, or compliance?
4. Can you share insights into how your organisation/farm has adopted and managed technological changes?
5. What is the significant food loss that your farm or food business faces?
6. How do you quantify your food loss?
7. What impact does technology have, if any, on food loss and waste in your organisation/farm? How do you measure/quantify these changes, if any?
8. What types of digital technologies do you currently use?

#### **Grassroots Innovation and Resourcefulness (For Large-Scale Farmers, Leaders of Cooperatives)**

1. How has your organisation or community used new methods or tools to improve farming or food loss and waste?
  - What inspired these changes or innovations?
2. How have you used simple technologies or local solutions to help your farming or agrifood business? Could you give examples?
  - How did you learn about these technologies or solutions?
3. Can you tell us when you have used available materials or resources in a new or different way to solve a food loss and waste problem in your farming or food business?
  - Follow-Up: What led you to use these materials in this way?
  - Prompt: Have you ever had to fix a tool with what you had on hand or use a household item in your farming work?
4. Have you ever faced a situation where you had to come up with a quick solution to a farming challenge? What did you do?

- Follow-Up: How often do such situations occur where you need to think on your feet?
  - What are some of the biggest challenges you face in your work related to farming or food production?
  - How have you managed to overcome these challenges?
5. In your community, what are the common ways or practices of using everyday items or local materials for farming or managing food?
    - Follow-Up: How are these practices shared or passed down within the community?
    - Do you have any examples of these practices that you have adopted or adapted?
  6. When you need access to specific tools or technology, how do you manage to get your work done?
    - Follow-Up: What guides your decisions when you must make do with limited resources?
  7. What have you learned from experiences where you had to improvise or use available resources?
    - Follow-Up: How have these learnings influenced your approach to farming or business?
    - Prompt: Do these experiences change how you prepare for or think about future challenges?
  8. How have your new methods or technologies made a difference in your work?
    - Could you share a specific example of how these innovations have helped?
  9. Do you work with other farmers or community members to come up with new ideas or share knowledge? Can you tell us about that?
    - How important is community cooperation in finding new ways to do things?
  10. In situations where you haven't received much support or guidance from the government or other organisations, how have you found solutions or improved your work?
    - What kinds of support would be most helpful for you and your community?
  11. What changes or improvements would you like to see in your farming or food production activities?

## Conclusion

1. What advice would you give to other farmers or communities who might be facing challenges similar to yours?
2. What has been the most valuable lesson you've learned from your experiences?

## **Strategic Alignment and Compliance (For AgriTech Firms, Agri-focused venture capitalists, Government ministries and agencies for food regulation)**

1. In what ways does your organisational strategy reflect a response to the existing regulatory frameworks and market forces in the agri-food sector?

2. How do institutional norms and regulatory environments shape your technology-adoption decision-making processes?
3. Could you detail the digital technologies adopted by your organisation to enhance supply chain efficiency and reduce food waste?
  - What impacts, both expected and unexpected, have these technologies had on operational efficiency and waste management?
4. How have institutional pressures, such as regulations and policies, influenced your organisation's approach towards technology adoption for food waste management?
  - Can you describe an instance where regulatory changes necessitated a strategic shift in your technology approach?
5. How do your organisation's abundant resources facilitate a strategic response to market behaviours in the agri-food sector?
6. What strategies does your organisation employ to balance regulatory compliance and achieving a competitive edge?
7. What are the predominant challenges encountered in implementing technologies aimed at food waste reduction?
  - Could you share innovative practices or technological breakthroughs your organisation has initiated to address these challenges?
8. What methodologies does your organisation employ to assess the effectiveness of implemented technologies in food waste reduction?
  - Are there any success stories or significant learnings from your digital transformation initiatives to minimise food loss?

## Conclusion

1. What trends do you foresee in adopting digital technologies for food waste reduction in the agri-food sector?
2. Based on your experiences, what insights would you offer to other organisations aiming to align technologically with institutional pressures for waste reduction?

## **Innovation and Competitive Differentiation (for Large private sector companies in agri-processing, technology and innovation centres and acceleration programmes, NGOs)**

1. How does your organisation allocate resources to foster technological innovation in Nigeria's business environment?
2. Could you describe a situation where the unique Nigerian market conditions enabled or required innovative use of technology in your operations?
3. How has your organisation used technological innovation to establish a competitive edge in Nigeria's agri-food sector?
  - Can you provide a Nigerian-specific example where technology adoption significantly altered your market position or operational efficiency?
4. How does your organisation balance technological innovation with the evolving market dynamics and consumer behaviours specific to Nigeria?
  - How do local market insights and Nigerian consumer feedback shape your technology strategies?



5. How does Nigeria's institutionally weak environment influence your technology adoption and innovation approach?
  - What unique challenges or opportunities have shaped your organisation's technological advancements in Nigeria?
6. How does your organisation's culture within the Nigerian context support technological innovation?
7. What role do Nigerian market dynamics and leadership play in driving technological changes within your organisation?
8. What specific metrics or indicators does your organisation use to measure the success of its technological innovations in Nigeria?
  - Could you share a case where a technological initiative significantly impacted your operations within the Nigerian market?
9. What future technological trends do you anticipate in Nigeria's agri-food sector, and how is your organisation preparing to adapt or lead in these areas?
  - Considering Nigeria's unique market conditions, what future technological advancements do you foresee being most impactful?

## Conclusion

1. Based on your experiences in Nigeria, what advice would you offer to similar organisations seeking to leverage technology for competitive advantage?

## **Compliance-Driven Resource Development (For Selected Local smallholder farmer cooperatives, small food processing Units, Microfinance banks for agriculture, and Local Agritech startups)**

1. How does your organisation strategise its technology adoption in Nigeria's regulatory landscape to meet compliance requirements?
2. Could you describe a specific instance where regulatory compliance directly influenced your decision to adopt a particular technology?
3. Considering your organisation's resource constraints, how do you prioritise technological investments to optimise operations?
4. Can you provide an example of a low-cost or resource-efficient technology your organisation has successfully implemented?
5. How do your organisation's resource constraints impact its ability to navigate Nigeria's robust institutional environment?
  - What unique challenges has your organisation faced in this context, and how have you addressed them?
6. Has your organisation formed partnerships or collaborations to overcome resource limitations in adopting necessary technologies?
  - How have these partnerships facilitated compliance and technological advancement within your organisation?
7. How has technology adoption improved operational efficiency within your resource-constrained environment?

- Can you share measurable outcomes or benefits from these technological adoptions?
- 8. What innovative practices has your organisation developed to manage resources more effectively while complying with Nigeria's regulations?
  - How do these practices contribute to your organisation's sustainability and growth?
- 9. Looking ahead, what are your organisation's anticipated challenges and opportunities in continuing to adopt technology within Nigeria's regulatory framework?
  - How is your organisation preparing to meet these future challenges?

### **Conclusion**

1. Based on your experiences, what advice would you give to other resource-constrained organisations in Nigeria facing similar compliance-driven challenges?

### **Focus Group Questions**

#### **Warm-Up (5-10 minutes)**

1. Participant Introduction
  - Ask each participant to introduce themselves and briefly share their farming or business activities.
2. Ice-Breaker Question
  - "What's one thing you enjoy most about your work in farming or food production?"

#### **Main Discussion (30-45 minutes)**

1. Resource Utilization and Improvisation
  - "Can you share an experience where you had to use available materials differently to solve a problem in your work?"
  - Follow up: "What made you think of using these materials in this way?"
2. Creative Problem-Solving
  - "Have there been times you had to come up with a solution on your farm quickly to prevent food loss or waste? What did you do?"
3. Community Practices
  - "Are there common ways in your community to use everyday items for farming and to reduce food loss? How do you learn these practices?"
4. Adaptation to Limitations

- “When specific tools or technologies are not available, how do you manage to complete your work without them?”
5. Learning from Experiences
- “What have you learned from situations where you had to improvise? How has this influenced your work?”

### **Wrap-Up and Conclusion (10-15 minutes)**

#### 1. Final Thoughts

- “Is there anything else you’d like to share about your experiences or ideas that we haven’t covered?”

#### 2. Thank Participants

- Express gratitude for their participation and valuable contributions.

#### 3. Next Steps

- Briefly explain the next steps (e.g., how the findings will be used, potential follow-up).

#### 4. Closure

- Conclude the session and assist participants as needed (e.g., with refreshments or transport arrangements if provided).

## 9.8 Appendix 8: Rationale for Actor Group Categorisation

Table A 42: Rationale for Actor Categorisation for Primary Production Hubs

| Actor Group                 | Rationale                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Supporting Citations                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Primary Actors</b>       | Given the central role farmers play in AFSCs and production systems, this case categorises them as primary. Farmers in this case are responsible for cultivation, harvesting and the management of primary resources. Actors in this category vary in scale (e.g., smallholders, small farms and medium scale producers) and role (e.g., farmers, farm supervisors, farm managers etc.). However, they are considered primary decision makers in the production processes and play a crucial role as adopters of agricultural innovation and technology. These variations reflect the diverse capabilities and challenges | Farmers are regarded as primary value creators (Adekunle and Fatunbi, 2012), central innovation adopters (Klerkx et al., 2012) and play a critical role in shaping upstream supply chain dynamics (Ghosh et al., 2020). Predominantly smallholders in Nigerian agriculture and face resource and infrastructure challenges (Ojo et al., 2022) with medium scale farmers playing a crucial role as bridges between traditional practices and modern methods and technologies (Nwankwo and Iwe, 2021; Barrett et al., 2020). These actors can play a crucial role in enhancing supply chain flexibility (Choi and Hong, 2002). |
| <b>Support Actors</b>       | Support actors in this case include extension agents, agronomists, supply chain management firms, financial services providers and some logistics actors that directly interface with the primary actors. These support actors provide primary actors critical knowledge transfer and technical assistance. In addition, they facilitate innovation diffusion enabling farmers integrate modern practices and technologies while maintaining cultural resilience. These actors facilitate productivity by addressing knowledge gaps, bridging research and practice.                                                      | Extension services actors act as knowledge brokers (Cousins et al., 2006; Faure et al., 2012) and intermediaries between the farmgate implementation and research outputs (Klerkx and Leeuwis, 2008; Aker, 2011). These support actors support soil and crop management (Eze et al., 2020) providing farmgate actors with practical knowledge and skills and facilitating the diffusion of innovation (Fèvres, 2012; Hazen et al., 2012).                                                                                                                                                                                    |
| <b>Market Actors</b>        | Market actors in the tomato supply chain are small scale retailers, aggregators and market coordinators that ensure the flow of produce from the farm to the market. They influence price discovery, support value chain coordination and manage the distribution network                                                                                                                                                                                                                                                                                                                                                 | Market actors play a key role in determining price volatility (Tadesse and Shively, 2009), act as intermediaries (Wiggins and Keats, 2013) and aggregators that connect primary actors to larger supply chains (Sheahan and Barrett, 2017; Christopher, 2022)                                                                                                                                                                                                                                                                                                                                                                |
| <b>Institutional Actors</b> | Institutional actors in this case include cooperative leaders, nonprofit actors and local government actors that create the environment for production. These actors influence policy formation/ implementation, collective action facilitation, resource allocation and capacity building/collective action facilitation                                                                                                                                                                                                                                                                                                 | Institutional actors shape supply chain capabilities (Ketokivi and Mahoney, 2020), address systemic barriers such as the access to finance and infrastructure (World Bank, 2020). Cooperatives support collective bargaining and resource pooling/ access to credit (Chukwuemeka and Anya, 2021)                                                                                                                                                                                                                                                                                                                             |

Table A 43: Rationale for Actor Categorisation for Emerging Production Hubs

| Actor Group                              | Rationale                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Supporting Citations                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Innovation-Focused Primary Actors</b> | Innovation-focused farmers represent a distinct category of agricultural practitioners who actively engage with technological innovation while operating under various resource constraints. Unlike traditional farmers, these practitioners show higher propensity for technological experimentation and actively participate in digital platform usage. They demonstrate particular strength in developing localized solutions to technological challenges and actively participate in knowledge sharing networks.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Innovation-focused farmers are identified as crucial boundary spanners between traditional and modern agricultural practices (von Hippel, 2005), early adopters of agricultural innovation (Rogers, 2003), and knowledge brokers in agricultural communities (Brown and Duguid, 1991). Their role in adapting and implementing new technologies while maintaining operational viability is particularly significant in emerging market contexts (Barrett et al., 2020).                                                                                                                                                                                                                              |
| <b>Support Actors</b>                    | Support actors provide critical technical, financial, and operational expertise that enables the implementation of technological innovation. They serve as knowledge brokers who translate between academic understanding and practical application, while also providing crucial resources and services that enable technological adoption and scaling. Project management professionals engage in complex orchestration work that aligns technological solutions with farmer needs and market requirements. Their role extends beyond simple project management to encompass institutional entrepreneurship, actively creating new arrangements that facilitate technology adoption and value creation. They serve as crucial intermediaries in establishing the legitimacy of new technological approaches while ensuring their practical applicability. Research and advisory actors serve as knowledge generators and translators within the innovation ecosystem. They focus on developing and validating technological solutions while also facilitating knowledge transfer between academic institutions and practical implementation contexts. | Support actors are identified as crucial intermediaries in innovation systems (Klerkx et al., 2012), facilitators of knowledge transfer (Szulanski, 1996), and enablers of technological adoption (Rogers, 2003). Their role in bridging institutional voids is particularly significant in emerging market contexts (Mair et al., 2012). Project management professionals are recognized as institutional entrepreneurs (Battilana et al., 2009), network orchestrators (Dhanaraj and Parkhe, 2006), and knowledge brokers (Carlile, 2004). Their role in facilitating technological adoption and institutional change is particularly critical in emerging market contexts (Mair and Marti, 2009). |
| <b>Technology Actors</b>                 | Technology actors serve as primary catalysts for digital transformation in agricultural innovation systems. They develop and implement digital platforms, create technological solutions for agricultural operations, and bridge traditional farming practices with digital capabilities. These actors demonstrate sophisticated understanding of both technological possibilities and local constraints, enabling them to develop contextually appropriate solutions that address specific challenges in the Nigerian agricultural sector.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Technology actors are recognized as crucial innovation intermediaries (Klerkx and Leeuwis, 2008), digital transformation agents (Nambisan et al., 2017), and institutional entrepreneurs in emerging markets (Maguire et al., 2004). Their role in developing contextually appropriate solutions is particularly critical in resource-constrained environments (George et al., 2012), where they must navigate between global technological standards and local operational realities (Barrett et al., 2020).                                                                                                                                                                                        |

|                             |                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                            |
|-----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Institutional Actors</b> | Regulatory authorities provide the institutional framework that shapes digital transformation initiatives in the agricultural sector. They play crucial roles in policy formulation, infrastructure development, and coordination of multi-stakeholder initiatives aimed at modernizing agricultural practices. | Regulatory authorities are identified as crucial institutional actors (Scott, 2008), shapers of innovation ecosystems (Adner and Kapoor, 2010), and facilitators of technological transition (Geels, 2004). Their role in creating enabling environments for innovation is particularly significant in emerging market contexts (Khanna and Palepu, 2010). |
|-----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table A 44: Rationale for Actor Categorisation for Commercial Innovation Hubs

| <b>Actor Group</b>                       | <b>Rationale</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | <b>Supporting Citations</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Innovation-Focused Primary Actors</b> | Innovation-focused farmers represent a distinct category of agricultural practitioners who actively engage with technological innovation while operating under various resource constraints. Unlike traditional farmers, these practitioners show higher propensity for technological experimentation and actively participate in digital platform usage. They demonstrate particular strength in developing localized solutions to technological challenges and actively participate in knowledge sharing networks.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Innovation-focused farmers are identified as crucial boundary spanners between traditional and modern agricultural practices (von Hippel, 2005), early adopters of agricultural innovation (Rogers, 2003), and knowledge brokers in agricultural communities (Brown and Duguid, 1991). Their role in adapting and implementing new technologies while maintaining operational viability is particularly significant in emerging market contexts (Barrett et al., 2020).                                                                                                                                                                                                                              |
| <b>Support Actors</b>                    | Support actors provide critical technical, financial, and operational expertise that enables the implementation of technological innovation. They serve as knowledge brokers who translate between academic understanding and practical application, while also providing crucial resources and services that enable technological adoption and scaling. Project management professionals engage in complex orchestration work that aligns technological solutions with farmer needs and market requirements. Their role extends beyond simple project management to encompass institutional entrepreneurship, actively creating new arrangements that facilitate technology adoption and value creation. They serve as crucial intermediaries in establishing the legitimacy of new technological approaches while ensuring their practical applicability. Research and advisory actors serve as knowledge generators and translators within the innovation ecosystem. They focus on developing and validating technological solutions while also facilitating knowledge transfer between academic institutions and practical implementation contexts. | Support actors are identified as crucial intermediaries in innovation systems (Klerkx et al., 2012), facilitators of knowledge transfer (Szulanski, 1996), and enablers of technological adoption (Rogers, 2003). Their role in bridging institutional voids is particularly significant in emerging market contexts (Mair et al., 2012). Project management professionals are recognized as institutional entrepreneurs (Battilana et al., 2009), network orchestrators (Dhanaraj and Parkhe, 2006), and knowledge brokers (Carlile, 2004). Their role in facilitating technological adoption and institutional change is particularly critical in emerging market contexts (Mair and Marti, 2009). |

|                             |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Technology Actors</b>    | Technology actors serve as primary catalysts for digital transformation in agricultural innovation systems. They develop and implement digital platforms, create technological solutions for agricultural operations, and bridge traditional farming practices with digital capabilities. These actors demonstrate sophisticated understanding of both technological possibilities and local constraints, enabling them to develop contextually appropriate solutions that address specific challenges in the Nigerian agricultural sector. | Technology actors are recognized as crucial innovation intermediaries (Klerkx and Leeuwis, 2008), digital transformation agents (Nambisan et al., 2017), and institutional entrepreneurs in emerging markets (Maguire et al., 2004). Their role in developing contextually appropriate solutions is particularly critical in resource-constrained environments (George et al., 2012), where they must navigate between global technological standards and local operational realities (Barrett et al., 2020). |
| <b>Institutional Actors</b> | Regulatory authorities provide the institutional framework that shapes digital transformation initiatives in the agricultural sector. They play crucial roles in policy formulation, infrastructure development, and coordination of multi-stakeholder initiatives aimed at modernizing agricultural practices.                                                                                                                                                                                                                             | Regulatory authorities are identified as crucial institutional actors (Scott, 2008), shapers of innovation ecosystems (Adner and Kapoor, 2010), and facilitators of technological transition (Geels, 2004). Their role in creating enabling environments for innovation is particularly significant in emerging market contexts (Khanna and Palepu, 2010).                                                                                                                                                    |

## 9.9 Appendix 9: Codes and Quotes from First-Order to Conceptual Categories

Table A 45: Coding From Case 1: Primary Production Hubs

| Detailed Quotes                                                                                                                                                                                                                                           | First-Order Code                                                                                                  | Second-Order Code         | Higher Analytical Category | Conceptual Category                                   |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|---------------------------|----------------------------|-------------------------------------------------------|
| "I don't use any fancy soil monitoring devices or environmental sensors... I just use traditional methods, like holding a stick and roping it to support the tomatoes." (FRM05)                                                                           | Soil monitoring devices, Environmental sensors, Digital pest identification, Weather monitoring tools             | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "We don't have any machines for automatic cultivation or weather monitoring tools... we are not even aware of digital pest identification systems that could help us." (FRM04)                                                                            | Soil monitoring devices, Environmental sensors, Digital pest identification, Weather monitoring tools             | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "I use a soil moisture sensor that helps me determine the amount of water in the soil... I also use a pH meter, which measures the acidity or alkalinity of the soil, and an EC meter which measures the concentration of nutrients in the soil." (AGR02) | Soil monitoring devices, Environmental sensors, Digital pest identification, Weather monitoring tools             | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "Most times, our storage facilities are very limited, and the transport infrastructure is poor... now, we also don't have consistent power supply or enough water access." (FRM01)                                                                        | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "We must sell quickly or let the produce go to waste because of our storage facility limitations and transport infrastructure gaps... Unfortunately, there are no solutions with our inconsistent power supply." (FRM13)                                  | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "One of the key things bringing high percentage losses is storage facilities... if you are transporting tomatoes from Jigawa State to Lagos, by the time the vehicle gets there, 40% of the tomatoes are rotting because of poor road networks." (EXT01)  | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "All the greenhouses that are in operation do not have controlled environments because we cannot control the temperature... we don't have the cooling facilities [because] one needs electrical energy, and we don't have that capacity." (ORG01)         | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "Now, I face many smartphone adoption barriers and internet connectivity issues... When I can overcome the device cost constraints, I open YouTube to                                                                                                     | Smartphone adoption barriers, Internet connectivity issues, Device                                                | Digital Access            | Digital Access             | Digital Access & Knowledge Fragmentation              |



| Detailed Quotes                                                                                                                                                                                                                                      | First-Order Code                                                                                           | Second-Order Code   | Higher Analytical Category       | Conceptual Category                               |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|---------------------|----------------------------------|---------------------------------------------------|
| search how to use modern technologies despite my digital literacy gaps." (FRM05)                                                                                                                                                                     | cost constraints, Digital literacy gaps                                                                    |                     |                                  |                                                   |
| "Many farmers in our area are unable to fully use these technologies due to network limitations and a lack of accessible digital tools... some farmers do not have a phone, and most [phones they own] are not smartphones." (EXT05)                 | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps | Digital Access      | Digital Access                   | Digital Access & Knowledge Fragmentation          |
| "Most subsistence farmers are in rural areas where, in Nigeria, there are no mobile networks... some don't even have [phones] because they don't have access to the internet; there is no need for them to have an Android phone." (AGR02)           | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps | Digital Access      | Digital Access                   | Digital Access & Knowledge Fragmentation          |
| "We are actually farming in the same environment and rely on extension service contacts... I can ask my neighbour from our peer learning groups or WhatsApp networks what solutions I can use through our farmer associations." (FRM17)              | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations                   | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation          |
| "We have frontline extension agents who we normally use to get to our smallholder farmers... I believe with the current technological improvement, the only way we can improve agricultural production is by adopting digital technologies." (EXT01) | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations                   | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation          |
| "We are in a greenhouse production group that is mainly for farmers who produce peppers, tomatoes, and other produce, where we normally share knowledge that would help other farmers." (AGR09)                                                      | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations                   | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation          |
| "I called my friend who manages demonstration plots and other family members and introduced that variety we saw during field trials and training workshops..." (FRM02)                                                                               | Demonstration plots, Field trials, Training workshops, Extension materials                                 | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "The challenge we face is lack of access to demonstration plots and field trials... since we don't have any training workshops or extension materials at the moment." (FRM17)                                                                        | Demonstration plots, Field trials, Training workshops, Extension materials                                 | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "Farmers can more easily adopt new practices when introduced through demonstration trials... seeing the techniques in action on demonstration plots allows farmers to understand and apply the innovations more effectively." (EXT05)                | Demonstration plots, Field trials, Training workshops, Extension materials                                 | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "Regulations are intended to guide behaviour among stakeholders, but a major issue arises when these                                                                                                                                                 | Policy implementation gaps, Regulatory                                                                     | Governance          | Institutional Reconfiguration    | Regulatory Control & Market Coordination Failures |

| Detailed Quotes                                                                                                                                                                                                                    | First-Order Code                                                                                              | Second-Order Code    | Higher Analytical Category                                              | Conceptual Category                                                     |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|----------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------|
| policies are not effectively implemented... this gap between policy design and actual implementation is a critical problem." (EXT05)                                                                                               | frameworks, Enforcement mechanisms, Compliance systems                                                        |                      |                                                                         |                                                                         |
| "We are not aware of those policies... the only policy that we're aware of is the policy of importation restraint to improve local production, which was also defeated by the smugglers." (ORG01)                                  | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems                 | Governance           | Institutional Reconfiguration                                           | Regulatory Control & Market Coordination Failures                       |
| "While interventions exist, they often fail to reach many farmers... there can be a gap between policy and practice. Monitoring and implementing these interventions is crucial." (AGR03)                                          | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems                 | Governance           | Institutional Reconfiguration                                           | Regulatory Control & Market Coordination Failures                       |
| "Tomatoes are perishable... we face cold storage inadequacy, temperature control issues, transport refrigeration gaps, and preservation system limits, so we either have to sell them immediately or risk them perishing." (FRM13) | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "During the time that we normally harvest, we use cold rooms to keep them there... if they are not going to be sold for a week or two weeks, we keep them inside the cold room, which reduces damage significantly." (AGR09)       | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "There is a need for businesses to invest in the way we transport... we need to start transporting produce in cold vans. I visited Japan, Germany, and China and [I saw] vegetable transportation in cold vans." (EXT01)           | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "If the buyer is buying in bulk, we use cold vans... cold vans actually help to reduce that loss, or if possible eliminate the loss altogether, but when it's not in bulk, dispatchers don't have such facilities." (AGR02)        | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "One of the solutions is cyber security... government must really work hard on it so that people will feel secure to deploy their businesses into such technologies and rest assured that their security is guaranteed." (EXT01)   | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust           | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "When we try to introduce digital payment, both the off-takers and the farmers rejected it at once because they feel they cannot transact on this platform                                                                         | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust           | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |

| Detailed Quotes                                                                                                                                                                                                                                                                      | First-Order Code                                                                                       | Second-Order Code        | Higher Analytical Category     | Conceptual Category                                    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|--------------------------|--------------------------------|--------------------------------------------------------|
| because they cannot guarantee the security of their money." (EXT01)                                                                                                                                                                                                                  |                                                                                                        |                          |                                |                                                        |
| "Many of our farmers had to resort to borrowing money because our online registration systems, mobile banking platforms, and digital payment systems aren't accessible... we attempted e-commerce integration but were left with little to show." (FRM02)                            | Online registration systems, Mobile banking platforms, E-commerce integration, Digital payment systems | Digital Service Delivery | Digital Financial Integration  | Contract Enforcement Rigidity & Financial Lock-ins     |
| "We have deployed an application that serves as a meeting point for buyers and sellers... on that platform, the demand is communicated by the customer, the farmer agrees to supply, and the agreement is confirmed on the platform." (EXT01)                                        | Online registration systems, Mobile banking platforms, E-commerce integration, Digital payment systems | Digital Service Delivery | Digital Financial Integration  | Contract Enforcement Rigidity & Financial Lock-ins     |
| "Post-production, we deal more with the e-commerce aspects... [this involves] being able to reach out to customers [so that] customers can make their orders online. We use both the website and WhatsApp business apps to run a shopping cart." (AGR02)                             | Online registration systems, Mobile banking platforms, E-commerce integration, Digital payment systems | Digital Service Delivery | Digital Financial Integration  | Contract Enforcement Rigidity & Financial Lock-ins     |
| "The association helps us with group loan arrangements and cooperative savings... when they harvest using our shared resources, they pay back what they borrowed through joint purchasing." (FRM17)                                                                                  | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                       | Collective Access        | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "We still cooperate as a team through group loan arrangements and cooperative savings, as an organisation with shared resources and joint purchasing..." (FRM04)                                                                                                                     | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                       | Collective Access        | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "We are trying to encourage producer organisations... if these farmers with 0.5 hectares can come together and produce as a group, that group will begin to have a voice and influence in price-fixing and technology use." (EXT01)                                                  | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                       | Collective Access        | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "Unless a platform is created within the financial institution and the farmer's association in conjunction with the Central Bank so that they can regulate the interest and the risk... the farmer's association will [not be able to] monitor farmers in terms of payment." (ORG01) | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                       | Collective Access        | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "My own innovation uses traditional preservation methods and local cooling techniques... I pour the fertilisers inside and cover it, drawing on our cultural farming practices." (FRM02)                                                                                             | Traditional preservation methods, Local cooling techniques, Cultural                                   | Indigenous Knowledge     | Knowledge Hybridization        | Path Dependency & Indigenous Knowledge Marginalization |

| Detailed Quotes                                                                                                                                                                                                                                                                   | First-Order Code                                                                                              | Second-Order Code    | Higher Analytical Category | Conceptual Category                                    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|----------------------|----------------------------|--------------------------------------------------------|
|                                                                                                                                                                                                                                                                                   | farming practices,<br>Community adaptations                                                                   |                      |                            |                                                        |
| "In the past, we relied heavily on chemical pesticides... now we use traditional preservation methods and community adaptations like ash and pepper from our cultural farming practices." (FRM05)                                                                                 | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization    | Path Dependency & Indigenous Knowledge Marginalization |
| "During hot season, some farmers cannot afford shade nets, so I advise them to use palm fronds, which are cheaper... you can reduce the damage from hot season by at least 80%, which I've tested and verified." (AGR09)                                                          | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization    | Path Dependency & Indigenous Knowledge Marginalization |
| "Tomatoes don't need to be stored in a hot place. Just keep them in a cool, dry environment... I separate the tomatoes into categories: ripe, unripe, and overripe. This sorting helps prevent spoilage." (RTL01)                                                                 | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization    | Path Dependency & Indigenous Knowledge Marginalization |
| "We have collaboration with the International Institute of Agriculture and the Department of Agriculture... we are using the [pheromone lures] and the traps to monitor pest activity across the 10 states." (ORG01)                                                              | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |
| "There is standardisation from the Standards Organisation of Nigeria... all those policies are there. But we have to improve in terms of post-harvest loss by using plastic crates." (ORG01)                                                                                      | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |
| "We as professionals serve [as intermediaries] because the person giving the order will give the quality, variety, and specification of what he wants... once the farmer agrees, the extension agent will monitor them and make sure they produce at that specification." (EXT01) | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |

Table A 46: Coding From Case 1: Emerging Production Hubs

| Detailed Quotes                                                                                                                                                                                                                                                | First-Order Code                                                                                                  | Second-Order Code         | Higher Analytical Category | Conceptual Category                                   |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|---------------------------|----------------------------|-------------------------------------------------------|
| "We use soil monitoring devices and environmental sensors on internet through our phones to detect plant diseases and get solutions using digital pest identification." (FRM09)                                                                                | Soil monitoring devices, Environmental sensors, Digital pest identification, Weather monitoring tools             | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "If we join together, we can access soil monitoring devices, environmental sensors, digital pest identification tools, and weather monitoring tools that individually we cannot afford." (FRM09)                                                               | Soil monitoring devices, Environmental sensors, Digital pest identification, Weather monitoring tools             | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "In Nigeria, you need soil monitoring devices, environmental sensors, digital pest identification, and weather monitoring tools to be hands-on to avoid being taken advantage of in the market." (FRM12)                                                       | Soil monitoring devices, Environmental sensors, Digital pest identification, Weather monitoring tools             | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "It takes time and patience to train workers to use soil monitoring devices, environmental sensors, digital pest identification tools, and weather monitoring tools properly and maintain them." (FRM09)                                                       | Soil monitoring devices, Environmental sensors, Digital pest identification, Weather monitoring tools             | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "On my own farm, we have drones with AI technology that helps to do sensing... we use the DJI drone for GPS mapping." (AGR01)                                                                                                                                  | Soil monitoring devices, Environmental sensors, Digital pest identification, Weather monitoring tools             | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "With precision agriculture, we face storage facility limitations and transport infrastructure gaps while trying to determine exact nutrient requirements, alongside power supply inconsistency and water access constraints." (FRM14)                         | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "Some farmers are close friends that we meet regularly to share equipment to overcome storage facility limitations, transport infrastructure gaps, power supply inconsistency, and water access constraints." (FRM09)                                          | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "Most times, it's storage facility limitations and transport infrastructure gaps that allow the middleman to go and buy and still bring it down to Elorie despite power supply inconsistency and water access constraints, making most of the profit." (FRM07) | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |

| Detailed Quotes                                                                                                                                                                                                                 | First-Order Code                                                                                                  | Second-Order Code         | Higher Analytical Category       | Conceptual Category                                   |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|---------------------------|----------------------------------|-------------------------------------------------------|
| "I would like to know what this survey about storage facility limitations, transport infrastructure gaps, power supply inconsistency, and water access constraints is about and how it can help farmers." (FRM07)               | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination            | Technological Absorption & Infrastructure Constraints |
| "The issue of logistics in Nigeria is [that], one, most products do not have efficient means of transport... the infrastructure for logistics, these are some of the issues affecting farmers." (AGR01)                         | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination            | Technological Absorption & Infrastructure Constraints |
| "We struggle with smartphone adoption barriers and internet connectivity issues, plus the device cost constraints and digital literacy gaps affect our ability to implement drip irrigation systems." (FRM09)                   | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps        | Digital Access            | Digital Access                   | Digital Access & Knowledge Fragmentation              |
| "We face smartphone adoption barriers and internet connectivity issues, plus we are not the developers of the app so we cannot control device cost constraints or address digital literacy gaps." (FRM09)                       | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps        | Digital Access            | Digital Access                   | Digital Access & Knowledge Fragmentation              |
| "With these rates now and the smartphone adoption barriers, internet connectivity issues, device cost constraints, and digital literacy gaps we are facing with the exchange rates, the capital can be very intensive." (FRM09) | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps        | Digital Access            | Digital Access                   | Digital Access & Knowledge Fragmentation              |
| "We need more training to overcome smartphone adoption barriers, internet connectivity issues, device cost constraints, and digital literacy gaps from extension workers to understand new farming methods." (FRM06)            | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps        | Digital Access            | Digital Access                   | Digital Access & Knowledge Fragmentation              |
| "We make use of extension service contacts and participate in peer learning groups, including WhatsApp networks and farmer associations, to share information about humidity checkers in the nursery." (FRM03)                  | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations                          | Network Stewardship       | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation              |
| "You need reliable extension service contacts and peer learning groups with strong WhatsApp networks to maintain farmer associations, which is a challenge." (FRM14)                                                            | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations                          | Network Stewardship       | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation              |
| "The cost of greenhouse is too high because of limited extension service contacts, peer learning                                                                                                                                | Extension service contacts, Peer learning                                                                         | Network Stewardship       | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation              |

| Detailed Quotes                                                                                                                                                                                                                                               | First-Order Code                                                                              | Second-Order Code   | Higher Analytical Category       | Conceptual Category                               |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|---------------------|----------------------------------|---------------------------------------------------|
| groups, WhatsApp networks, and farmer associations that could help small farmers afford proper equipment." (FRM14)                                                                                                                                            | groups, WhatsApp networks, Farmer associations                                                |                     |                                  |                                                   |
| "We use manure, poultry waste, and manure seed while consulting extension service contacts, peer learning groups, WhatsApp networks, and farmer associations as part of our sustainability guideline." (FRM03)                                                | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations      | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation          |
| "On Instagram, we are about 40,000 [members in our] family-strong network. A simple message is enough to get across to everybody... a WhatsApp call with everyone would be more effective than hosting a Zoom meeting." (AGR01)                               | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations      | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation          |
| "Majority of farmers don't have access to demonstration plots or field trials, and there's limited training workshops and extension materials - they don't even have android phones and where they live there is no internet connectivity." (FRM07)           | Demonstration plots, Field trials, Training workshops, Extension materials                    | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "Many farmers have no access to demonstration plots or field trials, and without training workshops or extension materials, they remain unaware of prevailing market prices, which negatively impacts their production and financial stability." (FRM14)      | Demonstration plots, Field trials, Training workshops, Extension materials                    | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "We need greenhouses, demonstration plots, field trials, training workshops, and extension materials to deal with unpredictable weather patterns." (FRM14)                                                                                                    | Demonstration plots, Field trials, Training workshops, Extension materials                    | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "Using demonstration plots to show how ginger controls insects and field trials for eggshells providing calcium, we offer training workshops and share extension materials that show our innovative approaches." (FRM09)                                      | Demonstration plots, Field trials, Training workshops, Extension materials                    | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "We face policy implementation gaps and inadequate regulatory frameworks, making accessing useful farming apps quite challenging. Enforcement mechanisms are weak, and compliance systems don't ensure farming apps rather than games are available." (FRM12) | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance          | Institutional Reconfiguration    | Regulatory Control & Market Coordination Failures |
| "Policy implementation gaps mean if I send someone else to check prices, they might misinform me. In Nigeria, regulatory frameworks and enforcement mechanisms require you to be hands-on with compliance systems." (FRM12)                                   | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance          | Institutional Reconfiguration    | Regulatory Control & Market Coordination Failures |



| Detailed Quotes                                                                                                                                                                                                                         | First-Order Code                                                                                              | Second-Order Code        | Higher Analytical Category                                              | Conceptual Category                                                     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|--------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------|
| "The problem of tomato price in the last few months stems from policy implementation gaps, regulatory frameworks, enforcement mechanisms, and compliance systems failing to address weather and climate change." (FRM09)                | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems                 | Governance               | Institutional Reconfiguration                                           | Regulatory Control & Market Coordination Failures                       |
| "For insects, we need policy implementation gaps to be addressed, better regulatory frameworks, stronger enforcement mechanisms, and improved compliance systems while using ginger to control them and eggshells for calcium." (FRM09) | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems                 | Governance               | Institutional Reconfiguration                                           | Regulatory Control & Market Coordination Failures                       |
| "Investing in cold chain logistics and improved methods of storage is where the problem is... you do not expect [that] in 2024 we are still transporting perishables without proper cold chain systems." (AGR01)                        | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics     | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "Storage creates data privacy concerns and mechanization raises cybersecurity issues - those are some of the information control worries and digital payment fears we are facing." (FRM06)                                              | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust               | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "I'm working on addressing data privacy concerns and cybersecurity issues by getting the state government to visit and assess our information control worries and digital payment fears." (FRM12)                                       | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust               | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "I used to watch YouTube videos, managing data privacy concerns and cybersecurity issues while exchanging ideas with our farmer group where we discuss information control worries and digital payment fears." (FRM09)                  | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust               | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "We repurpose feed sacks as mulching material to address data privacy concerns and cybersecurity issues instead of expensive commercial options that might create information control worries and digital payment fears." (FRM14)       | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust               | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "We connect small-scale Nigerian farmers to final end consumers... we do this through the use of open-source technological tools to boost productivity." (AGR01)                                                                        | Online registration systems, Mobile banking platforms, E-commerce integration, Digital payment systems        | Digital Service Delivery | Digital Financial Integration                                           | Contract Enforcement Rigidity & Financial Lock-ins                      |
| "An average Nigerian spends the most time on WhatsApp every day... these are some of the platforms we use instead of building software from scratch." (AGR01)                                                                           | Online registration systems, Mobile banking platforms, E-commerce                                             | Digital Service Delivery | Digital Financial Integration                                           | Contract Enforcement Rigidity & Financial Lock-ins                      |



| Detailed Quotes                                                                                                                                                                                                                                               | First-Order Code                                                                                              | Second-Order Code    | Higher Analytical Category     | Conceptual Category                                    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|----------------------|--------------------------------|--------------------------------------------------------|
|                                                                                                                                                                                                                                                               | integration, Digital payment systems                                                                          |                      |                                |                                                        |
| "The challenge we're facing is with group loan arrangements and cooperative savings; we're burning more of our shared resources because we lack joint purchasing power for irrigation." (FRM03)                                                               | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "Policymakers should collaborate with enforcement agents to ensure proper group loan arrangements, cooperative savings, shared resources, and joint purchasing for agricultural practices." (FRM14)                                                           | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "We have WhatsApp groups where we establish group loan arrangements, cooperative savings, shared resources, and joint purchasing to exchange knowledge and support each other in our agricultural endeavors." (FRM14)                                         | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "We use group loan arrangements and cooperative savings to invest in indigenous pots which are wonderful for storage, through shared resources and joint purchasing." (FRM06)                                                                                 | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "The simple solution is resource pooling, because no farmer can do this alone... we should provide it for them, more like a resource centre." (AGR01)                                                                                                         | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "The main problem they have is number one, funding. Funding is a major problem to Nigerian farmers... your platform should be as easy as DIY, do it yourself." (AGR01)                                                                                        | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "We used traditional preservation methods like sticks and nets sourced from local markets to construct a shade house using local cooling techniques and cultural farming practices that serves like a greenhouse, showing our community adaptations." (FRM12) | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization        | Path Dependency & Indigenous Knowledge Marginalization |
| "We take samples randomly using traditional preservation methods and local cooling techniques, following cultural farming practices with community adaptations to give us an average and ensure quality." (FRM03)                                             | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization        | Path Dependency & Indigenous Knowledge Marginalization |
| "These workers don't understand traditional preservation methods or local cooling techniques. They just want a job without learning cultural farming                                                                                                          | Traditional preservation methods, Local cooling techniques, Cultural                                          | Indigenous Knowledge | Knowledge Hybridization        | Path Dependency & Indigenous Knowledge Marginalization |

| Detailed Quotes                                                                                                                                                                                                                                                      | First-Order Code                                                                                              | Second-Order Code    | Higher Analytical Category | Conceptual Category                                    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|----------------------|----------------------------|--------------------------------------------------------|
| practices. As the one in charge, it's my responsibility to teach them community adaptations." (FRM12)                                                                                                                                                                | farming practices, Community adaptations                                                                      |                      |                            |                                                        |
| "The process is typically localized using traditional preservation methods and local cooling techniques, choosing the right location and land according to cultural farming practices, even adapting the process of planting through community adaptations." (FRM06) | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization    | Path Dependency & Indigenous Knowledge Marginalization |
| "We make use of chemical usage tracking and product traceability through mosquito nets and local materials to create effective solutions without high costs, ensuring quality certification and standards compliance." (FRM14)                                       | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |
| "We follow specific chemical usage tracking and product traceability procedures to maintain quality certification and meet standards compliance requirements in the market." (FRM14)                                                                                 | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |
| "The biggest challenge is teaching farmers to adopt chemical usage tracking, product traceability, quality certification, and standards compliance practices effectively." (FRM12)                                                                                   | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |
| "It is a farm-centric platform... it gives consumers [the ability to know] where [their] food is coming from. Consumers can [identify] what farm it is coming from." (AGR01)                                                                                         | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |

| Detailed Quotes                                                                                                                                                                                                                             | First-Order Code                                                                                               | Second-Order Code         | Higher Analytical Category | Conceptual Category                                   |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|---------------------------|----------------------------|-------------------------------------------------------|
| "We use soil monitoring devices and environmental sensors on internet through our phones to detect plant diseases and get solutions using digital pest identification." (FRM09)                                                             | Soil monitoring devices,<br>Environmental sensors,<br>Digital pest identification,<br>Weather monitoring tools | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "If we join together, we can access soil monitoring devices, environmental sensors, digital pest identification tools, and weather monitoring tools that individually we cannot afford." (FRM09)                                            | Soil monitoring devices,<br>Environmental sensors,<br>Digital pest identification,<br>Weather monitoring tools | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "In Nigeria, you need soil monitoring devices, environmental sensors, digital pest identification, and weather monitoring tools to be hands-on to avoid being taken advantage of in the market." (FRM12)                                    | Soil monitoring devices,<br>Environmental sensors,<br>Digital pest identification,<br>Weather monitoring tools | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "It takes time and patience to train workers to use soil monitoring devices, environmental sensors, digital pest identification tools, and weather monitoring tools properly and maintain them." (FRM09)                                    | Soil monitoring devices,<br>Environmental sensors,<br>Digital pest identification,<br>Weather monitoring tools | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "iWIT is a precision IoT irrigation system that allows a farmer to intelligently monitor their irrigation activities and analyze water use and automatically schedule irrigation for them." (TEC01)                                         | Soil monitoring devices,<br>Environmental sensors,<br>Digital pest identification,<br>Weather monitoring tools | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "We developed Farm Factory as a climate control system... you can turn your traditional greenhouse into a smart greenhouse by controlling the temperature, relative humidity, and lighting systems." (TEC01)                                | Soil monitoring devices,<br>Environmental sensors,<br>Digital pest identification,<br>Weather monitoring tools | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "You need IoT devices, like the sensors, you need data collection... the IoT sensors really want to collect real time data, like maybe soil moisture, humidity... then you create a dashboard that can feed into people's devices." (TEC03) | Soil monitoring devices,<br>Environmental sensors,<br>Digital pest identification,<br>Weather monitoring tools | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "We delivered an automated dryer that you can control via Wi-Fi, tell it what to do, can log [it] into [the] internet and control it everywhere and collect data." (RSR01)                                                                  | Soil monitoring devices,<br>Environmental sensors,<br>Digital pest identification,<br>Weather monitoring tools | Technology Integration    | Technology-enabled Systems | Technological Absorption & Infrastructure Constraints |
| "With precision agriculture, we face storage facility limitations and transport infrastructure gaps while trying to determine exact nutrient requirements,                                                                                  | Storage facility limitations,<br>Transport infrastructure gaps,<br>Power supply                                | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |

| Detailed Quotes                                                                                                                                                                                                                                      | First-Order Code                                                                                                  | Second-Order Code         | Higher Analytical Category | Conceptual Category                                   |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|---------------------------|----------------------------|-------------------------------------------------------|
| alongside power supply inconsistency and water access constraints." (FRM14)                                                                                                                                                                          | inconsistency, Water access constraints                                                                           |                           |                            |                                                       |
| "Some farmers are close friends that we meet regularly to share equipment to overcome storage facility limitations, transport infrastructure gaps, power supply inconsistency, and water access constraints." (FRM09)                                | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "Most times, it's storage facility limitations and transport infrastructure gaps that allow the middleman to go and buy and still bring it down despite power supply inconsistency and water access constraints, making most of the profit." (FRM07) | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "I would like to know what this survey about storage facility limitations, transport infrastructure gaps, power supply inconsistency, and water access constraints is about and how it can help farmers." (FRM07)                                    | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "End-to-end technology can be quite costly, hosting your servers, your infrastructure... servers are priced in US dollars... there's a glaring lack of anything that looks like insurance." (SCM01)                                                  | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "There's the bad state of [physical] infrastructure... when it starts to rain or when things are happening, there's disruptions to movement of goods. Those are the things that will cost you the most." (SCM01)                                     | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "Post-harvest loss is massive... we're having an energy crisis. And the energy crisis, even when they have equipment, for example [a] dryer, they still need energy to process." (RSR01)                                                             | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "We have massive plants that have been set up and they have to close down... the Dangote tomato plant in Kano is down, then we have Erisco Foods, that plant is down too." (RSR01)                                                                   | Storage facility limitations, Transport infrastructure gaps, Power supply inconsistency, Water access constraints | Infrastructure Management | Resource Coordination      | Technological Absorption & Infrastructure Constraints |
| "We struggle with smartphone adoption barriers and internet connectivity issues, plus the device cost constraints and digital literacy gaps affect our ability to implement drip irrigation systems." (FRM09)                                        | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps        | Digital Access            | Digital Access             | Digital Access & Knowledge Fragmentation              |

| Detailed Quotes                                                                                                                                                                                                                 | First-Order Code                                                                                           | Second-Order Code   | Higher Analytical Category       | Conceptual Category                      |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|---------------------|----------------------------------|------------------------------------------|
| "We face smartphone adoption barriers and internet connectivity issues, plus we are not the developers of the app so we cannot control device cost constraints or address digital literacy gaps." (FRM09)                       | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps | Digital Access      | Digital Access                   | Digital Access & Knowledge Fragmentation |
| "With these rates now and the smartphone adoption barriers, internet connectivity issues, device cost constraints, and digital literacy gaps we are facing with the exchange rates, the capital can be very intensive." (FRM09) | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps | Digital Access      | Digital Access                   | Digital Access & Knowledge Fragmentation |
| "We need more training to overcome smartphone adoption barriers, internet connectivity issues, device cost constraints, and digital literacy gaps from extension workers to understand new farming methods." (FRM06)            | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps | Digital Access      | Digital Access                   | Digital Access & Knowledge Fragmentation |
| "Most of these people are illiterates... we are not really using digital technology yet. Not to a greater extent, only very few of them." (FIN01)                                                                               | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps | Digital Access      | Digital Access                   | Digital Access & Knowledge Fragmentation |
| "One of the things I see is to even have them get credits to buy phones. Even if it's small phones, we can give them credits to say, okay, you pay gradually." (FIN01)                                                          | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps | Digital Access      | Digital Access                   | Digital Access & Knowledge Fragmentation |
| "There's a lot of places... the location that I know as the address... I've never seen it on Google Maps... basically there are some locations that might not really easily be found on Google Maps." (TEC02)                   | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps | Digital Access      | Digital Access                   | Digital Access & Knowledge Fragmentation |
| "We also don't have enough data about our farmers... some of our farmers are illiterates and they don't keep records of the things they do." (FIN01)                                                                            | Smartphone adoption barriers, Internet connectivity issues, Device cost constraints, Digital literacy gaps | Digital Access      | Digital Access                   | Digital Access & Knowledge Fragmentation |
| "We make use of extension service contacts and participate in peer learning groups, including WhatsApp networks and farmer associations, to share information about humidity checkers in the nursery." (FRM03)                  | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations                   | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation |
| "You need reliable extension service contacts and peer learning groups with strong WhatsApp networks                                                                                                                            | Extension service contacts, Peer learning                                                                  | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation |

| Detailed Quotes                                                                                                                                                                                                                                          | First-Order Code                                                                         | Second-Order Code   | Higher Analytical Category       | Conceptual Category                               |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|---------------------|----------------------------------|---------------------------------------------------|
| to maintain farmer associations, which is a challenge." (FRM14)                                                                                                                                                                                          | groups, WhatsApp networks, Farmer associations                                           |                     |                                  |                                                   |
| "The cost of greenhouse is too high because of limited extension service contacts, peer learning groups, WhatsApp networks, and farmer associations that could help small farmers afford proper equipment." (FRM14)                                      | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation          |
| "We use manure, poultry waste, and manure seed while consulting extension service contacts, peer learning groups, WhatsApp networks, and farmer associations as part of our sustainability guideline." (FRM03)                                           | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation          |
| "We established a digital market platform through the Alliance for a Green Revolution in Africa... we utilize social media, like WhatsApp, to communicate with farmers." (PRJ01)                                                                         | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation          |
| "We formed a consortium with three or four partners, including those responsible for soil amendments and NUNS, an association focused on creating market linkages." (PRJ01)                                                                              | Extension service contacts, Peer learning groups, WhatsApp networks, Farmer associations | Network Stewardship | Institutional Knowledge Networks | Digital Access & Knowledge Fragmentation          |
| "Majority of farmers don't have access to demonstration plots or field trials, and there's limited training workshops and extension materials - they don't even have android phones and where they live there is no internet connectivity." (FRM07)      | Demonstration plots, Field trials, Training workshops, Extension materials               | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "Many farmers have no access to demonstration plots or field trials, and without training workshops or extension materials, they remain unaware of prevailing market prices, which negatively impacts their production and financial stability." (FRM14) | Demonstration plots, Field trials, Training workshops, Extension materials               | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "We need greenhouses, demonstration plots, field trials, training workshops, and extension materials to deal with unpredictable weather patterns." (FRM14)                                                                                               | Demonstration plots, Field trials, Training workshops, Extension materials               | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |
| "Using demonstration plots to show how ginger controls insects and field trials for eggshells providing calcium, we offer training workshops and share extension materials that show our innovative approaches." (FRM09)                                 | Demonstration plots, Field trials, Training workshops, Extension materials               | Knowledge Transfer  | Knowledge Governance             | Regulatory Control & Market Coordination Failures |

| Detailed Quotes                                                                                                                                                                                                                                               | First-Order Code                                                                              | Second-Order Code | Higher Analytical Category    | Conceptual Category                               |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-------------------|-------------------------------|---------------------------------------------------|
| "We face policy implementation gaps and inadequate regulatory frameworks, making accessing useful farming apps quite challenging. Enforcement mechanisms are weak, and compliance systems don't ensure farming apps rather than games are available." (FRM12) | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance        | Institutional Reconfiguration | Regulatory Control & Market Coordination Failures |
| "Policy implementation gaps mean if I send someone else to check prices, they might misinform me. In Nigeria, regulatory frameworks and enforcement mechanisms require you to be hands-on with compliance systems." (FRM12)                                   | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance        | Institutional Reconfiguration | Regulatory Control & Market Coordination Failures |
| "The problem of tomato price in the last few months stems from policy implementation gaps, regulatory frameworks, enforcement mechanisms, and compliance systems failing to address weather and climate change." (FRM09)                                      | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance        | Institutional Reconfiguration | Regulatory Control & Market Coordination Failures |
| "For insects, we need policy implementation gaps to be addressed, better regulatory frameworks, stronger enforcement mechanisms, and improved compliance systems while using ginger to control them and eggshells for calcium." (FRM09)                       | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance        | Institutional Reconfiguration | Regulatory Control & Market Coordination Failures |
| "We don't have any specific initiatives in this area... all our regulations and guidelines are posted there, and I don't believe any of them directly address agriculture or the food value chain." (REG01)                                                   | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance        | Institutional Reconfiguration | Regulatory Control & Market Coordination Failures |
| "If AWS is going to come and build a region in Nigeria, the policies state that your data has to reside in Nigeria... that kind of thing will not make them bring in that kind of investment." (TEC03)                                                        | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance        | Institutional Reconfiguration | Regulatory Control & Market Coordination Failures |
| "In terms of regulation, the policies that I've seen so far, they are designed and they look good. The area is the area of implementation and continuous modification to suit the current environment." (RSR01)                                               | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance        | Institutional Reconfiguration | Regulatory Control & Market Coordination Failures |
| "Funding from the research end is a major issue... one thing is for you to develop a technology, but you need to make people know that technology exists for adoption." (RSR01)                                                                               | Policy implementation gaps, Regulatory frameworks, Enforcement mechanisms, Compliance systems | Governance        | Institutional Reconfiguration | Regulatory Control & Market Coordination Failures |



| Detailed Quotes                                                                                                                                                                                                                      | First-Order Code                                                                                              | Second-Order Code    | Higher Analytical Category                                              | Conceptual Category                                                     |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|----------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------|
| "If you're going to introduce things like freeze boxes or using reefers for transportation, then you need real time temperature monitoring... you need dashboards that have uptime 24 hours where you can actually monitor." (SCM01) | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "I would build holding facilities close to the main production sites... invest in a bunch of reefers, and move them from my storage to the main markets. But there's so much risk." (SCM01)                                          | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "ECHO2 is a post-harvest system that allows a cooling environment using our RFID to operate, whereby you can come and store your produce at a particular temperature, and everybody has a tag, an RFID tag." (TEC01)                 | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "If we had cold vehicles, if the roads are good, we have cold vehicles [that] can transport these things from here to Lagos within a day or two with their moisture intact." (FIN01)                                                 | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "Cold Hubs... literally modified local deep freezers... they built it to be solar powered. Their primary focus is at the market where the traders can pay, not at the production where a lot more of the losses happen." (SCM01)     | Cold storage inadequacy, Temperature control issues, Transport refrigeration gaps, Preservation system limits | Cold Chain Logistics | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "Storage creates data privacy concerns and mechanization raises cybersecurity issues - those are some of the information control worries and digital payment fears we are facing." (FRM06)                                           | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust           | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "I'm working on addressing data privacy concerns and cybersecurity issues by getting the state government to visit and assess our information control worries and digital payment fears." (FRM12)                                    | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust           | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "I used to watch YouTube videos, managing data privacy concerns and cybersecurity issues while exchanging ideas with our farmer group where we discuss information control worries and digital payment fears." (FRM09)               | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust           | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "We repurpose feed sacks as mulching material to address data privacy concerns and cybersecurity issues instead of expensive commercial options that                                                                                 | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears               | Data Trust           | Institutional Knowledge Networks                                        | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |



| Detailed Quotes                                                                                                                                                                                                                     | First-Order Code                                                                                       | Second-Order Code        | Higher Analytical Category       | Conceptual Category                                                     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|--------------------------|----------------------------------|-------------------------------------------------------------------------|
| might create information control worries and digital payment fears." (FRM14)                                                                                                                                                        |                                                                                                        |                          |                                  |                                                                         |
| "There's a bit of information asymmetry because someone has to take his phone and call... you're exposed to all sorts of sharp actors who can manipulate pricing in whatever direction they choose." (SCM01)                        | Data privacy concerns, Cybersecurity issues, Information control worries, Digital payment fears        | Data Trust               | Institutional Knowledge Networks | Algorithmic Supply Chain Control & Power Asymmetries in Digital Control |
| "We use tracking devices, because you know you need to know where your farmers are situated... Android phones are also used to receive alerts and sometimes some information we may have for them when they are in groups." (FIN01) | Online registration systems, Mobile banking platforms, E-commerce integration, Digital payment systems | Digital Service Delivery | Digital Financial Integration    | Contract Enforcement Rigidity & Financial Lock-ins                      |
| "We provided digital scales to help them measure their produce accurately... farmers can price their produce accurately without middlemen taking a share of their profits." (PRJ01)                                                 | Online registration systems, Mobile banking platforms, E-commerce integration, Digital payment systems | Digital Service Delivery | Digital Financial Integration    | Contract Enforcement Rigidity & Financial Lock-ins                      |
| "We need to have partners. We are currently working with NIPS to see if they can [develop] software, an accounting [system] for microfinance banks." (FIN01)                                                                        | Online registration systems, Mobile banking platforms, E-commerce integration, Digital payment systems | Digital Service Delivery | Digital Financial Integration    | Contract Enforcement Rigidity & Financial Lock-ins                      |
| "A lot of what we saw at the markets were cash-based deals... situations where people were like, look, this is the money that is here now. You either take it or you see your tomatoes getting spoiled." (SCM01)                    | Online registration systems, Mobile banking platforms, E-commerce integration, Digital payment systems | Digital Service Delivery | Digital Financial Integration    | Contract Enforcement Rigidity & Financial Lock-ins                      |
| "Market information is crucial, and the internet plays a significant role here. It allows farmers to access current market prices and updates. If these farmers are unaware of market prices, off-takers can exploit them." (PRJ01) | Online registration systems, Mobile banking platforms, E-commerce integration, Digital payment systems | Digital Service Delivery | Digital Financial Integration    | Contract Enforcement Rigidity & Financial Lock-ins                      |
| "The challenge we're facing is with group loan arrangements and cooperative savings; we're burning more of our shared resources because we lack joint purchasing power for irrigation." (FRM03)                                     | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                       | Collective Access        | Risk Management Infrastructure   | Contract Enforcement Rigidity & Financial Lock-ins                      |
| "Policymakers should collaborate with enforcement agents to ensure proper group loan arrangements, cooperative savings, shared resources, and joint purchasing for agricultural practices." (FRM14)                                 | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                       | Collective Access        | Risk Management Infrastructure   | Contract Enforcement Rigidity & Financial Lock-ins                      |
| "We have WhatsApp groups where we establish group loan arrangements, cooperative savings,                                                                                                                                           | Group loan arrangements, Cooperative savings,                                                          | Collective Access        | Risk Management Infrastructure   | Contract Enforcement Rigidity & Financial Lock-ins                      |

| Detailed Quotes                                                                                                                                                                                                                                                      | First-Order Code                                                                                              | Second-Order Code    | Higher Analytical Category     | Conceptual Category                                    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|----------------------|--------------------------------|--------------------------------------------------------|
| shared resources, and joint purchasing to exchange knowledge and support each other in our agricultural endeavors." (FRM14)                                                                                                                                          | Shared resources, Joint purchasing                                                                            |                      |                                |                                                        |
| "We use group loan arrangements and cooperative savings to invest in indigenous pots which are wonderful for storage, through shared resources and joint purchasing." (FRM06)                                                                                        | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "Big banks don't like this process. They don't like sponsoring, going into farming and hearing stories of floods, droughts... there's also a very glaring lack of anything that looks like insurance." (FIN01)                                                       | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "Most of our loans must be group lending. That is the only way we can reduce our exposure... we will be able to know their challenges and also teach them a few of these things." (FIN01)                                                                            | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "There's been a lot of work that has been done on identifying farming clusters and farming groups and geo-tagging them. If you take that information and use that as the basis to deploy cold chain assets." (SCM01)                                                 | Group loan arrangements, Cooperative savings, Shared resources, Joint purchasing                              | Collective Access    | Risk Management Infrastructure | Contract Enforcement Rigidity & Financial Lock-ins     |
| "We used traditional preservation methods like sticks and nets sourced from local markets to construct a shade house using local cooling techniques and cultural farming practices that serves like a greenhouse, showing our community adaptations." (FRM12)        | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization        | Path Dependency & Indigenous Knowledge Marginalization |
| "We take samples randomly using traditional preservation methods and local cooling techniques, following cultural farming practices with community adaptations to give us an average and ensure quality." (FRM03)                                                    | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization        | Path Dependency & Indigenous Knowledge Marginalization |
| "These workers don't understand traditional preservation methods or local cooling techniques. They just want a job without learning cultural farming practices. As the one in charge, it's my responsibility to teach them community adaptations." (FRM12)           | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization        | Path Dependency & Indigenous Knowledge Marginalization |
| "The process is typically localized using traditional preservation methods and local cooling techniques, choosing the right location and land according to cultural farming practices, even adapting the process of planting through community adaptations." (FRM06) | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization        | Path Dependency & Indigenous Knowledge Marginalization |

| Detailed Quotes                                                                                                                                                                                                                               | First-Order Code                                                                                              | Second-Order Code    | Higher Analytical Category | Conceptual Category                                    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|----------------------|----------------------------|--------------------------------------------------------|
| "We encourage farmers not to burn crop residues from their fields. Instead, we suggest they use these residues to create compost or as mulch." (PRJ01)                                                                                        | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization    | Path Dependency & Indigenous Knowledge Marginalization |
| "We started introducing organic fertilizers or biochar. The region is rich in rice husks, so we decided to utilize what's locally available to amend the soil." (PRJ01)                                                                       | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization    | Path Dependency & Indigenous Knowledge Marginalization |
| "We design based on the materials we have available... sustainability is always in the core of our design. Whether it is how the water is used for washing, whether it is the material used, weight, how it impacts the environment." (RSR01) | Traditional preservation methods, Local cooling techniques, Cultural farming practices, Community adaptations | Indigenous Knowledge | Knowledge Hybridization    | Path Dependency & Indigenous Knowledge Marginalization |
| "We make use of chemical usage tracking and product traceability through mosquito nets and local materials to create effective solutions without high costs, ensuring quality certification and standards compliance." (FRM14)                | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |
| "We follow specific chemical usage tracking and product traceability procedures to maintain quality certification and meet standards compliance requirements in the market." (FRM14)                                                          | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |
| "The biggest challenge is teaching farmers to adopt chemical usage tracking, product traceability, quality certification, and standards compliance practices effectively." (FRM12)                                                            | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |
| "I believe it's crucial, especially regarding pesticide use. Sometimes, I hesitate to consume tomatoes because I'm uncertain about their source. Farmers often use chemicals incorrectly, which can lead to dangerous residues." (PRJ01)      | Chemical usage tracking, Product traceability, Quality certification, Standards compliance                    | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |
| "Is there a data bank for most of this agricultural produce, do we have a list of, is it structured, do we have like a list of maybe farmers, middlemen... you need to have very good data." (TEC03)                                          | Product traceability, Quality certification, Standards compliance                                             | Transparency Systems | Trust-based Governance     | Path Dependency & Indigenous Knowledge Marginalization |

## 9.10 Appendix 10: Parent-child Mapping of Data

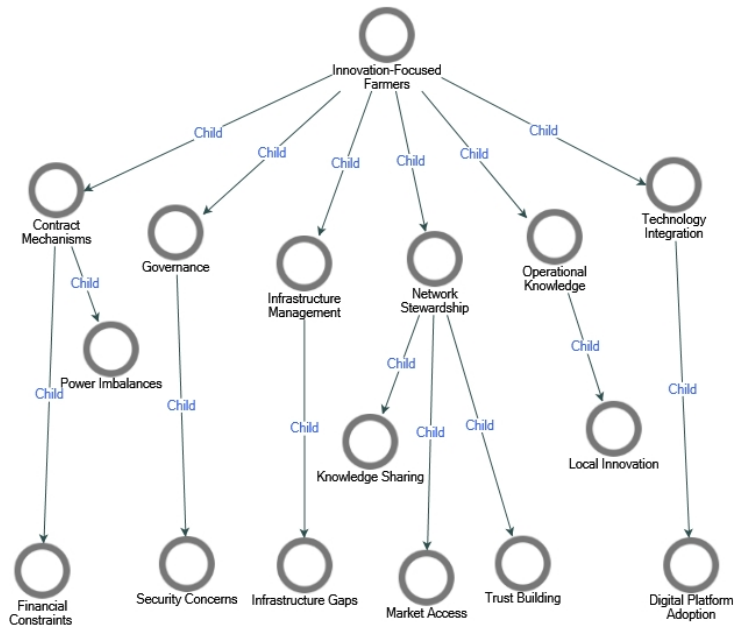


Fig. A 4: Parent-Child Mapping for Innovative Farmers

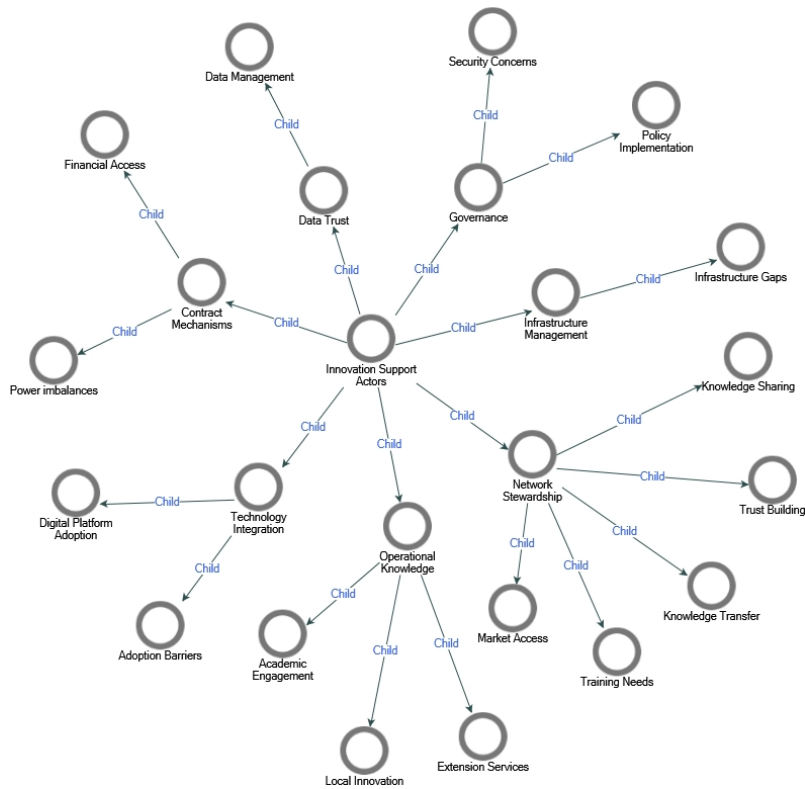


Fig. A 5: Parent-Child Mapping for Commercial Innovation Hubs

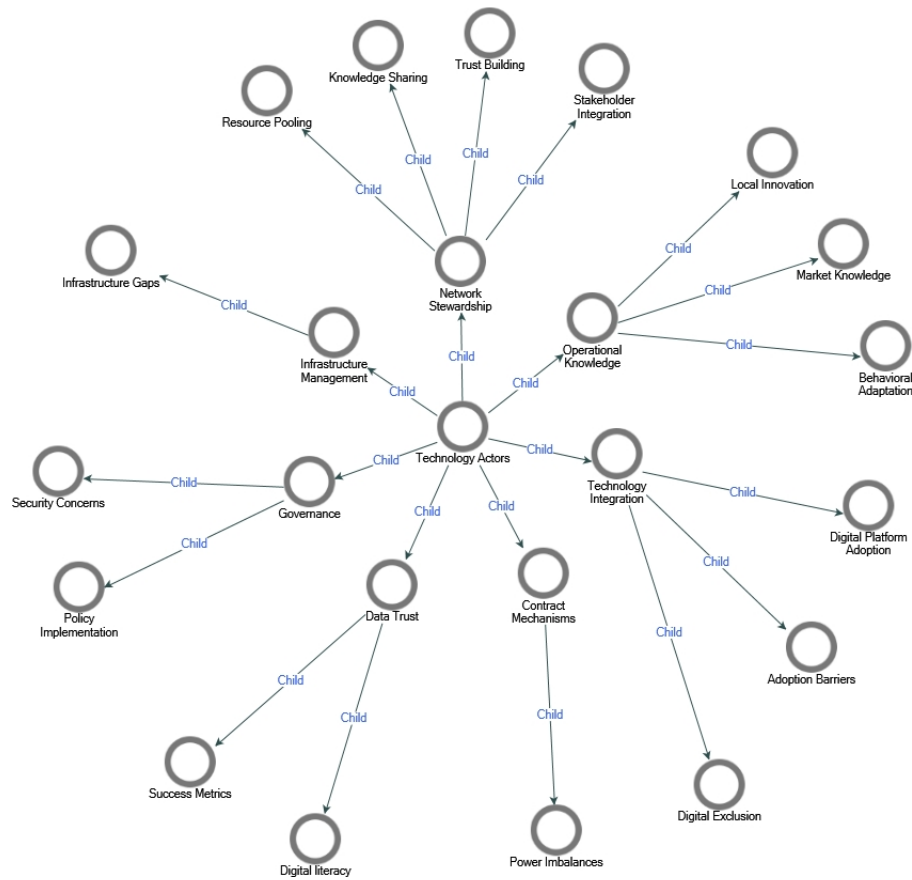


Fig. A 6: Parent-Child Mapping for Technology Actors