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Enabling modern bioenergy deployment in Nigeria to support industry and local communities

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ABSTRACT

Nigeria intends to rank among the top 20 global economies by 2030 by focusing on industrialisation. However, limiting energy access may slow the rate of industrialisation. Bioenergy integration into Nigeria's energy mix can accelerate the industrialisation agenda due to the co-benefits it offers. We used a disaggregated approach to map agri-residue availability and identify knowledge gaps in agri-residue application to support modern and sustainable bioenergy integration into Nigeria's energy mix. Expert interviews with stakeholders from government departments, small- and large-scale industries, and feedstock producers were used to validate the biomass mapping. The output of the biomass mapping shows that residues from yam, sorghum, wheat, palm, cassava, rice, sugarcane, etc, have knowledge gaps in agri-residue application and they could support the industrialisation agenda of Nigeria. The output of the stakeholder engagement shows that fossil fuels are the main energy source for productive uses in Nigeria. Current waste management practices involve onsite burning and disposal on land. Bioenergy technologies currently deployed in Nigeria are predominantly anaerobic digestion and combustion. Stakeholders have a strong preference for electricity to be the predominant energy vector. However, awareness of modern bioenergy applications and technologies was limited even though Nigeria's Energy Masterplan supports the efficient use of biomass to generate clean heat, electricity and biofuel for industrial, transport and household applications. Based on these findings, we have developed a suite of novel bioenergy case studies to support biomass integration into Nigeria's energy system.

1. Introduction

The vision of Nigeria is to grow its economy to within the 20 largest economies in the world by 2030 through industrialisation [1]. To achieve the vision, considerable amounts of energy in the form of electricity, fuel, and heat are needed in the industrial and transport sectors to meet the demand. However, fossil fuel dominates the energy mix projected to meet the industrial energy demand in the Energy Masterplan of Nigeria [1]. On the contrary, the Nigerian government removed fossil fuel subsidies, which could slow the pace of industrialisation. The fossil fuel subsidy removal aims to reduce Nigeria's dependency on imported fuel, support local energy production, increase employment and redeploy financial resources to other sectors of the economy [2]. As for many other nations, an increase in the share of renewable energy can help decarbonise and support the energy demand of Nigeria's industrial, transport and household sectors [3–8]. Bioenergy can support the energy supply of these sectors and offer renewable carbon benefits and a high level of flexibility [5,9].

To show how to advance knowledge on modern bioenergy development and deployment, Okoro et al. [10] conducted a comprehensive review assessing the current state of bioenergy in Nigeria and other Sub-Saharan African countries. The study provided valuable insights, highlighting key research needs and knowledge gaps. The reviewed literature offers an opportunity for expanded research and potential knowledge transfer to low- and middle-income countries [4,10–35]. A look into the existing knowledge on bioenergy in Nigeria reveals limited research on the development and deployment of modern bioenergy in the context of agricultural residues. Current studies primarily focus on less aggregated and largely available feedstocks, leading to some miss match between availability assessments, applications, and feedstock-technology compatibility [24,30,36–43]. Ensuring a proper match between feedstock and technology is crucial for the success of bioenergy systems, as a mismatch could potentially result in the failure of a bioenergy project [10]. Nigerian biomass mapping currently does not adequately account for feedstock mobilisation losses due to competition from other users, aggregation and transportation [10]. To

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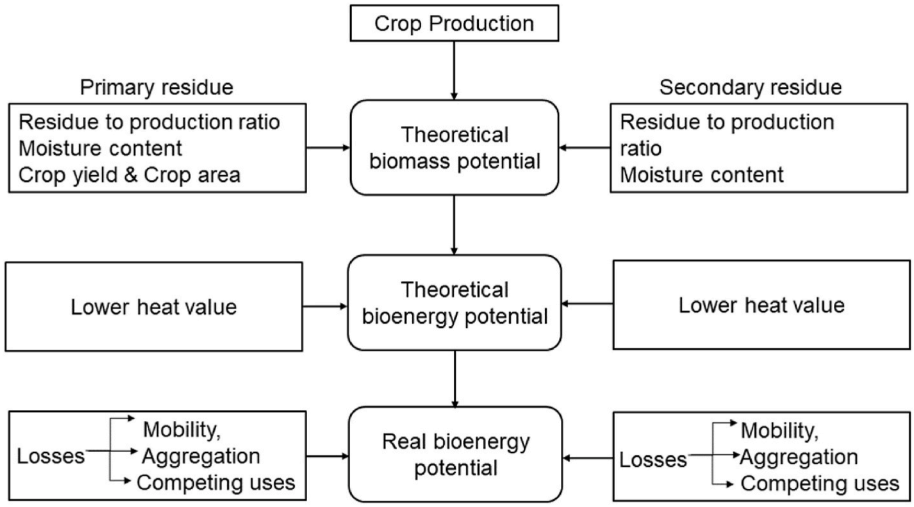

Fig. 1. Biomass mapping framework.

accelerate bioenergy deployment to support industry and communities in Nigeria, there is a need to map the biomass potential of all crops grown in the country because it can play a vital role in determining the scale, application and feedstock-technology-energy fit and location-specific businesses model [10,44,45]. Assessing context and location-specific business models is necessary to understand projects' economic feasibility and profitability [4]. As well as the market and non-market benefits of the business model in the location. Such business models can take into consideration the unique characteristics and constraints of small-scale agriculture in Nigeria and aim to establish reliable and consistent agri-residue supply chains to ensure the efficient and sustainable operation of bioenergy facilities [46–48]. The business model could also consider a range of disaggregated agri-residues in Nigeria that would provide high economic and socio-economic benefits including energy and food security, climate change reduction, economic growth and development, increase in export earnings and forex reserves and rural community development [10].

Furthermore, the existing knowledge in bioenergy system development does not consider involving stakeholders in developing a bioenergy business model for Nigeria [10]. Neglecting stakeholder engagement in bioenergy development can cause the failure of bioenergy projects. To enable modern bioenergy deployment in Nigeria that benefits industry and local communities, stakeholders from relevant sectors in Nigeria must be involved [10]. Involving relevant stakeholders will allow them the opportunity to determine their own energy needs while understanding real feedstock mobilisation potential, appropriate technology deployment and paving the way for novel bioenergy technologies in Nigeria [9,10,49–51].

Against this background, this research aimed at co-creating suites of modern bioenergy case studies to support industry and local communities in Nigeria. In the first step, a disaggregated approach was used to map agri-residue availability and identify knowledge gaps in agri-residue application to support modern and sustainable bioenergy integration into Nigeria's energy mix. Stakeholder engagement with representatives from industry, policy and feedstock producers was used to validate the biomass mapping. The stakeholder engagement provided information on the current agri-residue management, real feedstock mobilisation potential, stakeholders' current energy outlook, aspirational shifts in energy outlook, how bioenergy could supply their aspirational energy requirements, current bioenergy deployment in Nigeria and policy support for bioenergy in Nigeria. Based on the results of stakeholder engagement and the understanding of biomass resources, we created a series of novel modern bioenergy case studies for future consideration in Nigeria. The case studies include a). Exporting electricity to the national grid; b). Community bioenergy application for CHP; c). Biorefinery for transport sector application and d). Integrated bioenergy application for an integrated food processing company. The case studies were validated through guided discussion with the stakeholders, review of Nigeria bioenergy policies and bioenergy investment strategies of Nigeria. The case study selections also considered the different generations of biomass. The first-generation biomass also known as food-based biomass refers to biofuels derived from food crops such as corn, sugarcane, wheat and vegetable oils. The main advantage is the feedstocks relies on well-established technologies, but the feedstock can lead to competition with food production and limited GHG reduction. The second-generation biomass is non-food biomass and are referred to biofuels produced from agri-residues, wood, grasses and waste biomass. They have no competition with food, offers waste utilisation and better GHG reductions, but they can require advance technologies and new infrastructure which can be capital intensive. The third-generation biomass focuses on using algae to produce biofuels. The feedstock has no land requirement, high yield but the technology is capital and energy intensive. The fourth-generation biomass is an emerging field that involves genetically engineered organisms and synthetic biology to enhance biofuel production. They have negative emission and enhanced yield potential, but they are unproven at scale and are capital intensive. Given that this research aims to support industry and local communities in Nigeria, the focus is on second-generation biomass because of the benefits it can offer Nigeria. The bioenergy case studies cover a range of second-generation feedstocks, biological and thermo-chemical applications, as well as energy vectors and users. The case studies are zonal specific, showing the feasibility of utilising available feedstocks in each zone.

The purpose of this whole system case study development approach is to provide industry and policy decision makers with potential resource utilisation alternatives while directly creating a viable route into modern bioenergy deployment that is beneficial for industry at different scales.

2. Method

2.1. Assessment of biomass and bioenergy potentials of agri-residues in Nigeria

Fig. 1 presents the methodological approach used for the biomass resource assessment. The resource assessment provides insights into agri-residues availability, mobilisation, and energy potential of all the crops grown in Nigeria. The biomass resource assessment in this study

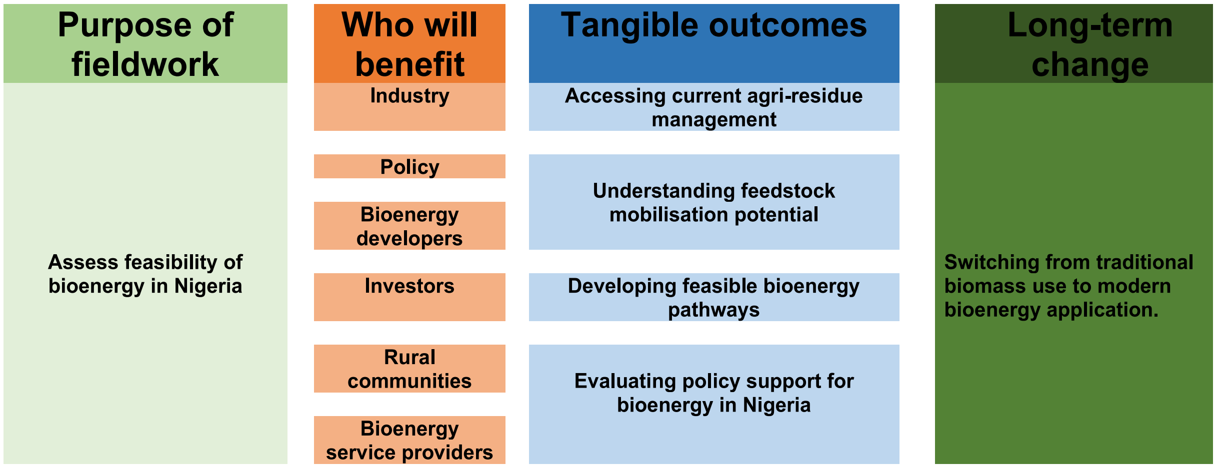

Fig. 2. The stakeholder activity goal framework.

quantifies the biomass feedstock and energy potential from agri-residues only. The assessment considered the knowledge gaps in the scientific literature [10]. A disaggregated approach was used to conduct the assessment to provide complete insight into the biomass and bioenergy potentials of the residues for all the crops grown in Nigeria. The following calculation methods were used to determine agricultural residue availability and the potential for Nigeria's medium-to large--scale energy production. The agricultural residues were first identified as either primary or secondary residues. Those that remain in the field post-harvest are primary residues. Secondary residues are those left at processing facilities. Both primary and secondary residues possess different residue to production ratio and embedded energy content, known as bioenergy potential. The assessment was performed considering two scenarios – theoretical and real biomass potentials.

2.1.1. Assessment of biomass potential from primary residues

Primary residues are residues left in the field after crop harvesting [52], like rice straws, palm fronds, etc. First, the area and crop production data were obtained from the FAO database on the national distribution of all the crop production in Nigeria from 2010 to 2020 [47]. The average annual production, area harvested and yields for each crop were calculated for the period under review and were used for the biomass potential assessment. The primary residue biomass potential was obtained from the product of the average crop area, yield and residue to production ratio (RPR) of each crop. The RPR was obtained from different scientific literature [53,54].

2.1.2. Assessment of biomass potential from secondary residues

Secondary residues are those left at the processing facilities like rice husk, palm kernel shell, corn cob, cassava peel, etc. [52]. The secondary residue biomass potential was obtained from the product of the average annual crop production and RPR of each crop.

2.1.3. Assessment of bioenergy potential for primary and secondary residues

The theoretical bioenergy potential of the residues was calculated using equation (1).

$$Bioenergy\ potential = LHV_{avg} \times W \times \frac{1000}{3.6} \tag{1}$$

Where LHV_{avg} (MJ/kg) is the average low heating value of the residue, W (tonnes) is the weight of the residues, and 1 kWh = 3.6 MJ is converting ratio.

The real biomass and bioenergy potentials of both primary and secondary residues were calculated considering the losses due to mobility, aggregation and competition with other uses. Their estimates were obtained from different scientific literature [55,56].

2.2. Co-designed case studies

Fig. 2 shows the stakeholder activity goal framework. The stakeholder engagement was used to validate the findings of the biomass resource mapping and to assess the feasibility of modern bioenergy in Nigeria.

The stakeholder engagement allowed participants to identify their current and future energy needs for themselves. The advantage of this approach is that it generates a more in-depth and multi-faceted understanding of how to develop a suite of bioenergy case studies and how the case studies could be sustainably deployed within Nigeria. We facilitated series of expert interviews between May 2023 and July 2023 to discuss the potential deployment scales and applications of the case studies as well as their role and impact on Nigeria's energy and agricultural sectors. Stakeholder engagement interviews were held in Abuja, Enugu, Ebonyi, Abia and Lagos states, with experts from policy, industry and feedstock producers. Participants were drawn from:

- **Policy:** We targeted policy makers responsible for initiating and implementing policies that can enable energy production from agricultural residues.
- **Agricultural processing** like palm, rice, sorghum, barley, yam, cassava, potatoes, sugarcane, cashew-nuts, orange, pineapple, pawpaw, banana and vegetables. Most of these crops are knowledge gaps in the feedstock assessment of this research and have high biomass and bioenergy potential. Additionally, they have great potential to positively impact Nigeria's industrial, commercial and export sectors.
- **Steel processing company** as Nigeria has a high deposit of steel that can be mined to support infrastructural development that will trigger and boost industrialisation in Nigeria.
- **Nigerian energy business development company** as energy demand increases with an increase in population and infrastructure.
- **Feedstock producers** including yam, palm, rice and cassava, as these crops are knowledge gaps identified in the feedstock assessment and have high biomass and bioenergy potential. And have great export potential that can contribute to Nigeria's foreign exchange earnings and forex reserve. We informed the participants about the purpose of the research - to assess the feasibility of modern bioenergy in Nigeria. The interview was used to map the current and future deployment of bioenergy in Nigeria and identified a series of priority research themes on which participants agreed modern bioenergy research should focus. The key questions guiding the discussion with the Nigeria stakeholders are;

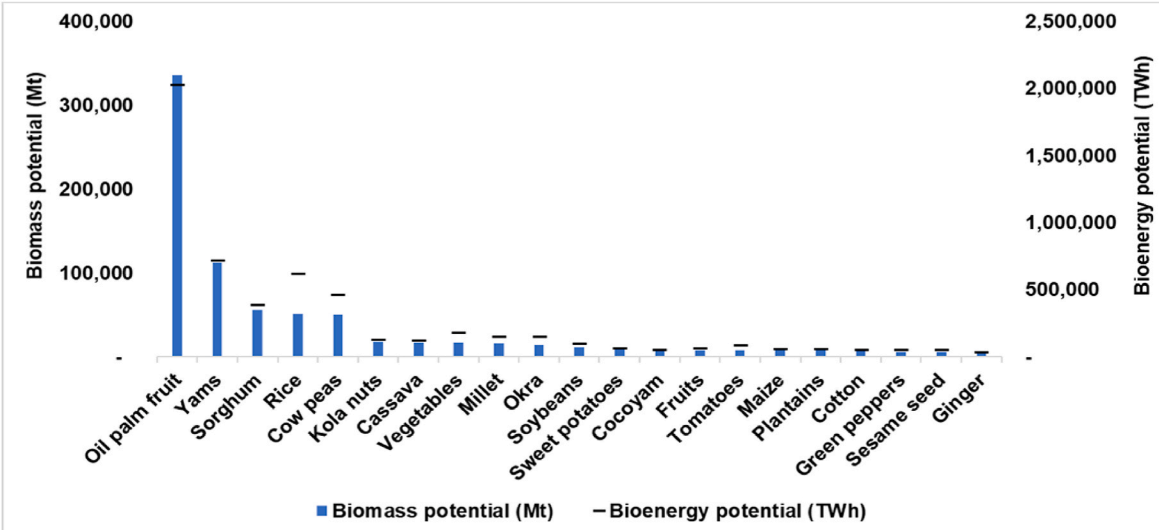

Fig. 3. The most prominent biomass and bioenergy potentials for primary residues.

Table 1
Real feedstock mobilisation potential.

Table 1: Real feedstock mobilisation potential

Factors identified by stakeholders	Observation during fieldwork	Statements from stakeholders	How the identified factors can improve feedstock mobilisation potential
Improved variety	Farmers utilize various crop varieties for farming, with palm farmers employing around three distinct varieties, each with differing fruition periods, fresh bunch sizes, palm fruit sizes, fresh fruit bunch production rates, and harvesting periods. Rice farmers engaged uses FARRO 44 and FARRO 52 varieties for cultivation.	FARRO 44, an improved rice variety in Nigeria, offers some level of drought tolerance, disease resistance, and a shorter harvesting period of 3 to 4 months post-planting. Farmers utilizing FARRO 44 can achieve two cycles of farming annually without irrigation. On the other hand, farmers cultivating with FARRO 52 have a longer harvesting period of 5 to 6 months and can farm one cycle annually.	Among different varieties, those within the improved variety has potential to enhance production, consequently leading to increased feedstock yields.
Planting method	Most rice farmers engaged uses a method known as broadcasting for planting their rice. Using this method expose the grain on the surface of the field.	During the period between broadcasting and germination, birds and other rodents often consume a significant portion of the broadcasted rice grains, leading to a reduction in the quantity of rice that successfully germinates, consequently reducing rice production.	Planting rice grains in nurseries and subsequently transplanting them to the rice fields, reduces the risk of bird and rodent damage. In turn, increases the number of rice grains that successfully grow in the rice fields, thereby boosting rice production.
Access to Farm Inputs	Despite owning extensive hectares of land, many rice farmers struggle to utilize them fully due to limited access to farm inputs.	Lack of access to supports and funds to purchase inputs is primary obstacle to farming. Most can procure only a fraction of the inputs they require, relative to the size of their rice fields. As a result, they make do with a reduced quantity of inputs, leading to reduced rice production.	By facilitating access to these inputs, farmers can optimize crop growth, effectively manage pests and diseases, and ultimately enhance overall productivity leading to high feedstock production.
Mechanized Farming	During stakeholder engagement in different states, farmers including yam, oil palm, cassava, and rice farmers, rely predominantly on human labour for crop cultivation. For example, rice farmers utilize human labour for tasks such as clearing the rice fields, planting rice grains, harvesting ripe rice, and separating rice paddy from the straw.	Farmers emphasized that these manual processes consume substantial human energy and incur high costs, restricting them to cultivating only small portions of their rice fields, thus reducing rice paddy production. However, the introduction of mechanized farming practices, such as the utilization of tractors, harvesters, and other machinery, offers the potential to address these challenges.	Mechanized farming practices, such as the use of tractors, harvesters, and other machinery for tasks such as land preparation, planting, and harvesting can be accomplished more swiftly and efficiently, resulting in higher crop yields and increased feedstock production.
Irrigation	Farmers participated in the stakeholder engagements agreed that irrigation could increase crop production significant.	Rice farmers highlighted that with irrigation, those utilizing FARRO 44 could cultivate three cycles annually, while those using FARRO 52 could also achieve two cycles annually.	The increase in farming directly contributes to increase rice production and subsequent feedstock yield.
Planting and harvesting on time	Farmers utilizing FARRO 44 and FARRO 52 are limited to one cycle annually regardless of irrigation availability if planting and harvesting were delayed.	Delaying the harvest of ripe rice leaves crops vulnerable to bird and rodent predation, as well as diseases. For cassava and yam farmers, untimely harvesting can result in the decay of matured tubers leading to regermination. Additionally, matured yams and cassavas become prone to rodent attacks if not harvested promptly.	Planting and harvesting on time improve yields and reduces crop waste leading to high production of food and feedstocks.
Access to markets	Most farmers reside in the interior villages of Nigeria. They sell their produce on specific market days within a designated time frame. Some manage to sell all their products on these occasions, while others are left with leftovers that either go to waste or are sold at heavily discounted prices	The farmers emphasised that having stable access to markets would enable them to sell their crops in a timely manner and at better prices. This, in turn, would facilitate planting at the right time and utilizing optimal planting periods.	Selling at higher market prices would provide them with more financial resources to invest in farm inputs, enabling them to cultivate larger portions of their uncultivated lands. Leading to improvements in both crop and feedstock production.
Financial support	Most farmers have limited financial support both from government and private organisations.	The farmers believe that providing them with access to affordable credit, grants, subsidies, insurance, and other financial services can enable them to invest in inputs, technology, and infrastructure needed to increase crop production.	Financial support reduces barriers helps farmers manage risks associated with farming, ultimately leading to increased income, higher crop and feedstock yields.
Mobility	Most farmers cultivate their farmlands in remote villages, with limited feeder roads connecting these areas to urban centres where crops are sold.	The absence of adequate transportation infrastructure discourages farmers from cultivating large portions of their farmlands due to the challenges involved in transporting their crops to market. The poor condition of these roads increases the risk of accidents, leading to damage to harvested crops during transportation via cars, motorcycles, and bicycles.	Enhanced transportation facilitates more efficient transportation of crops to markets and provides farmers with access to the information and resources necessary to enhance productivity.
Government policies	Ministry of Agriculture have policy supports for crop production.	The stakeholders agreed that implementing supportive policies and regulations that promote sustainable agriculture, research and development, extension services, and market access can create an enabling environment for increased crop production.	Government policies can incentivize investment in agriculture, provide regulatory frameworks for input and output markets, and support research and extension services to improve farming practices.
Training of farmers	Farmers have limited access to training. Most farmers use traditional approach of farming.	The farmers believe that providing them with access to training, extension services, and technical assistance can improve their knowledge and skills in crop production, pest management, soil conservation, and other agricultural practices.	Training programs empower farmers to adopt modern farming techniques, technologies, and best practices, leading to improved livelihoods, increased crop and feedstock yields.
Sustainable crop processing	Framers uses traditional approach of crop processing.	Palm farmers utilize palm residues as a heat source to parboil their fresh fruits. After parboiling, they transfer the fruits to a local container called 'ikwe' and use their feet, or 'Odu' as the locals call it, to smash them, separating the kernel from the oil pulp. They sieve out the crude palm oil and use some palm residues to heat it further into the final edible palm oil. These oil palm farmers express dissatisfaction with the tedious process of processing their fresh fruit, which discourages them from processing in large quantities.	The use of such unsustainable processing methods significantly impacts feedstock production.

i. What is the current management practice of agricultural wastes in Nigeria?
ii. What affects the availability of agricultural wastes in Nigeria?
iii. Are there feasible energy pathways from agricultural wastes in Nigeria?
iv. Are there adequate institutional frameworks in Nigeria that support the generation of energy from agricultural waste?

3. Results and discussion

The biomass resource assessment was used to identity research gap in agri-residues and their application in Nigeria. A disaggregated approach was used to conduct the assessment to allow a complete insight into the biomass and bioenergy potential of the residues for all the crops grown in Nigeria.

Table 2
Overview of BCS 1 selection criteria and impacts.

Rationale for selection	i. The national grid of Nigeria is highly unreliable with a combined average of about 24 total and partial national grid collapse annually. ii. It would provide industrial, commercial and household energy supplies. iii. It would improve sugar production, create additional jobs for people working on the value chain, and provide a sustainable way for residue management.
Feedstock	The feedstock for this case study is sugarcane bagasse and straw. Sugarcane grown specifically in northern Nigeria is the target for this case study. A whole plant harvesting system would be used to mobilise the cane to the facility.
Conversion	A mixture of the feedstock would be dried to a certain moisture content. Circulating fluidised bed gasifier would be used to convert the feedstock to syngas.
Bioenergy vectors	The syngas produced will be used for CHP to supply industrial energy demand and excess energy exported to the national grid.
Bioenergy system impacts	The techno-economic and socio-economic benefits of the case study will be assessed. The assessment would include the overall sustainability performance of the case study considering feedstock sourcing, conversion technology, and the end-use of the energy.
Potential opportunities	1. **Sustainable energy production** **Use of agri-residues:** Utilising sugarcane bagasse and straw can promote circular economy and reduces waste disposal issues. **Reduction in fossil fuel dependence:** By generating electricity from renewable biomass, the case study supports the transition away from fossil fuels, reducing greenhouse gas emissions and contributing to national clean energy targets. 2. **Energy security and local economic development:** **Stable energy supply:** Producing electricity locally and exporting excess to the national grid can enhance energy security particularly in rural or industrial areas where the sugarcane industry operates. **Job creation:** The development of bioenergy plants, coupled with operations and logistics related to feedstock sourcing, could stimulate local employment opportunities and contribute to rural development. **GDP growth and export earnings:** The solution has great export potential that can contribute to Nigeria's foreign exchange earnings, forex reserve and GDP growth. 3. **Revenue streams and flexibility:** **Multiple outputs:** Industrial energy demands can be met on-site, reducing operational costs for sugarcane processing facilities. Surplus electricity can generate additional income when exported to the grid. **Carbon credits and incentives:** With many countries offering incentives for renewable energy production, this project could benefit from carbon credits or renewable energy certificates (RECs), improving financial returns. 4. **Scalability and replicability:** **Potential for expansion:** Once proven, this bioenergy model could be scaled or replicated across other regions, benefiting from economies of scale and contributing to larger bioenergy adoption.
Potential challenges	1. **Feedstock supply variability:** **Availability of sugarcane bagasse and straw:** Variability in sugarcane harvest due to climatic factors (droughts, floods, etc.) can lead to fluctuations in feedstock availability. **Storage:** The moisture content of bagasse and straw needs to be controlled to ensure efficient gasification and it could require significant infrastructure investment. 2. **Technical and operational issues:** **Gasifier efficiency:** Circulating fluidised bed gasifiers, while efficient, require careful monitoring and maintenance to ensure optimal conversion of biomass to syngas. Issues like feedstock quality, incomplete gasification, or tar formation can lead to lower syngas quality, affecting the efficiency of the combined heat and power (CHP) system. **Grid connection:** Ensuring that the bioenergy plant meets grid code requirements can add complexity to the operation. 3. **Economic viability:** **Cost of technology:** While biomass is often cost-competitive, the initial capital expenditure for gasification technology, CHP systems, and grid connection infrastructure can be high. **Market conditions:** The selling price of electricity to the grid may vary based on government policies, subsidies, and market demand. 4. **Environmental and social concerns:** **Sustainability of biomass sourcing:** Over-reliance on these residues might lead to soil fertility issues if not enough organic material is left for soil regeneration.

3.1. Biomass mapping output

3.1.1. Primary residues biomass and bioenergy potential results

Fig. 3 presents the resource assessment results for the prominent primary residues. Detailed results of the 45 assessed crops are shown in Tables 1 and 3 of Appendixes 1 and 2 of the supplementary material. An average of 1616 Gt primary residues with an embedded energy content of 11,484 PWh could be theoretically mobilised annually in Nigeria. The theoretical biomass potential represents 100 % of the total amount of residue generated without consideration of any other uses, e.g., animal feed, return to the soil, or energy use. In practice, collecting and utilising 100 % of residues is impossible. Even under optimised biomass collection operation, there will be losses and contamination. These constraints were considered in assessing the real biomass potential, such as losses and rejection due to unmet quality constraints along the supply chain during collection, handling and transport, loading and unloading from transport, storage, etc. [55–57].

The real biomass potential is a more realistic assessment whereby 25 % of the residues were assumed to be left in the field to maintain soil fertility [55], 10 % were lost due to contamination [55,56], 5 % were lost during mobility and storage [57] and 10 % lost from other uses (animal feed and bedding, traditional fuel, construction, etc.) [55,56]. After considering these losses, more realistic potentials were obtained. An average of **808** Gt primary residues with an embedded energy content of **5742** PWh can be realistically mobilised annually in Nigeria.

Primary agri-residues provide the largest biomass and bioenergy potential compared to the secondary residues, with the major share coming from oil palm trees followed by staple crops and cereals like yam, sorghum, rice, cowpeas, including kola-nuts and cassava. These residues are plentiful due to large production and a high residue-to-product ratio. Furthermore, the residues have a high dry matter content, making them suitable for thermal conversion like combustion and gasification but less suitable for biological processes like AD. However, crops such as sugarcane, onions, and garlic have a high crop yield, but relatively low crop production and low RPR (see Table 1 of appendix 1 in the supplementary material). This means that their biomass potential is lower than crops with high production and high RPR. Moreover, residues from other produce categories; including pulses, roots and tubers, nuts, oilseeds, and vegetables, tend to have significantly lower availability due to the scale of crop production. Additionally, these residues often contain a high moisture content, which makes them more suitable for anaerobic digestion or may require drying before thermal conversion. Based on this finding, it is important to consider crops with high production and RPR when choosing residues for practical bioenergy applications. This approach would ensure regular residue availability, reduce biomass plant downtime, and increase bioenergy access and security.

The bioenergy potential of all crop residues was evaluated by considering each crop's lower heating value (LHV) and biomass potential. Oil palm residue has the highest bioenergy potential, followed by yam, rice, cowpea, sorghum, vegetables, millet, and okra, as shown in Fig. 3. Their bioenergy potential is high due to high biomass potential and high LHV. Fig. 3 shows that certain crops, such as sorghum, kola-nut, and cassava, have high biomass potential. However, their

Table 3
Overview of BCS 2 selection criteria and impacts.

Rationale for selection	i. The current rice paddy processing is not sustainable. For instance, during the fieldwork we discovered that the farmers make about 5 dollars after spending about 13 h processing 100 kg of rice paddy. ii. Rice husk and straw management are not sustainable. The husk and straw are managed by burning and disposal on land. iii. It would improve rice production, reduce climate action and create additional jobs to people working on the value chain.
Feedstock	Rice husk produced in the processing facility and straw from farm would be used for this case study. Rice paddy grown specifically in eastern Nigeria is target for this case study.
Conversion	A mixture of the feedstock would be dried to a certain amount of moisture content. Circulating fluidised bed gasifier would be used to convert the feedstock to syngas.
Bioenergy vectors	The syngas produced will be used for CHP to provide rice paddy parboiling, drying and milling service for smallholder rice farmers.
Bioenergy system impacts	Same as case study 1.
Potential opportunities	1. **Utilisation of agricultural waste** **Efficient use of rice residues:** Instead of burning the residues in open fields (which contributes to air pollution) or dumping them on ground, the bioenergy plant can provide a sustainable way to convert the residues into energy, benefiting both farmers and the environment. 2. **Improved energy access for smallholder farmers:** **Reliable energy for rice processing:** Access to locally produced energy can reduce dependency on expensive and unreliable diesel generators, improving processing efficiency and reducing costs. **Increased productivity:** Reliable energy supply would allow farmers to process their rice more efficiently and consistently, leading to improved productivity, reduced post-harvest losses, and potentially higher incomes. 3. **Rural development and job creation:** **Employment opportunities:** The bioenergy project can create jobs in feedstock collection, transportation, facility operation, and maintenance. Additionally, skills related to operating advanced gasification technology can be developed locally, fostering rural capacity-building. **Supporting smallholder farmers:** By providing affordable and accessible energy for rice processing, the project directly benefits smallholder farmers, helping them improve the quality of their products and increasing their access to markets. **Reduced energy costs:** With local energy production, smallholder farmers may experience lower energy costs compared to traditional energy sources. This cost reduction can translate into higher profitability for farmers and increased economic resilience for the community. 4. **Climate change mitigation and environmental benefits:** **Reduction in greenhouse gas emissions:** It can help avoid methane emissions from decomposing residues and reduces open burning, which contributes to air pollution and respiratory problems. **Carbon credits and incentives:** The project could potentially benefit from carbon credits or government incentives aimed at promoting renewable energy and reducing carbon emissions. This could enhance its economic viability. 5. **Scalability and replicability:** **Model for other regions:** Once successful, this project could be replicated in other rice-producing regions in Nigeria or other countries with similar agricultural residues.
Potential challenges	1. **Feedstock supply and quality:** **Seasonal availability of rice husk and straw:** The availability of rice husk and straw depends on the rice harvesting and processing cycle which can greatly impact the solution. **Feedstock collection and transportation:** Gathering rice straw from scattered farms and rice husk from processing facilities can be logistically complex. **Moisture content and drying:** Drying the feedstock could require additional energy, impacting the investment cost. 2. **Technical and operational risks:** **Gasification technology reliability:** Consistent operation might be challenging, particularly in rural areas where access to skilled technicians and spare parts may be limited. **Efficiency of CHP for rice processing:** While the CHP system can provide heat and power for rice processing (parboiling, drying, and milling), it needs to be sized correctly to meet fluctuating energy demands from smallholder farmers. 3. **Community engagement and buy-in:** **Social acceptance and awareness:** There may be resistance to new technologies or concerns about changes in traditional farming practices. **Land use and resource competition:** Rice straw is sometimes used for animal bedding or left on the field to improve soil fertility. Farmers might be hesitant to divert straw from these uses unless the benefits are clear. 4. **Economic viability and investment:** **High initial capital costs:** Establishing the gasification plant, CHP system, and associated infrastructure requires significant upfront investment. Securing adequate funding or investment, especially in rural regions, can be challenging. **Revenue generation and market fluctuations:** If the service charges are too high, farmers may not be able to afford the services, limiting revenue. Additionally, fluctuating market prices for rice could indirectly affect the project's profitability. 5. **Environmental and regulatory concerns:** **Waste management:** The gasification process generates byproducts such as ash, which will need to be managed effectively to prevent environmental pollution.

bioenergy potential may be lower than crops with lower biomass potential, such as rice, cowpea, vegetable millet, etc. This is due to the difference in the energy content of the individual residues. Therefore, when selecting a feedstock for bioenergy application, the energy content of agri-residues should be carefully considered.

3.1.2. Biomass and bioenergy potentials of secondary residues

Fig. 4 presents the resource assessment results for the prominent secondary residues. More detailed results can be seen in Tables 2 and 4 of Appendixes 1 and 2 of the supplementary material. About 47 Gt primary residues with an embedded energy content of 315 TWh could be theoretically mobilised per year in Nigeria. Theoretical assessments often assume 100 % collection of agricultural residues, which may not be feasible in practical applications. Therefore, it is important to consider other competing uses of these residues and their mobilisation and aggregation. For practical purposes, it is realistic to assume that an average of 25 % of residues will be used for other applications, such as cooking, animal bedding, animal feed, and construction. Additionally, an average of 10 % of the residues can be lost due to logistics, storage, handling, and other factors [56,57].

After considering these losses, more realistic potentials were obtained. An average of **31** Gt primary residues with an embedded energy content of 204 TWh can be realistically mobilised per year in Nigeria, with the major share coming from cassava followed by yam, oil palm, maize, sorghum, groundnuts, rice and including cowpeas. These residues are plentiful due to large production and a high residue-to-product ratio. Furthermore, most residues have a high dry matter content, making them suitable for thermal conversion like combustion and gasification but less suitable for biological processes like AD. Some crops, such as maize, groundnut, barley, and cocoyam, have lower biomass potential for primary residues but higher biomass potential for secondary residues. This can be attributed to the large amounts of processing residues that these crops generate.

Additionally, residues from other product categories, including pulses, roots and tubers, nuts, oilseeds, and spices, tend to have significantly

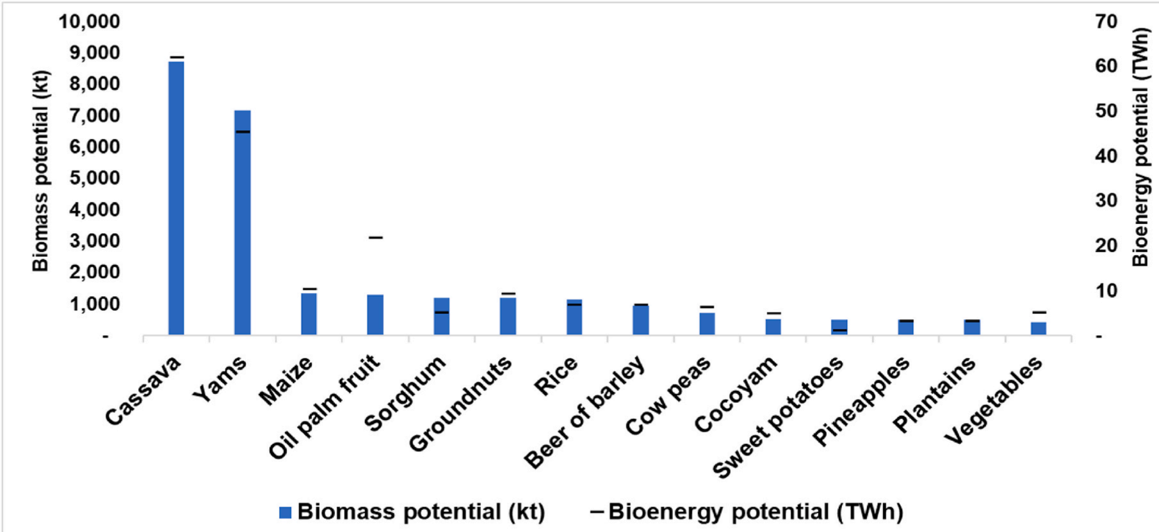

Fig. 4. The most prominent biomass and bioenergy potentials for secondary residues.

lower availability due to the scale of crop production. Furthermore, these residues often contain a high moisture content, which makes them more suitable for anaerobic digestion or may require drying before thermal conversion. The assessment of bioenergy potential for secondary residues was conducted using the same methodology as for primary residues, and the results are presented in Fig. 4. The assessment revealed that crops such as cassava, yam, oil palm fruits, maize, groundnuts, barley, and rice have the highest bioenergy potential for secondary residues. Some crops, such as oil palm, groundnut, and rice, have lower biomass potential but higher bioenergy potential than other residues, likely due to their higher energy content. This finding underscores the importance of considering the energy content of feedstock in practical bioenergy applications, in addition to factors such as high production and high RPR when selecting a feedstock.

The biomass potential of primary residues is higher than that of secondary residues because primary residues have higher RPR than secondary residues. However, while choosing the type of residues to use in practical bioenergy applications, one needs to consider the residue that offers the best trade-off regarding the supply chain. Secondary residues can offer competitive advantages over primary residues when utilised for bioenergy applications in the processing facility as it will reduce mobilisation costs and other aggregation barriers.

3.1.3. Suitable bioenergy deployment for different zones in Nigeria

Fig. 5 shows the percentage distribution of the top 10 residues across the 6 zones of Nigeria. In developing a sustainable bioenergy solution for Nigeria, it is important to understand the zonal availability of biomass to identify appropriate technology and scale to reduce collection and transport costs. Nigeria has six zones: north-central, north-east, north-west, south-east, south-south and south-west, as shown in Fig. 5.

The agricultural zones in Nigeria are highly diversified in terms of agri-ecological conditions, enabling the production of a wide range of crops and agricultural systems. Moreover, the cultivated area, crop types, and yields vary greatly due to specific soil conditions, farming practices, and climatic conditions across the different zones in Nigeria. As variations in crop production occur from season to season and zone to zone, it is essential to understand how the top residues are distributed across the six zones in Nigeria. Fig. 5 shows the percentage distribution of the top residues across the six zones of Nigeria. The percentage was obtained from the annual biomass potential of each of the residues.

The north-west, north-east, and north-central regions have considerable biomass potential in cowpeas, yam, rice, and sorghum. The residues from cowpeas and rice tends to have low moisture content making them suitable for thermochemical processes such as combustion and gasification. Residues from yam and sorghum tends to have high moisture content making them suitable for biochemical processes such as AD and fermentation. As these residues are available in considerable amount, there is potential for medium-to large-scale bioenergy production. The south-west has considerable biomass potential in oil palm, yam, rice, sorghum, and cassava. Disaggregating the biomass from the palm reveals that it has different residues including sent bunch, palm kernel shell, mesocarp fibre, palm oil mill effluent, oil palm frond and trunk. Some of the residues from the oil palm with low moisture content and rice residues are suitable for thermochemical processes. Residues from yam, sorghum, cassava and some from oil palm are suitable for biochemical process. Given that these residues are largely available in this region, they have potential for medium-to large-scale bioenergy production. The South-East region has considerable biomass potential in oil palm, yam, rice, cassava, and cowpeas. Residues from cassava, yam and some from oil palm are suitable for biochemical processes while residues from rice, cowpeas and some from oil palm are suitable for thermochemical processes. As these residues are available in considerable amount, there is potential for medium-to large-scale bioenergy production within this region. The South-South region has considerable biomass potential in oil palm, rice, yam, and cassava. The region has the highest oil palm biomass potential in Nigeria. Some residues from oil palm and rice tends to have low moisture content making them suitable for thermochemical processes such as combustion and gasification. Residues from yam and cassava tends to have high moisture content making them suitable for biochemical processes such as AD and fermentation. As these residues are available in considerable amount, they have potential for medium-to large-scale bioenergy production. Other residues among the top 10 including millet, maize, groundnuts and barley are mostly grown in the northern region. They tend to have low moisture content making them suitable for thermochemical process and they have potential for medium-to large-scale bioenergy production. Each zone produces a significant amount of rice residues. Residues from sugarcane, fruits and vegetables are among the 20 top residues and are mostly grown in the north. They tend to have high moisture content making them suitable for biochemical process and they have potential for medium-to large-scale bioenergy production. The residues with high moisture content can also undergo thermochemical conversion but they need to be pretreated. It is important to note that some zones do not have a share of certain residues, which does not necessarily mean that the crop cannot be grown there. For example, there are no sorghum and millet residues in the south-east and south-south zones and no cowpea

Table 4
Overview of BCS 3 selection criteria and impacts.

Rationale for selection	i. To introduce renewable fuel to Nigeria's fossil fuel. The facility will be in crude oil refinery to support Nigeria's transport sector. ii. Sustainable waste management. iii. It would improve palm production and create additional job to people working on the value chain.
Feedstock	Range of palm residues in the processing facility would be used for this case study. Palm trees grown specifically in south-south Nigeria is target for this case study.
Conversion	i. A mixture of solid residues are converted to syngas by gasification conversion process. The syngas is converted to biodiesel through a Fischer-Tropsch process. ii. A mixture of solid residues are converted to bioethanol through biochemical conversion process. iii. Liquid residue will be used to produce biogas via anaerobic digestion for CHP application to energise the facility.
Bioenergy vectors	Biodiesel and bioethanol for transport fuel and CHP to energise the facility.
Bioenergy system impacts	Same as case study 1.
Potential opportunities	1. **Waste-to-energy potential:** **Utilisation of palm residues:** This case study can promote a circular economy by maximising the value derived from all the oil palm tree residues, reducing waste, and improving the overall sustainability of the palm oil value chain. **Environmental benefits:** By using residues, the project can help reduce methane emissions that occur when palm residues decompose in landfills. Additionally, the production of renewable fuels reduces dependence on fossil fuels, lowering greenhouse gas emissions and contributing to climate change mitigation. 2. **Local energy security and economic development:** **Renewable fuel for transport:** The biodiesel and bioethanol production provides a renewable, domestically produced fuel source for transportation, reducing Nigeria's reliance on imported fossil fuels. **Job creation and rural development:** The establishment of a biorefinery and associated CHP facility would create local employment opportunities in the collection, transportation, and processing of palm residues. This can contribute to rural development, raise local incomes, and improve living standards in the South-South region of Nigeria. 3. **Economic diversification and export potential:** **Biofuel blending mandates:** Nigeria, like many countries, has blending mandates that require a percentage of biofuel to be mixed with fossil fuels. This can create a stable market for biodiesel and bioethanol production. The project can capitalize on these mandates to ensure demand for its products. **Export opportunities:** As global demand for sustainable biofuels increases, particularly in Europe and other regions with strict carbon emissions targets, Nigeria's biorefinery could potentially export biodiesel or bioethanol to international markets. It can also lead to the export of oil palm value added products. 4. **Carbon reduction and climate mitigation:** **Lower greenhouse gas emissions:** Biofuels like biodiesel and bioethanol produce fewer emissions compared to traditional fossil fuels, helping reduce the carbon footprint of the transport sector. Additionally, the biorefinery can contribute to Nigeria's commitments under international climate agreements by reducing its reliance on carbon-intensive fuels. **Carbon credits and incentives:** The project could benefit from carbon credits or international climate finance mechanisms that incentivize the production of low-carbon fuels. This could improve the financial returns of the biorefinery and create opportunities for additional revenue streams. 5. **CHP for energy efficiency:** **Improved energy use in processing:** The CHP system would increase the energy efficiency of the biorefinery by using the syngas produced from palm residues to generate both electricity and heat. This provides a reliable, on-site energy source to power the biorefinery operations, reducing energy costs and reliance on external energy supplies. **Sustainable energy for local communities:** Excess energy generated by the CHP system could potentially be supplied to local communities or industries, contributing to rural electrification and providing affordable, sustainable energy to areas with limited grid access. 6. **Scalability and replicability:** **Expanding to other regions:** If successful, the biorefinery model can be scaled or replicated in other oil palm-growing regions of Nigeria or in other countries with similar agricultural waste resources. **Diversification of feedstocks:** While this project focuses on palm residues, the biorefinery could potentially diversify by using other agricultural residues (such as cassava peels, maize stalks, or sugarcane bagasse) in the future, expanding its product range and improving its economic resilience.
Potential challenges	1. **Feedstock supply and collection:** **Residue availability:** Although palm residues (such as empty fruit bunches, palm kernel shells, and fibers) are abundant in the oil palm value chain, their availability might fluctuate based on the harvest cycles and yield of oil palms. **Feedstock logistics and storage:** Collecting and transporting large volumes of palm residues to the biorefinery requires efficient logistics and infrastructure. The residues also need to be stored properly to avoid degradation and loss of quality, which could affect the efficiency of fuel production. 2. **Technological complexity and efficiency:** **Conversion technologies:** Producing both biodiesel and bioethanol from palm residues involves multiple complex conversion processes. These processes require advanced biorefinery technology, which may face operational issues and may require significant expertise and maintenance. 3. **Economic viability and market conditions:** **High initial capital investment:** Setting up a biorefinery capable of producing biodiesel, bioethanol, and CHP requires a substantial upfront investment. **Market competition and fuel pricing:** Biodiesel and bioethanol are often competing with cheaper fossil fuels, especially in regions where fossil fuel subsidies exist. If fossil fuel prices remain low, biofuel producers may struggle to compete unless supported by subsidies or mandates. 4. **Environmental and social considerations:** **Sustainability of palm residue sourcing:** Issues such as deforestation, loss of biodiversity, and land-use change associated with palm oil cultivation can lead to negative public perception or opposition from environmental groups. **Land use and social impacts:** Expanding oil palm plantations to increase residue production might lead to competition for land, potentially displacing local communities or causing conflicts over land ownership. 5. **Regulatory and policy challenges:** **Policy uncertainty:** Inconsistent or unclear regulations can create uncertainty, making it difficult to plan long-term investments in biorefinery projects. **Sustainability certification:** To access both domestic and international markets, biofuels may need to meet specific sustainability criteria or certifications (such as the Roundtable on Sustainable Palm Oil or RSPO certification). Achieving and maintaining these certifications can be resource-intensive and could add to the cost and complexity of the project.

residues in the south-south zone. This information will aid the development of an economically feasible approach to produce energy from these residues using appropriate technology and budget.

Crop residues from yam, sorghum, barley, wheat, soybean, maize, palm, cassava, rice, sugarcane, fruits and vegetables are knowledge gaps in the feedstock assessment of this project, they are abundant and can be used to generate energy to support modern and sustainable bioenergy integration to Nigeria energy mix.

3.2. Stakeholder engagement output

This section provides the answers to the key questions that guided discussions with stakeholders during the fieldwork.

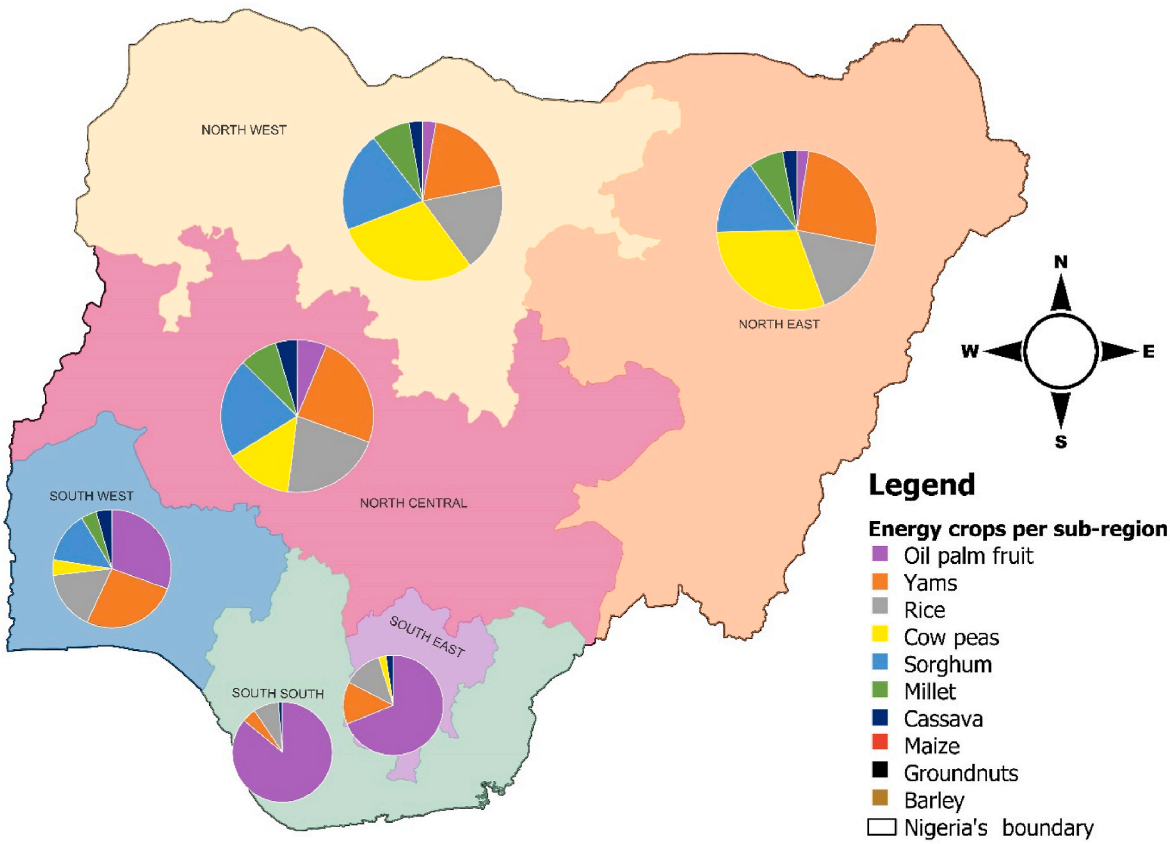

Fig. 5. Percentage distribution of top 10 residues across the 6 zones of Nigeria.

3.2.1. *Current waste management practice*

Fig. 6 shows the output of stakeholder engagement in waste management practices of Nigeria. It outlines various stakeholders, their associated feedstocks, management approaches, and infrastructural utilisation in waste management activities. The stakeholders involved represent industries, farmers, and the Ministry of Environment.

Both industrial stakeholders and farmers used a similar waste management approach and infrastructure. They generate different agri-residues originating from rice, cashew, sugarcane, oil palm, yam, cassava, vegetables, potatoes, and fruits. The industrial stakeholders and farmers reuse some of the waste as a heat source. Specifically, the cashew industry uses cashew shells for oven fuel during nut drying processes. The sugarcane industry utilises bagasse as a feedstock in combustion technology, to generate process heat. Rice farmers uses some rice husks alongside wood fuels to generate heat for parboiling rice. Palm farmers utilise some of their palm kernel shells, mesocarp fibres, and dried oil palm fronds for parboiling fresh palm fruit. Similarly, the palm industry uses palm kernel shells and mesocarp fibres via combustion technology to produce process steam for parboiling fresh fruit bunches. The industrial stakeholders and farmers also sell some of the agri-residues. Rice farmers, for example, not only supply rice husks to individuals for local combustion cooking and animal bedding but also market rice briquettes for household and industrial use. Similarly, palm farmers sell some waste streams such as palm kernel shells, oil palm fronds, and trunks, catering to households and companies seeking heat sources or timber for construction projects. The volume of agri-residues reused or sold remains relatively low. Most agri-residues end up being burnt or deposited in landfills. The rice farmers typically burn nearly all the rice straw in their fields, while the rice husks are often disposed of in dumping sites within the rice mills. For example, in Abakaliki, Ebonyi state, the rice husks are deposited behind the rice mill cluster forming what locals refer to as "juju mountain", highlighting a need for more efficient waste management practices. In addition, palm farmers resort to burning the spent bunches and disposing of palm oil sludge in dug pits. Furthermore, unused or unsold palm kernel shells, mesocarp fibres, oil palm fronds, and trunks are often burnt. Similarly, oil palm processing companies burn the spent bunches and discharge the Palm Oil Mill Effluent (POME) to dug pits. Yam, cassava, potato, fruit, and vegetable processing companies dispose of peels and vegetable waste in dumping sites. Such practices highlight the urgent need for more sustainable waste management approaches across various sectors.

The Ministry of Environment, within one of the states where stakeholder engagement was conducted, has established a structured waste disposal system. Initially, they relied on house-to-house collection of waste but encountered challenges due to residents' reluctance to promptly present their waste for collection, resulting in illegal disposal. Presently, they have implemented two methods: house-to-house and zonal collection, which the ministry participants deem more effective for waste disposal in the state. In the house-to-house collection method, residents bring out their waste for collection by workers from the waste management department. Timeliness is emphasised, with waste expected to be presented between 6 a.m. and 6 p.m. for collection the following morning. Workers then collect the waste around 8 a.m. for disposal to the final dumping site, typically landfill. Under the zonal collection approach, the state is divided into 14 zones, each managed by coordinators supervised by the ministry. Coordinators are provided with necessary resources to effectively manage waste collection points within their zones. The ministry incentivises coordinators who excel in their tasks, fostering healthy competition among them to enhance performance. However, participants from the ministry identified several challenges that negatively impact operations, including public attitudes toward waste, financial constraints, and changes in government. Public attitudes toward waste pose a significant obstacle to waste management activities. Many believe that once they have finished using something, it

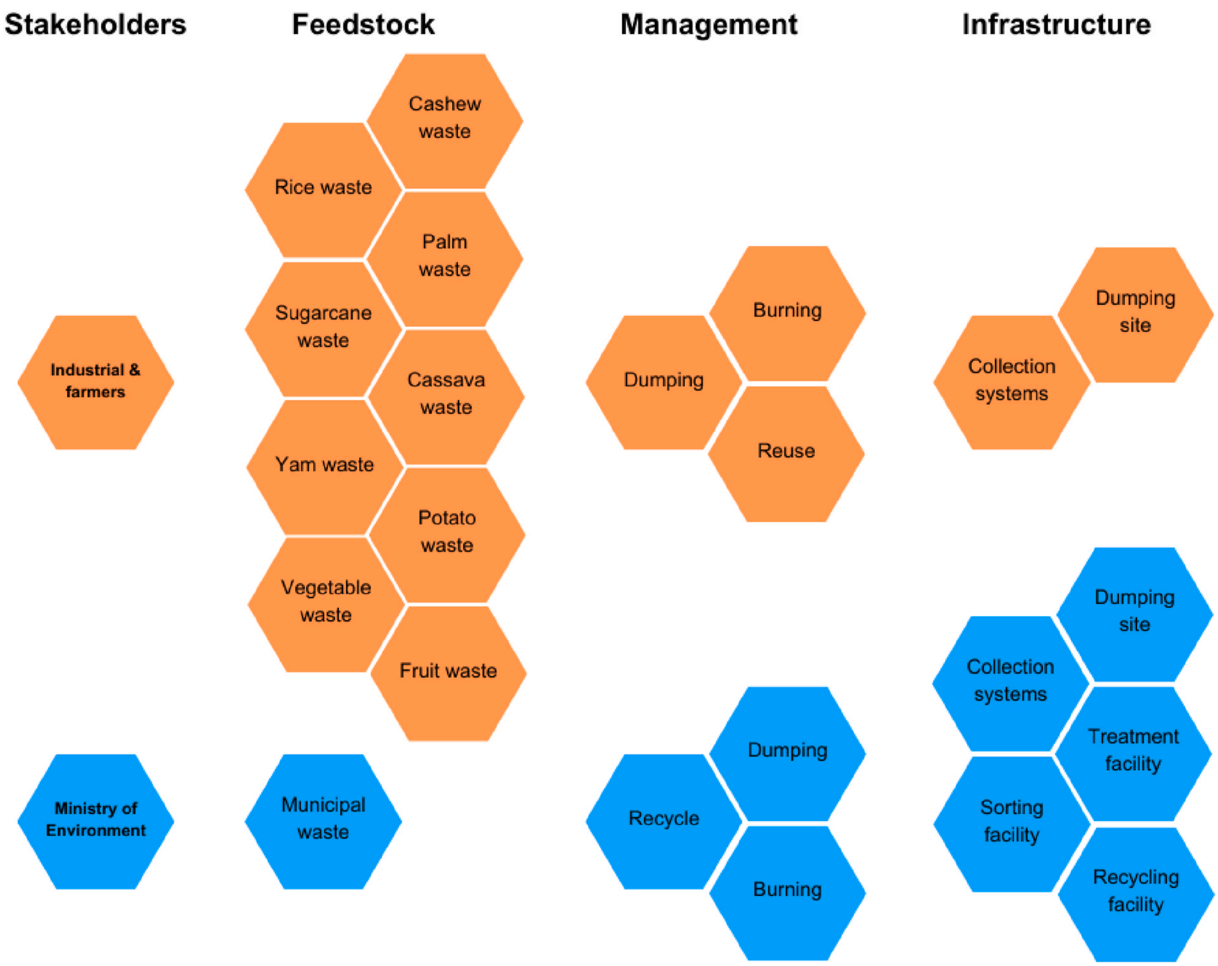

Fig. 6. Current waste management practice of stakeholders.

becomes waste, leading to a lack of concern for proper disposal. This attitude often progresses to the point where individuals ignore waste until it starts emitting odours, at which point they seek to distance themselves from the discomfort. As a result, waste heaps are often disregarded until they become unbearable, at which point they are hastily dealt with, only to be forgotten once removed. And the process starts again. Financial challenges arise because waste management is capital-intensive. When the government fails to provide the zonal coordinators with necessary support, there is a relapse, and the accumulation of waste intensifies rapidly. Without intervention, waste accumulates over time. With the availability of the necessary supports, the rate of waste removal may lag the rate of accumulation, creating a persistent problem. Furthermore, a change in government can pose challenges during the transition from one administration to another. The effectiveness of waste management largely depends on the leadership and political will to allocate funds. If the new government lacks the necessary political will, funding issues may arise, leading to operational difficulties. These challenges could impede waste management operations significantly. Furthermore, the involvement of zonal coordinators often involves political patronage, with some securing their positions through contributions to election campaigns. This can result in funds being diverted for personal gain. To address this issue, it is crucial to separate political considerations from job appointments. Implementing a standard bidding process for government positions can help ensure that individuals with genuine commitment and competence are selected for the job. The state, predominantly agrarian, generates about 70–80 % of its waste from agricultural activities and 20–30 % from market, household and industrial activities. The ministry prioritizes agricultural and residential waste for their potential in organic fertilizer production. The government has initiated the implementation of recycling plant. However, the current management of waste by the ministry is by landfills for waste disposal until the recycling plant option is implemented.

3.2.2. *Real feedstock mobilisation potential*

The availability of feedstock is fundamental to the viability and success of bioenergy projects. Fig. 7 shows the output of stakeholder engagement for real feedstock mobilisation potential. It outlines various stakeholders, their associated agri-residue, competing other uses, and factors that could improve crop production and directly improve feedstock production.

The stakeholders generate agri-residues from rice, cashew, sugarcane, oil palm, yam, cassava, vegetables, potatoes, and fruits. However, the full mobilisation of the agri-residues is hindered due to competition from other uses. For instance, agri-residues from rice, cashew nuts, sugarcane, and oil palm are utilised as heat sources both domestically and industrially. Additionally, some agri-residues are sold to individuals for briquette production and animal bedding. Others, originating from yam, cassava, potatoes, vegetables, and fruits, find application in animal feed, bedding, and organic fertilisers. But most feedstocks are burnt or disposed in borrow pits. Stakeholders identified various factors that could enhance crop production (see Fig. 7), consequently leading to improved feedstock production. The factors include improved varieties, planting methods, access to farm inputs, mechanised farming, irrigation, planting and harvesting on time, access to market, financial support, mobility, government policies, training and sustainable crop processing. A snapshot of the suggestions of the stakeholders is summarised in

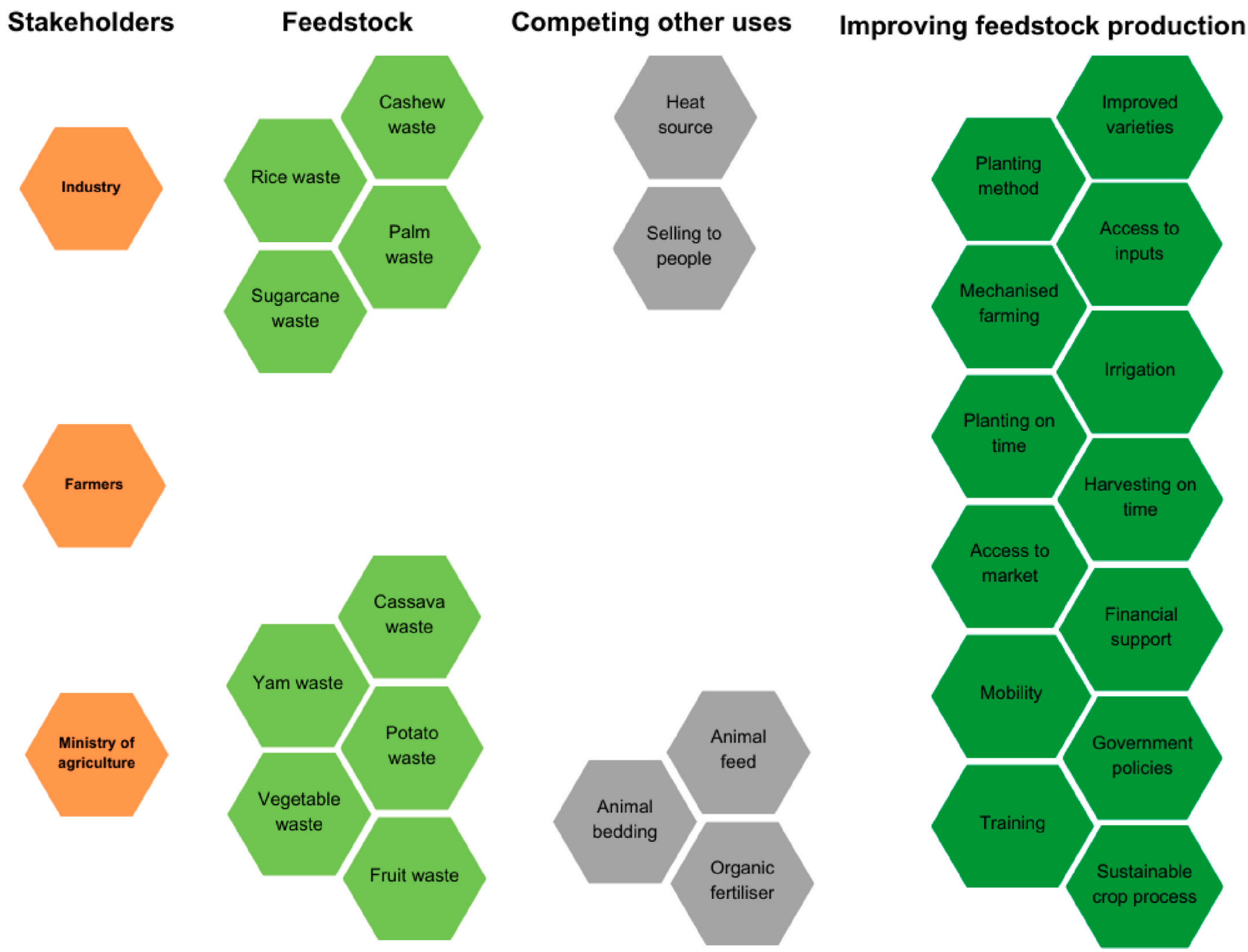

Fig. 7. Factors impacting feedstock mobilisation from stakeholders.

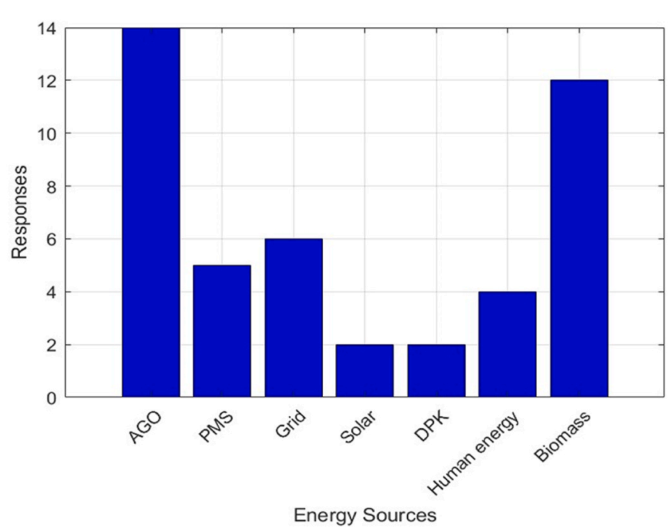

Fig. 8. The energy outlook of the engaged stakeholders.

Table 1.

3.2.3. Feasible energy pathways from agricultural wastes in Nigeria

To investigate the feasible bioenergy pathway, it is important to understand the energy outlook of stakeholders, aspirational change in the energy outlook of stakeholders, level bioenergy would offer the highest benefit and current bioenergy deployed in Nigeria.

3.2.3.1. Energy outlook of stakeholders. Fig. 8 shows the energy outlook of the engaged stakeholders. The main energy is automotive gasoline (AGO), commonly known as diesel in Nigeria. Nearly all small, medium, and large companies that participated in the stakeholder engagement own diesel generators, ranging from small capacities of 1 kW to more than 1 MW.

Most of them use it as a backup to national grid power, while a few rely on them as their primary energy source. These generators are predominantly used to power heavy industrial processing machinery due to their high efficiency and performance. Small-scale industries use diesel generators of lower capacity for crop processing. For example, rice milling stakeholders use diesel generators ranging from 5.5 to 6.5 hp for rice milling, destoning, and polishing. Similarly, some small-scale cassava and palm firms uses diesel generators of 2.5 kW for processing their crops. The second most prominent source of energy is traditional biomass, utilised extensively by both industrial stakeholders and farmers as a heat source. For instance, a participant from a large-scale

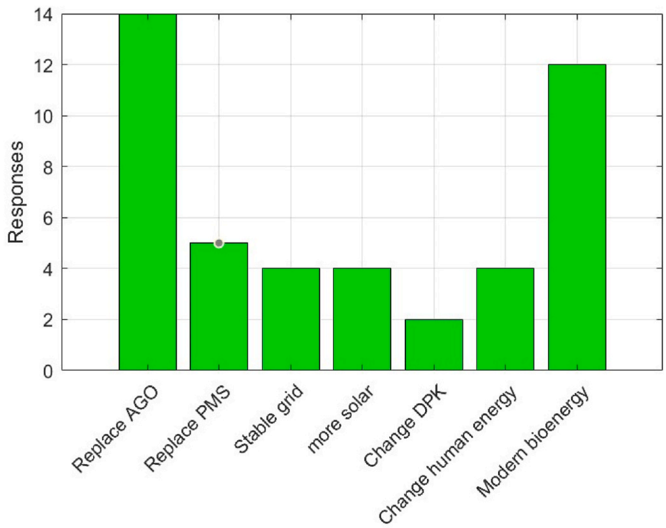

Fig. 9. Aspirational change in the energy outlook of the stakeholders.

sugar processing company said, "we supplement our power during mid-morning to mid-afternoon, leading us to store more bagasse for use from October/November, after the rain and before the harvest. Additionally, we purchase wood chips, rice husks, and sawdust from local sawmills and farmers to prolong boiler operation, as it is more cost-effective than diesel and is a renewable source." Furthermore, large palm fruit processing companies use some of their residues to generate steam for parboiling fresh fruits. Rice and palm farmers utilise some of the residues they produce as a heat source for crop processing. Stakeholders from various ministries reported biomass as the primary source of heat for cooking at home. The national power grid ranked third as the primary source of energy for the stakeholders. However, stakeholders emphasised the grid is highly unreliable, and they often experience days without electricity. Some receive as little as 1–4 h of electricity supply per day, leading them to heavily rely on diesel or Premium Motor Spirit (PMS) generators. PMS, commonly known as "petrol" or "fuel" in Nigeria, closely follows the national grid power as a source of energy for stakeholders. Industrial stakeholders and farmers use petrol generators to power their processing machines, noting that petrol generators are suitable for lighter industrial machinery. Stakeholders often possess both diesel and petrol generators to power different industrial machines. This is because, during the stakeholder engagement period, the cost of diesel was more than four times higher than petrol. To reduce costs, they utilise petrol generators to power lighter industrial machines rather than solely relying on diesel generators. However, industrial operations predominantly utilise heavy machinery, which explains why diesel ranks highest in the stakeholders' current energy outlook. The next source of energy is human labour, involving the use of tools such as hoes and cutlasses for agricultural activities. All engaged farmers rely on human energy for farming tasks. They use cutlasses for clearing the farm fields, hoes for tilling the soil and creating heaps, and manually walk around the heaps for planting crops and harvesting them when ripe. Human energy is the primary source of energy for the farmers involved in the stakeholder engagement. Dual-purpose kerosene (DPK) and solar systems represent the least utilised sources of energy among the engaged stakeholders. Industrial stakeholders do not extensively utilise kerosene due to the absence of kerosene-powered generators in Nigeria. However, farmers employ kerosene as an energy source for burning unused feedstocks and as fuel for local lanterns used for lighting during nighttime agricultural activities. Two industrial stakeholders have integrated solar energy into their energy company's mix. For instance, a sugarcane processing company has implemented a large-scale solar system of approximately 2 MW. Quoting the participant verbatim, "We have just commissioned 2 MW of solar power last week (phase 2 being 1.2 MW

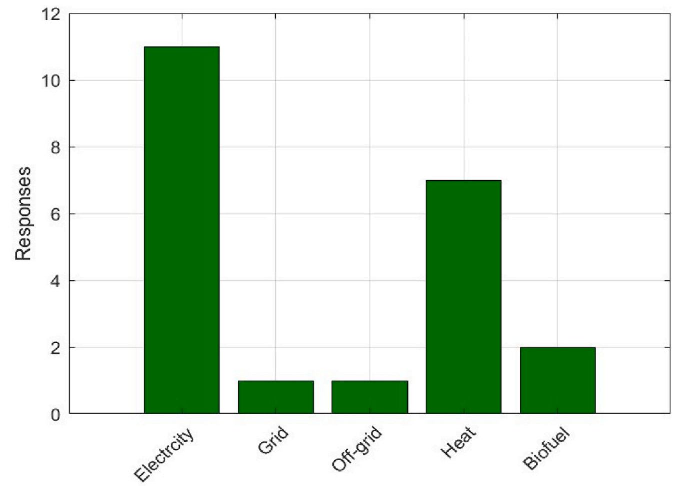

Fig. 10. Level bioenergy would offer the highest benefit.

with phase 1 being 800kW completed in Feb 2023)." They utilise the solar system alongside diesel generators and biomass to power their entire facility. Similarly, cashew nut stakeholders have implemented a smaller-scale solar system for specific processing machines. They utilise the solar system in combination with diesel and petrol generators, as well as biomass, to satisfy their energy requirements.

From the above, the major source of energy for the engaged stakeholders are fossil fuel, traditional biomass and human energy. The stakeholders reported that the reason they are dependent on these sources of energy is because they are the available energy source, and their businesses needs energy to operate.

3.2.3.2. Aspirational change in the energy outlook of stakeholders. Fig. 9 shows the aspirational change in the energy outlook of the stakeholders.

Stakeholders relying on diesel, petrol, and kerosene noted that they are actively seeking alternatives for these energy sources. This is primarily due to the significant rise in the cost of fossil fuels during the stakeholder engagement period, which escalated to approximately five times the initial cost. They expressed deep concern over the impact of these soaring costs on the production expenses of their products, resulting in reduced sales. The high increase in fossil fuel costs is attributed to the removal of fossil fuel subsidies, which prompted some of their decisions. But the cost of the national power grid is relatively cheap compared to the cost of diesel, petrol, and kerosene. Additionally, the national grid is suitable for both heavy and light industrial machines. Stakeholders strongly desire stability in the national power grid due to its cost-effectiveness and lack of noise pollution for consumers, as generators are typically situated far away from consumers. Most stakeholders utilise biomass in an unsustainable manner, using it for local combustion and as a source of process heat and cooking fuel. However, stakeholders' express concerns about the emissions associated with traditional biomass, which can pose health risks. They desire a transition from traditional biomass use to modern bioenergy applications. For example, stakeholders currently using diesel and petrol generators hope to see biomass converted into diesel and petrol to power their generators and support electricity generation for the national grid. The sugarcane company aims to utilise bagasse for efficient electricity generation and potentially export excess energy to the grid. The stakeholders from the ministries want the use of biomass for electricity generation and as a source of cooking gas for household applications. Farmers express a strong desire for a shift from human energy to mechanised farming, believing it to be more efficient, cost-effective, and capable of increasing crop production. Stakeholders who have implemented solar systems desire further adoption of solar energy due to its consistent power supply, lack of noise, and emission-free nature. However, stakeholders

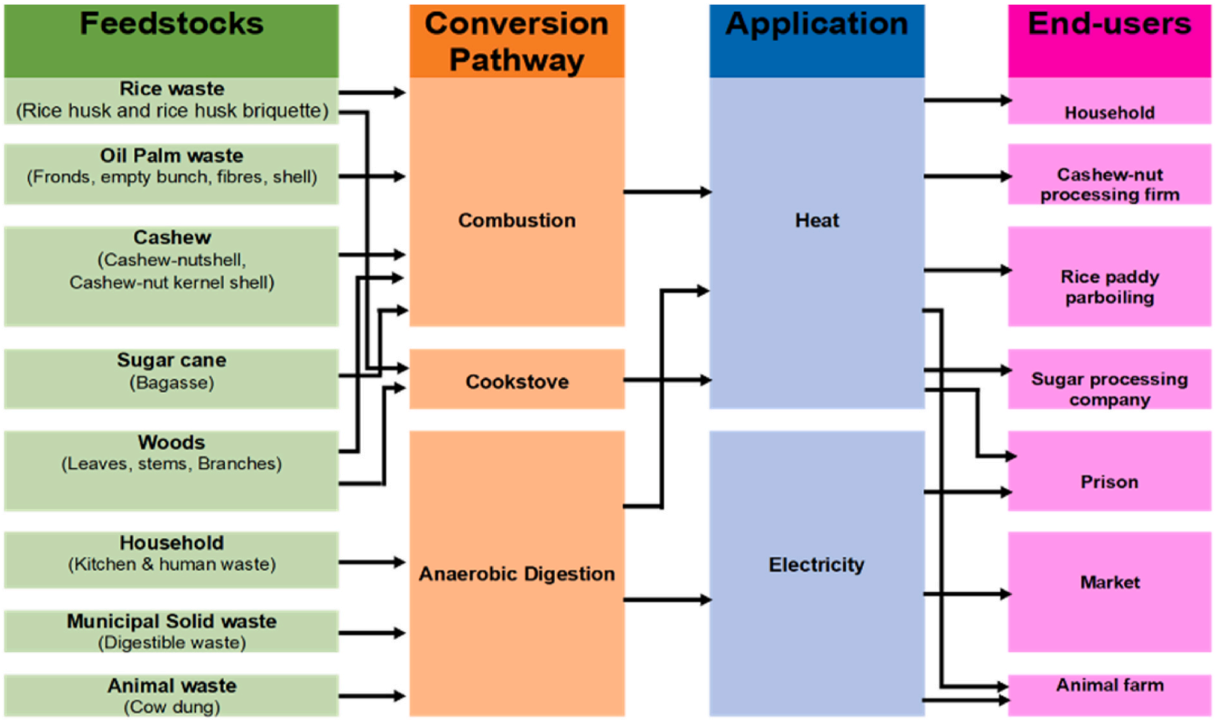

Fig. 11. Current bioenergy deployed in Nigeria.

highlight that the capital cost of solar systems could hinder further deployment. In general, engaged stakeholders prioritise energy sources with the lowest cost, minimal or no noise, and low emissions.

3.2.3.3. Level bioenergy would offer the highest benefit. Fig. 10 shows the level of agreement among stakeholders regarding the benefits modern bioenergy can offer. They have a strong preference for electricity to be the predominant energy vector, as most of their processing machines rely on it.

This preference extends to both on-grid and off-grid electricity. For instance, the palm processing company emphasised the need for constant electricity supply from either the grid or off-grid systems to fully maximise the benefits of their automated processing system. Similarly, rice farmers express a desire for bioenergy systems to modernise and enhance the efficiency of their paddy processing. In the words of one rice farmer, "we want to see farm made easy." Additionally, stakeholders emphasise the importance of sustainable heat generation, as process heat accounts for a significant portion of the total energy requirements for both industrial stakeholders and farmers. There was limited awareness of other modern bioenergy applications and technologies even though Nigeria's Energy Masterplan supports the efficient use of biomass to generate clean heat, electricity and biofuel for industrial, transport and household applications. Based on these findings, we have developed a suite of novel bioenergy case studies with stakeholders to support biomass integration into Nigeria's energy system.

3.2.3.4. Current bioenergy deployed in Nigeria. The feedstocks, conversion technologies, and energy vectors identified during the fieldwork are summarised in Fig. 11. They reflect the high flexibility inherent of bioenergy feedstock and the different conversion pathways applicable to these feedstocks. It also shows the various energy vectors and different end-uses that each individual bioenergy pathway supplies. The current technological expertise of the stakeholders is on combustion, cookstoves and anaerobic digestion. The majority of stakeholders use bioenergy feedstocks and conversion pathways in which they have expertise to supply some of their energy needs. For example, the stakeholders from rice, palm, cashew-nut and sugarcane processing companies use combustion technology to convert the range of agri-residues produced in their industries to process heat for processing their value-added products. While end-users from market, animal farms and prisons use anaerobic digestion to produce heat and electricity for process heat and to power their electrical loads.

3.2.4. Policy support for biomass and bioenergy in Nigeria

Nigeria's energy landscape is guided by several key policy frameworks, including the Nigeria Biofuels Policy and Incentives, National Energy Master Plan (NEMP), and National Energy Policy (NEP), each having dedicated sections for bioenergy applications. These documents outlined short-term, medium-term, and long-term strategies for policy implementation. They underscore a collaborative approach involving stakeholders from government ministries, large, medium, and small-scale companies, regulatory bodies, market operators, and farmers in the development and deployment of bioenergy solutions. Emphasising rural development, community and domestic heating, and mitigating health risks associated with biomass combustion, these policies prioritise the efficient utilisation of diverse biomass resources. Additionally, they advocate for both grid and off-grid electricity generation, the promotion of biofuel blending with fossil fuels, and the integration of hydrogen into the energy mix, reflecting a comprehensive vision for sustainable energy development in Nigeria. The bioenergy target for 2030 is bioelectricity generation of about 292 MW, bioethanol (E10) of 24.2 ML/day and biodiesel (B20) of 11.7 ML/day, The policy recommends.

i. Developing nurseries and intensifying the cultivation of plantations of fast-growing energy trees/plants;
ii. Building local capacity and training extension workers on the applications, installation, and maintenance of efficient biomass energy technologies.
iii. Identifying suitable bioenergy-based technologies and embarking on intensive R&D activities on same.
iv. Providing fiscal incentives to encourage local production of biomass energy systems.

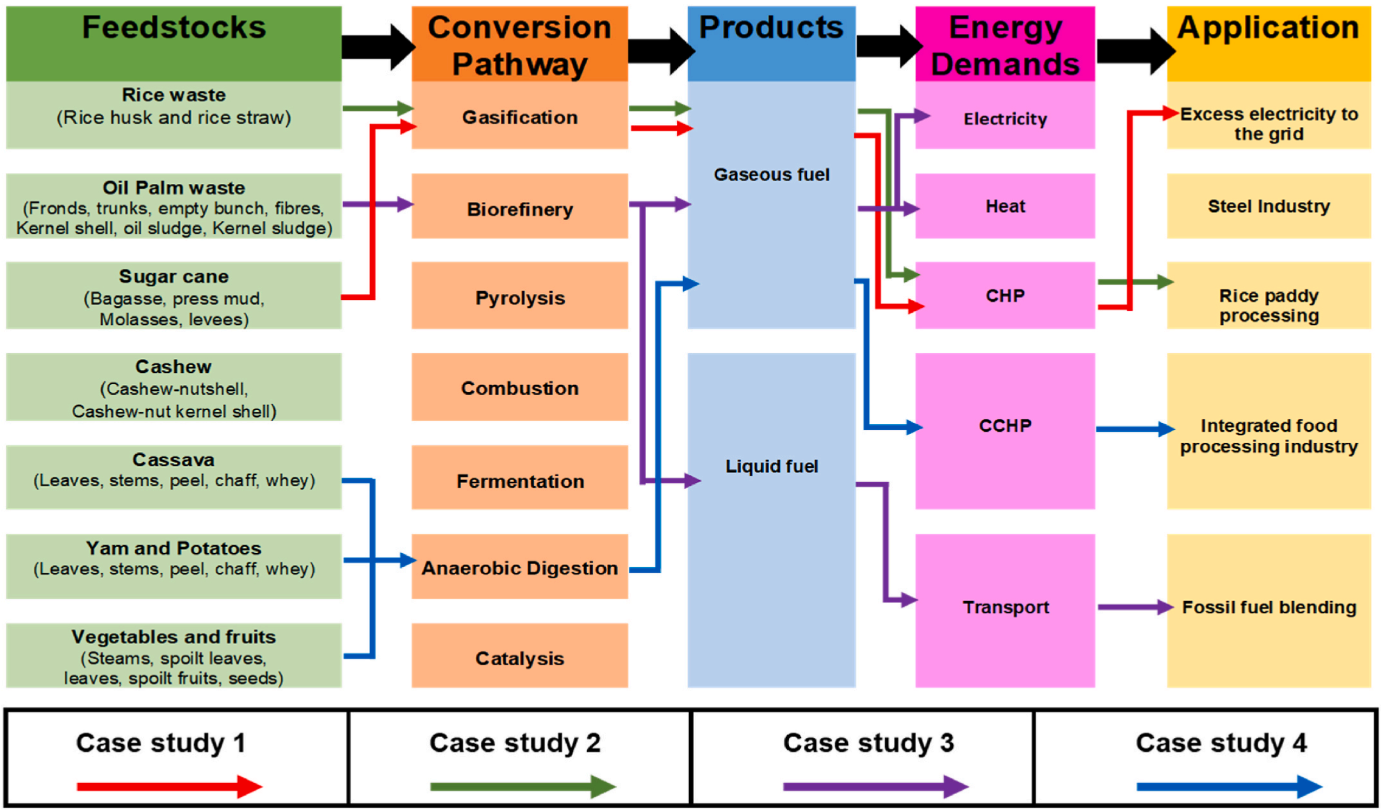

Fig. 12. The modern bioenergy value chain for Nigeria.

v. Establishing more shelter belts in the semi-arid frontal states and woodlots in the buffe states.
vi. Developing indigenous capacity in the design, development, installation and maintenance of renewable energy technologies.
vii. Building indigenous capacity in the design, development, installation and maintenance of efficient wood stoves and biomass briquetting machines.
viii. Setting minimum technical know-how for due diligence on potential biofuels partners.
ix. Enacting and enforcing biofuels usage Act Mandate on the use of E5, E10, B10 and B20 in Nigeria.
x. Formulating and implementing appropriate policy guidelines, regulatory and incentive regimes in the agricultural sectors to support the biofuels industry.

4. Case study development

Stakeholder engagement was used to validate the findings of the biomass resource mapping. And to focus our research on a series of specific real-life bioenergy systems that have been selected based on stakeholders' preference, feedstock availability, energy demand and novel bioenergy technologies that have high economic and socio-economic benefits for Nigeria. Fig. 12 shows the specific pathways agreed by the stakeholders, providing the framework of case studies to be undertaken in this research. The case studies were validated through guided discussion with the stakeholders, review of Nigeria bioenergy policies and bioenergy investment strategies of Nigeria. The modern bioenergy value chain (Fig. 12) highlights the range of bioenergy supply chain options including different feedstocks, conversion pathways, products, energy vectors and end-users. There are multiple ways of joining feedstocks, technologies and vectors to define a pathway and while these pathways may be specific there can be transferable learning generated if they are tailored with appropriately representative feedstocks, technologies, vectors and final demand.

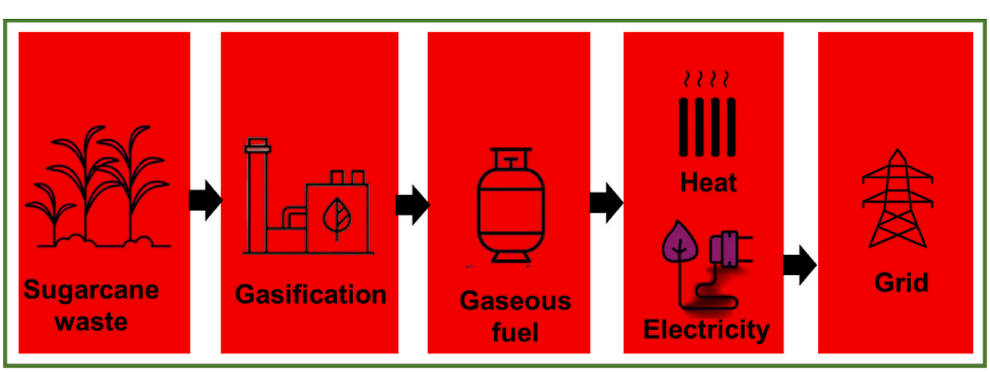

Fig. 13. The schematic diagram of the bioenergy case study 1.

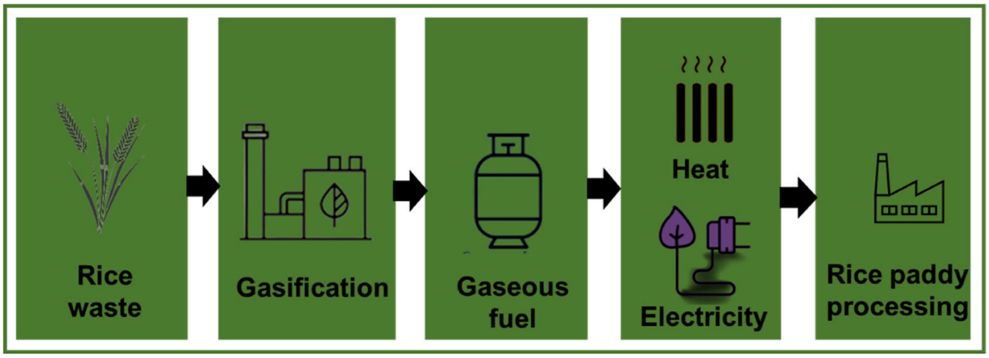

Fig. 14. The schematic diagram of the bioenergy case study 2.

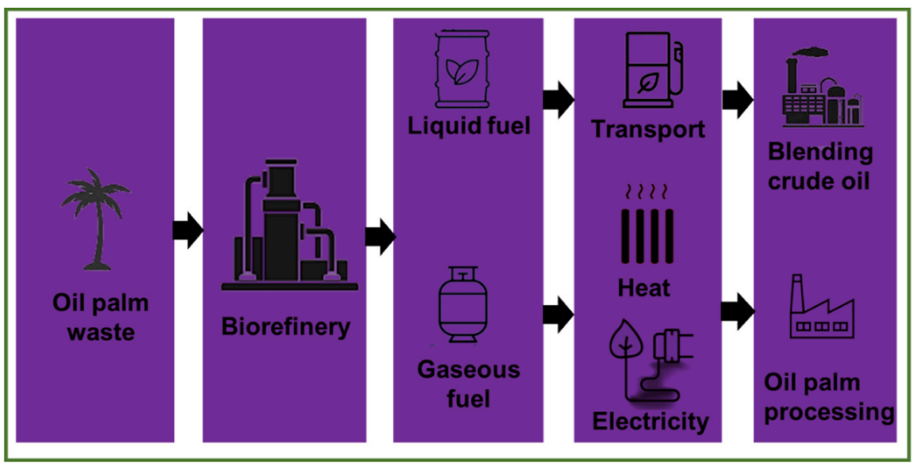

Fig. 15. Biorefinery for biogas, bioethanol and biodiesel production.

4.1. Bioenergy case study 1 (BCS 1): exporting electricity to the national grid

Bioenergy case study 1 is on a sugarcane value chain. The case study will target northern Nigeria. The biomass resource assessment of this project shows that the region has high sugarcane potential which was validated during stakeholder engagement. Fig. 13 shows the schematic diagram of BCS 1. Sugarcane bagasse and straw are used as feedstocks to generate syngas through gasification conversion pathway. The syngas is cleaned and used for combined heat and (CHP) to support the energy supply of a sugar mill while excess electricity is exported to the national grid. Table 2 shows the overview of BCS 1 section criteria and potential impacts.

4.2. Bioenergy case study 2 (BCS 2): community bioenergy (CHP application)

Bioenergy case study 2 is on a rice value chain. The case study targets eastern Nigeria as the biomass resource assessment of this project shows that eastern and northern region have high rice potential. This was also validated during the stakeholder engagement. Fig. 14 shows the schematic diagram of BSC 2. Rice husk and straw are used as feedstocks to

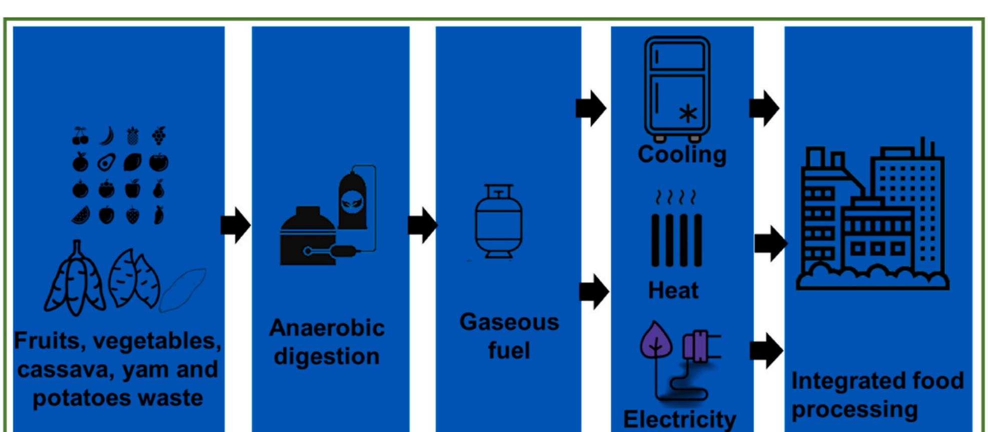

Fig. 16. Bioenergy for CCHP application.

Table 5
Overview of BCS 4 selection criteria and impacts.

Rationale for selection	i. The current residue management are not sustainable. During the fieldwork, we discovered that lots of tubers, fruits and vegetables are wasted. ii. It would reduce food wastage, create additional job to people working on the value chain and provide a sustainable way for the residue management. iii. Improve food production.
Feedstock	This case study would use a range of tubers, fruits, and vegetable residues in the processing facility. It targets an integrated food processing company in southwest Nigeria.
Conversion	A mixture of the feedstock would be converted to biogas via anaerobic digestion.
Bioenergy vectors	The biogas produced will be used for CCHP to provide cooling, drying, and power the electrical load of the company.
Bioenergy system impacts	Same as case study 1.
Potential opportunities	1. **Sustainable waste management:** **Utilising agricultural and processing residues:** The case study provides an efficient way to convert organic waste from the tuber, fruit, and vegetable value chain into biogas, reducing the need for landfilling or open-air burning of residues. This not only minimizes waste but also helps address environmental concerns such as greenhouse gas emissions, soil degradation, and air pollution. **Circular economy approach:** By transforming food processing waste into energy, the company can adopt a circular economy model, where waste products are reintegrated into the production cycle. This can enhance resource efficiency and reduce the overall environmental footprint of the food processing facility. 2. **Energy savings and independence:** **Reduction in energy costs:** By producing biogas on-site and using it for CCHP, the company can significantly reduce its reliance on grid electricity and fossil fuels for cooling, heating, and power. This will lead to lower operational costs, particularly in regions where energy prices are high, or supply is unreliable. **Energy resilience:** The use of biogas and a CCHP system enhances energy security for the company, reducing its vulnerability to energy price fluctuations and grid instability. This is particularly important in Nigeria, where electricity supply can be unreliable, especially in rural or industrial areas. 3. **Diversified energy output:** **Efficient energy use:** The CCHP system allows for the simultaneous generation of cooling, heating, and electricity from biogas. For an integrated food processing company, this means meeting energy demands for refrigeration, drying, and power in one system. **Application to food processing:** The cooling generated from the CCHP system can be used for preserving perishable products (such as fruits and vegetables), while the heat can be used for drying tubers or other agricultural products. This dual-use of energy helps optimize food processing operations and ensures product quality, extending the shelf life of products. 4. **Environmental and climate benefits:** **Reduction in greenhouse gas emissions:** By converting organic residues into biogas, the project reduces methane emissions that would otherwise result from the natural decomposition of agricultural waste. Moreover, the replacement of fossil fuels with biogas for energy generation lowers the carbon footprint of the company, contributing to national and international climate change mitigation goals. **Support for climate targets:** Nigeria, like many other countries, is increasingly focused on reducing carbon emissions and meeting renewable energy targets. Bioenergy projects such as this one support national climate policies and could help the company gain recognition or benefit from carbon credits or incentives related to renewable energy generation. 5. **Potential for revenue generation:** **Excess energy sales:** If the biogas or electricity generated exceeds the company's energy needs, there may be opportunities to sell excess energy to the grid or to nearby industries or communities. This provides an additional revenue stream and can enhance the overall profitability of the project. **Monetization of byproducts:** The digestate produced during anaerobic digestion is a nutrient-rich fertilizer that can be sold to farmers or used in agricultural activities. This presents a potential revenue opportunity, especially in regions where soil fertility is a concern, and organic fertilizers are in demand. 6. **Scalability and replicability:** **Application across multiple value chains:** The model of using food processing residues to generate biogas and power CCHP systems can be scaled up or replicated in other food processing sectors or regions. This can promote the widespread adoption of sustainable energy practices across Nigeria's agricultural and food processing industries. 7. **Improved company reputation:** **Corporate social responsibility:** Adopting bioenergy solutions can enhance the company's reputation as an environmentally responsible and sustainable business. It can also serve as a key component of the company's corporate social responsibility strategy, improving its brand image and potentially attracting environmentally conscious consumers or investors.
Potential challenges	1. **Feedstock supply and quality:** **Seasonal availability of residues:** Seasonal variations in the production of crops such as yams, cassava, and fruits could lead to inconsistent feedstock supply, which could affect the biogas production process. **Feedstock composition and moisture content:** Balancing the mixture of feedstock to ensure optimal biogas production may be technically challenging, especially when dealing with highly variable input materials. 2. **Technical and operational challenges:** **Integration of CCHP with food processing operations:** The CCHP system needs to be well-integrated with the company's cooling, drying, and power requirements. Mismatch in energy supply and demand can lead to inefficiencies, particularly when cooling or drying needs peak. 3. **Economic and financial viability:** **High initial capital investment:** This can be a barrier for companies without access to sufficient capital or financing options, particularly if the project does not have immediate financial returns. **Uncertainty of long-term financial returns:** If feedstock availability becomes inconsistent or market conditions change (e.g., fluctuations in energy prices), the project may struggle to generate consistent financial returns. 4. **Waste management and byproduct utilisation:** **Handling digestate:** The anaerobic digestion process produces a byproduct called digestate, a nutrient-rich material that can be used as fertilizer. However, managing and disposing of this digestate can be challenging. The company will need to develop a plan for handling and possibly monetizing this byproduct.

generate syngas through gasification conversion pathway. The syngas is cleaned and used for CHP to provide rice paddy parboiling, drying and milling service for smallholder rice farmers. Table 3 shows the overview of BCS 2 section criteria and potential impacts.

4.3. Bioenergy case study 3 (BCS 3): biorefinery for transport fuel application

Bioenergy case study 3 is on an oil palm value chain. The case study will target south-south of Nigeria. The biomass resource assessment of this project shows that the region has high oil palm potential, and it was validated during the stakeholder engagement. Furthermore, the region as the highest deposit of crude oil in Nigeria and this case study is for introducing renewable to the crude oil. Fig. 15 shows the schematic diagram of the BSC 3. A range of palm residues are used to produce, biogas, bioethanol and biodiesel. The biogas will be used to supply the energy demand of the biorefinery. The bioethanol and biodiesel will be used for blending with fossil fuel. Table 4 shows the overview of BCS 3 section criteria and potential impacts.

4.4. Bioenergy case study 4: integrated food processing company (CCHP application)

Bioenergy case study 4 is based on the tuber, fruits and vegetable value chain. The case study will target south-west Nigeria as most food processing companies are located there. Fig. 16 shows the schematic diagram of the BSC 4. A range of tuber, fruits and vegetable residues are used to produce biogas to support the energy demand of an integrated food processing company. The biogas will be used to produce process heat and electricity. The electricity will be used for powering processing machine, cold rooms and refrigeration systems. Table 5 shows the overview of BCS 4 section criteria and potential impacts.

Based on the four bioenergy case studies, several recommendations for future research can be put forward to deepen the understanding of bioenergy systems and address existing gaps in knowledge. Researchers can explore both technical and socio-economic aspects of bioenergy projects to optimize their design, implementation, and scalability. Below are some key recommendations for future research.

1. Feedstock supply chain optimisation and logistics.
2. Techno-economic feasibility of bioenergy systems in rural and urban areas.
3. Socio-economic impacts of bioenergy in rural and urban areas.
4. Policy and regulatory frameworks for scaling bioenergy.
5. Lifecycle assessment (LCA), sustainability assessment and environmental impacts of bioenergy systems.
6. Advanced conversion technologies for improved efficiency.
7. Integration of bioenergy into the circular economy.
8. Innovation in biofuel production and blending standards.
9. Community-based bioenergy models and ownership structures.
10. Hybrid bioenergy and renewable energy systems.
11. Exploring small-scale and modular bioenergy technologies

5. Conclusion

Nigeria aims to grow its economy by 2030 through industrialisation. To realise the vision, considerable amounts of energy are needed to drive the economy. Fossil fuel dominates the energy mix projected to meet the energy demand. But the industrialisation could be slow because of fossil fuel subsidy removal by the current government. Even though the fossil fuel subsidy removal has some benefit, other forms of energy are needed to support the government agenda. Bioenergy can support the industrialisation agenda, offer renewable carbon benefits and a high level of flexibility. To show how bioenergy can support the economy of Nigeria, biomass mapping was used to investigate agri-residue potential, identify knowledge gaps in agri-residue application and findings were validated through stakeholder engagement. The output of the biomass mapping shows that Nigeria has a considerable amount of disaggregated agri-residues with lots of the residue knowledge gaps in biomass application to support modern and sustainable bioenergy integration into Nigeria's energy mix. To validate the biomass mapping, expert interviews with stakeholders from policy, industry and feedstock producers in Nigeria were used to identify current bioenergy applications and preferences of bioenergy deployment. Stakeholders have a strong preference for electricity to be the predominant energy vector. There was a limited awareness of other modern bioenergy applications and technologies even though Nigeria's Energy Masterplan supports efficient use of biomass to generate clean energy to support Nigeria's energy demand. Based on these findings, we co-designed a suite of novel bioenergy case studies with the stakeholders to support the integration of biomass into Nigeria's energy system. This co-design process enabled the development of case studies that are both useful and meaningful for stakeholders, facilitating guided discussions about feasible options for them. While having these case studies is a significant achievement, an in-depth techno-economic and socio-economic assessment is necessary to determine their technical, economic, and social viability. The results of these assessments can inform policies, industries, and society about the role of modern bioenergy in Nigeria's industrialisation agenda and the costs associated with transitioning to a low-carbon future. Additionally, while there was limited awareness of modern bioenergy applications and technologies among the stakeholders, the Nigerian government can consider bioenergy public awareness and education campaigns policy. This is crucial as public perception and awareness are crucial for the success of bioenergy projects.

Data availability

Data are available from Food and Agriculture Organization: https://www.fao.org/countryprofiles/index/en/?iso3=NGA.

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CRediT authorship contribution statement

Prince Anthony Okoro: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Katie Chong:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Funding acquisition, Conceptualization. **Mirjam Röder:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Funding acquisition, Conceptualization.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2024.107403.

References

[1] Ministry of Science, Techology and Innovation, National Energy Master Plan, 2022.
[2] P.K. Ozili, K. Obiora, Implications of fuel subsidy removal on the Nigerian economy, in: Public Policy's Role in Achieving Sustainable Development Goals, 2023, https://doi.org/10.2139/ssrn.4535876.
[3] A.J. Welfle, et al., Sustainability of bioenergy – mapping the risks & benefits to inform future bioenergy systems, Biomass Bioenergy 177 (2023/10/01/2023) 106919, https://doi.org/10.1016/j.biombioe.2023.106919.
[4] O.S. Ejiofor, P.A. Okoro, U.C. Ogbuefic, C. VictorNnabuike, K.E. Okedu, Off-grid electricity generation in Nigeria based on rice husk gasification technology, Cleaner Engineering and Technology (2020), https://doi.org/10.1016/j.clet.2020.100009.
[5] M. Röder, C. Whittaker, P. Thornley, How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues, Biomass Bioenergy 79 (Aug 2015) 50–63, https://doi.org/10.1016/j.biombioe.2015.03.030.
[6] Thomas Horschig, Paul W.R. Adams, Mirjam Röder, Patricia Thornley, D. Thrän, Reasonable potential for GHG savings by anaerobic biomethane in Germany and

UK derived from economic and ecological analyses, Appl. Energy 184 (2016) 840–852, https://doi.org/10.1016/j.apenergy.2016.07.098.
[7] M. Röder, P. Thornley, Bioenergy as climate change mitigation option within a 2 °C target—uncertainties and temporal challenges of bioenergy systems, Energy, Sustainability and Society 6 (2016) 1–7, https://doi.org/10.1186/s13705-016-0070-3.
[8] Z. Zhaoa, K. Chongd, J. Jiangc, K. Wilsond, X. Zhanga, F. Wanga, Low-carbon roadmap of chemical production: a case study of ethylene in China, Renew. Sustain. Energy Rev. 97 (2018) 580–591, https://doi.org/10.1016/j.rser.2018.08.008.
[9] M. Röder, A. Mohr, Y. Liu, Sustainable bioenergy solutions to enable development in low- and middle-income countries beyond technology and energy access, Biomass Bioenergy 143 (Dec 2020) 105876, https://doi.org/10.1016/j.biombioe.2020.105876.
[10] P.A. Okoro, K. Chong, M. Röder, Bioenergy potential in Nigeria, how to advance knowledge and deployment to enable SDG 7, WIREs Energy and Environment 13 (4) (2024) e531, https://doi.org/10.1002/wene.531.
[11] A.O. Abdulrahman, D. Huisingh, The role of biomass as a cleaner energy source in Egypt's energy mix, J. Clean. Prod. 172 (Jan 20 2018) 3918–3930, https://doi.org/10.1016/j.jclepro.2017.05.049.
[12] D. Aboagye, N. Banadda, N. Kiggundu, I. Kabenge, Assessment of orange peel waste availability in Ghana and potential bio-oil yield using fast pyrolysis, Renewable Sustainable Energy Rev. 70 (Apr 2017) 814–821, https://doi.org/10.1016/j.rser.2016.11.262 (in English).
[13] H.I. El Shimi, S.S. Moustafa, Biodiesel production from microalgae grown on domestic wastewater: feasibility and Egyptian case study, Renewable Sustainable Energy Rev. 82 (Feb 2018) 4238–4244, https://doi.org/10.1016/j.rser.2017.05.073.
[14] H. Ezz, M.G. Ibrahim, M. Fujii, M. Nasr, Dual biogas and biochar production from rice straw biomass: a techno-economic and sustainable development approach, Biomass Conversion and Biorefinery (Sep 1 2021), https://doi.org/10.1007/s13399-021-01879-y (in English).
[15] E. Gnansounou, E.R. Pachon, B. Sinsin, O. Teka, E. Togbe, A. Mahamane, Using agricultural residues for sustainable transportation biofuels in 2050: case of West Africa, Bioresour. Technol. 305 (Feb 26 2020) 123080, https://doi.org/10.1016/j.biortech.2020.123080.
[16] S. Garcia-Freites, M. Röder, P. Thornley, Environmental trade-offs associated with bioenergy from agri-residues in sub-tropical regions: a case study of the Colombian coffee sector, Biomass Bioenergy 140 (Sep 2020) 105581, https://doi.org/10.1016/j.biombioe.2020.105581.
[17] V.H. Nguyen, et al., Generating a positive energy balance from using rice straw for anaerobic digestion, Energy Rep. 2 (Nov 2016) 117–122, https://doi.org/10.1016/j.egyr.2016.05.005.
[18] M. Röder, N. Stolz, P. Thornley, Sweet energy - bioenergy integration pathways for sugarcane residues. A case study of Nkomazi, District of Mpumalanga, South Africa, Renew. Energy 113 (Dec 2017) 1302–1310, https://doi.org/10.1016/j.renene.2017.06.093.
[19] T.T. Manhongo, A. Chimphango, P. Thornley, M. Röder, Techno-economic and environmental evaluation of integrated mango waste biorefineries, J. Clean. Prod. 325 (Nov 2021) 129335, https://doi.org/10.1016/j.jclepro.2021.129335.
[20] T.T. Manhongo, A. Chimphango, P. Thornley, M. Röder, An economic viability and environmental impact assessment of mango processing waste-based biorefineries for co-producing bioenergy and bioactive compounds, Renewable Sustainable Energy Rev. 148 (Sep 2021), https://doi.org/10.1016/j.rser.2021.111216. Art no. 111216.
[21] R.G. Hamid, R.E. Blanchard, An assessment of biogas as a domestic energy source in rural Kenya: developing a sustainable business model, Renew. Energy 121 (Jun 2018) 368–376, https://doi.org/10.1016/j.renene.2018.01.032.
[22] S.E. Hosseini, M.A. Wahid, Utilization of biogas released from palm oil mill effluent for power generation using self-preheated reactor, Energy Convers. Manag. 105 (Nov 15 2015) 957–966, https://doi.org/10.1016/j.enconman.2015.08.058.
[23] E.K.F. Kra, L. Yao, A. Akichi, Determination of the methanogenic potential of cassava (manihot esculenta crantz) waste from "ATTIEKE" production in YAMOUSSOUKRO city, cote D'IVOIRE, International Journal of Ecosystems and Ecology Science-Ijees 10 (4) (Sep-Dec 2020) 647–656, https://doi.org/10.31407/ijees10.410.
[24] A. Kuhe, F.A. Ibiang, D.I. Igbong, Potential of low pressure agricultural waste briquettes: an alternative energy source for cooking in Nigeria, J. Renew. Sustain. Energy 5 (1) (Jan 1 2013) 013109, https://doi.org/10.1063/1.4781048.
[25] J. Lansche, J. Mueller, Life cycle assessment (LCA) of biogas versus dung combustion household cooking systems in developing countries A case study in Ethiopia, J. Clean. Prod. 165 (Nov 1 2017) 828–835, https://doi.org/10.1016/j.jclepro.2017.07.116.
[26] M. Lubwama, V.A. Yiga, Development of groundnut shells and bagasse briquettes as sustainable fuel sources for domestic cooking applications in Uganda, Renew. Energy 111 (Oct 2017) 532–542, https://doi.org/10.1016/j.renene.2017.04.041 (in English).
[27] L. Makai, M. Molinas, Ieee, "biogas - an alternative household cooking technique for Zambia,", in: *3rd IEEE Global Humanitarian Technology Conference (GHTC)*, San Jose, CA, 2013 Oct 20-23 2013, 2013, p. 17 [Online]. Available: <Go to ISI>://WOS:000349918000004. [Online]. Available: <Go to ISI>://WOS:000349918000004.
[28] A. Malika, A. Mohammed, Y. Guhel, Energetic combustion characteristics and environmental impact of Moroccan biomass wastes and their solid biofuel, Waste and Biomass Valorization 10 (5) (May 2019) 1311–1322, https://doi.org/10.1007/s12649-017-0128-2.
[29] M.P. McHenry, D. Doepel, K. de Boer, Rural African renewable fuels and fridges: cassava waste for bioethanol, with stillage mixed with manure for biogas digestion for application with dual-fuel absorption refrigeration, Biofuels Bioproducts & Biorefining-Biofpr 8 (1) (Jan 2014) 103–113, https://doi.org/10.1002/bbb.1433 (in English).
[30] Y.S. Mohammed, M.W. Mustafa, N. Bashir, M.A. Ogundola, U. Umar, Sustainable potential of bioenergy resources for distributed power generation development in Nigeria, Renewable Sustainable Energy Rev. 34 (Jun 2014) 361–370, https://doi.org/10.1016/j.rser.2014.03.018 (in English).
[31] T. Molony, Bioenergy policies in Africa: mainstreaming gender amid an increasing focus on biofuels, Biofuels Bioproducts & Biorefining-Biofpr 5 (3) (May-Jun 2011) 330–341, https://doi.org/10.1002/bbb.293.
[32] K. Mugodo, P.P. Magama, K. Dhavu, Biogas production potential from agricultural and agro-processing waste in South Africa, Waste and Biomass Valorization 8 (7) (Oct 2017) 2383–2392, https://doi.org/10.1007/s12649-017-9923-z.
[33] N. Nwokolo, S. Mamphweli, E. Meyer, S. Tangwe, Electrical performance evaluation of Johansson biomass gasifier system coupled to a 150 KVA generator, Renew. Energy 71 (Nov 2014) 695–700, https://doi.org/10.1016/j.renene.2014.06.018 (in English).
[34] M. Röder, C. Jamieson, P. Thornley, (Stop) burning for biogas. Enabling positive sustainability trade-offs with business models for biogas from rice straw (in English), Biomass Bioenergy 138 (Jul 2020) 105598, https://doi.org/10.1016/j.biombioe.2020.105598. ARTN 105598.
[35] A. Roopnarain, R. Adeleke, Current status, hurdles and future prospects of biogas digestion technology in Africa, Renewable Sustainable Energy Rev. 67 (Jan 2017) 1162–1179, https://doi.org/10.1016/j.rser.2016.09.087.
[36] S.O. Jekayinfa, J.I. Orisaleye, R. Pecenka, An assessment of potential resources for biomass energy in Nigeria, Resources (2020).
[37] S.O. Jekayinfa, V. Scholz, Laboratory scale preparation of biogas from cassava tubers, cassava peels, and palm kernel oil residues, Energy Sources, Part A Recovery, Util. Environ. Eff. 35 (21) (Nov 2 2013) 2022–2032, https://doi.org/10.1080/15567036.2010.532190 (in English).
[38] R.O. Lamidi, Y.D. Wang, P.B. Pathare, A.P. Roskily, Evaluation of CHP for electricity and drying of agricultural products in a Nigerian rural community, in: *8th International Conference On Applied Energy (ICAE)*, Beijing Inst Technol, Beijing, PEOPLES R CHINA, 2017 Oct 08-11 2016, Vol. 105, in Energy Procedia, 2017, pp. 47–54, https://doi.org/10.1016/j.egypro.2017.03.278 [Online]. Available: <Go to ISI>://WOS:000404967900007.
[39] I.O. Ogundari, et al., Strategic issues in jatropha biofuel enterprise development in Nigeria, in: Portland International Center for Management of Engineering and Technology (PICMET 10), Natl Elect & Comp Technol Ctr (NECTEC), Natl Sci & Technol Dev Agcy, NSTDA, Portland, OR, 2010 2010, p. 2010 [Online]. Available: <Go to ISI>://WOS:000287527800297. [Online]. Available: <Go to ISI>://WOS:000287527800297.
[40] J.K. Ogunjobi, L. Lajide, The potential of cocoa pods and plantain peels as renewable sources in Nigeria, Int. J. Green Energy 12 (4) (2015 2015) 440–445, https://doi.org/10.1080/15435075.2013.848403.
[41] E.I. Ohimain, Can the Nigerian biofuel policy and incentives (2007) transform Nigeria into a biofuel economy? Energy Pol. 54 (Mar 2013) 352–359, https://doi.org/10.1016/j.enpol.2012.11.051.
[42] E.I. Ohimain, The evaluation of pioneering bioethanol projects in Nigeria following the announcement and implementation of the Nigerian biofuel policy and incentives, Energy Sources B Energy Econ. Plann. 10 (1) (2015 2015) 51–58, https://doi.org/10.1080/15567249.2010.512904.
[43] F.O. Olanrewaju, G.E. Andrews, H. Li, H.N. Phylaktou, Bioenergy potential in Nigeria, CHEMICAL ENGINEERING TRANSACTIONS (2019), https://doi.org/10.3303/CET1974011.
[44] Augustine Awaafo, et al., Crops production and the contribution of agricultural biomass power generation to Africa's clean energy transition: analysis of trends from 1990 to 2021, Biomass Bioenergy 186 (2024), https://doi.org/10.1016/j.biombioe.2024.107244.
[45] O.F. Ogunrewo, N.I. Nwulu, Optimisation framework of biomass supply chain in southwest Nigeria, Cleaner Engineering and Technology 18 (2024), https://doi.org/10.1016/j.clet.2023.100711.
[46] FAO. Nigeria Agriculture at a Glance [Online] Available: https://www.fao.org/nigeria/fao-in-nigeria/nigeria-at-a-glance/en/.
[47] FAO. Nigeria crop production [Online] Available: https://www.fao.org/countryprofiles/index/en/?iso3=NGA.
[48] FAO, Global, forest resources assessment. https://fra-data.fao.org/, 2021.
[49] Conor Walsh, P. Thornley, Barriers to improving energy efficiency within the process industries with a focus on low grade heat utilisation, J. Clean. Prod. 23 (1) (2012) 138–146, https://doi.org/10.1016/j.jclepro.2011.10.038.
[50] Djalila Gad, P. Leone, Productive use of energy of women-owned micro-, small-, and medium-sized enterprises: insights from food and textile businesses in selected African countries, Heliyon 10 (2024) e32313, https://doi.org/10.1016/j.heliyon.2024.e32313.
[51] Thi Khanh Chi Nguyen, N.Q. Toan, Developing biomass energy from agricultural by-products in the context of trade development, Energy Strategy Rev. 54 (2024), https://doi.org/10.1016/j.esr.2024.101417.
[52] N.I. Mohammed, N. Kabbashi, A. Alade, Signicance of agricultural residues in sustainable biofuel development. Agricultural Waste and Residues, 2018, https://doi.org/10.5772/intechopen.78374.
[53] A. Koopmans, J. Koppejan, Agricultural and forest residues - generation, utilization and availability, Regional Consultation on Modern Applications of Biomass Energy (1998). https://www.fao.org/3/AD576E/ad576e00.pdf.

[54] IRENA, Biofuel Potential in Sub-Saharan Africa: raising food yields, reducing food waste and utilising residues, International Renewable Energy Agency (2017). Abu Dhabi.

[55] FAO, CROP residues and livestock residues (user manual). https://www.fao.org/publications, 2014.

[56] D. Jölli, S. Giljum, Unused Biomass Extraction in Agriculture, Forestry and Fishery, Sustainable Europe Research Institute (SERI), 2005.

[57] A.A. Rentizelas, Biomass supply chains, Biomass combustion science, technology and engineering (2013), https://doi.org/10.1533/9780857097439.1.9.