Sustainable bioenergy solutions to enable development in low- and middle-income countries beyond technology and energy access

Mirjam Röder[1], Alison Mohr[2], Yan Liu[3]

[1] Supergen Bioenergy Hub, Energy & Bioproducts Research Institute, School of Engineering & Applied Science, Aston University, Aston Triangle, Birmingham, B4 7ET, United Kingdom
[2] School of Sociology and Social Policy, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom
[3] Department of Biosystems and Agricultural Engineering, Michigan State University, East Lansing, USA

Abstract

Bioenergy is the main renewable energy source and the main primary energy source in low- and middle-income countries (LMIC). However, in many cases biomass use is unsustainable and inefficient, resulting in significant environmental and health risks. This short communication synthesises the key findings from 15 research articles published in the Special Issue “Development of modern bioenergy approaches in low- and middle-income countries” published in the journal Biomass & Bioenergy and highlights the overarching research and deployment challenges of bioenergy in a LMIC context. The research presented in the Special Issue shows the relevance of demand-driven and participatory approaches and understanding the technical, environmental, economic and social implications of bioenergy and the synergies with other sectors to enable the full potential of sustainable bioenergy. The findings also show the contribution modern bioenergy systems can make to energy access and human and economic development, underpinning several of the Sustainable Development Goals. While there is large agreement that bioenergy can provide environmental, economic and social co-benefits, research not always capture the full breadth of sustainability and often focuses at the most obvious environmental and economic benefits such as climate change, energy access, related economic development and sustainable production and innovation. Including less visible co-benefits in the evaluation of bioenergy systems would strengthen the analysis of non-monetary values and would support institutional and commercial decision making beyond renewable energy and energy access, underpinning the overarching concept of the SDGS of “leaving no one behind”.

Keywords: Bioenergy, Low- and middle-income countries, International development, Technology innovation, Sustainability

1. Introduction

Access to affordable, reliable and clean energy is a key Sustainable Development Goal (SDG 7), which also underpins other SDGs since energy access facilitates economic development, food security, health and well-being, education and other related objectives [1].

Globally about 70% of renewable energy is supplied by biomass [2], however, this is in many cases traditional biomass and waste use [3]. Especially in low- and middle-income countries (LMIC) energy from biomass provides the main energy source for domestic and productive uses at different scales mainly for generating heat [4]. However, in LMICs, biomass use is often unsustainable and inefficient, resulting in deforestation, soil degradation, and health risks from indoor pollution that disproportionately affect women and children [5].

To realise the full potential of sustainable modern bioenergy systems for heat, electricity and transportation fuel production, system approaches are urgently needed. This would require the integration of fundamental and applied research and development, knowledge transfer, investment, stakeholder and end-user participation, and supporting governance frameworks. Across the world, research, industry, policy and the public sector are starting collaboration on developing holistic solutions for modern bioenergy deployment in LMICs. The aim of such solutions is often to improve clean energy access, energy security, economic development, but also to enhance livelihoods and cultural practices, mitigate climate change and adverse health and social impacts.

This paper synthesises the key findings from 15 research articles (Table 1) published in the Special Issue (SI) "Development of modern bioenergy approaches in low- and middle-income countries" in the journal Biomass & Bioenergy. The SI present recent bioenergy research and development, demonstrating potential regional bioenergy strategies and solutions in 12 different countries (Figure 1). The SI addresses different aspects of bioenergy from biomass resource availability, technology development and application, environmental implications to wider socio-economic aspects and governance frameworks. The key findings of the SI articles will be discussed in the following sections, following this high-level categorisation of four key themes a) biomass resource, b) technology development, c) environment and d) socio-economics & governance. The research fields and themes covered by the 15 SI articles are not exhaustive, but provide a snapshot of current research trends for bioenergy development in LMICs.

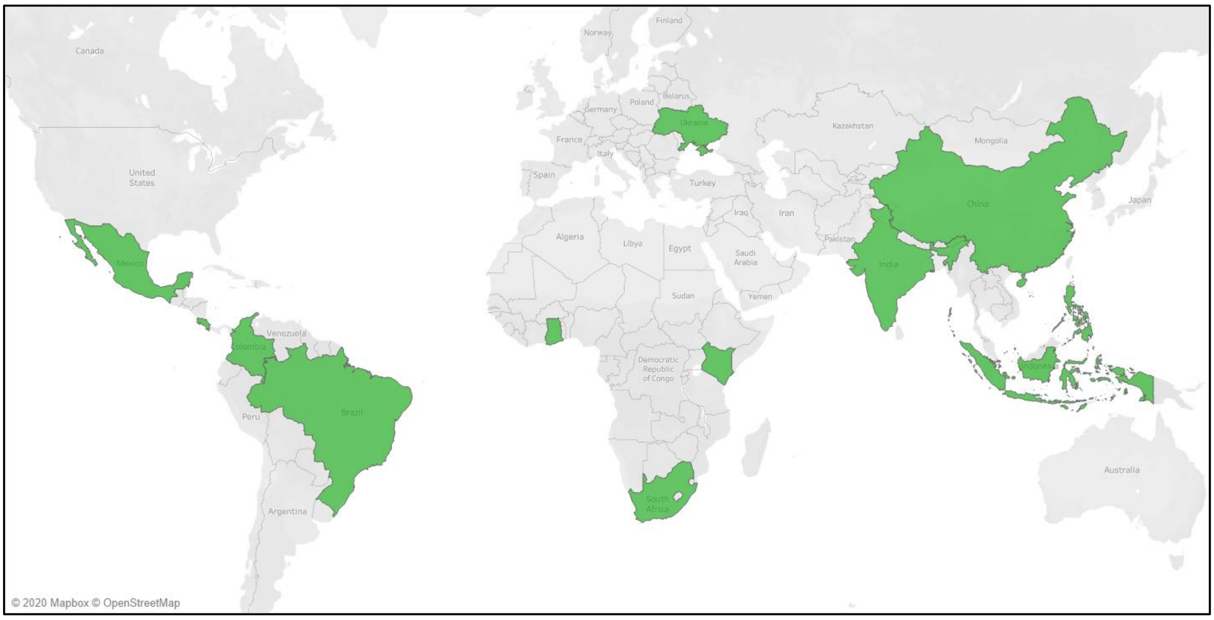

Figure 1: Countries covered by research of the Special Issue “Development of modern bioenergy approaches in low- and middle-income countries” in Biomass & Bioenergy

As part of the synthesis we also evaluated which of the SDGs the SI articles address. We considered whether the research provided evidence that would directly or partly address the SGDs, with the latter being presented as co-benefits of the assessment. This evaluation also helped to highlight gaps the research of the SI articles, and if addressing these could enable wider sustainability co-benefits, in particular non-monetary social values of modern bioenergy solutions.

Table 1: List of articles published in the Special Issue “Development of modern bioenergy approaches in low- and middle-income countries” in Biomass & Bioenergy, highlighting key areas of research (green) and related research areas included in the in the assessment (yellow)

Author and title	Article focus	Biomass resource	Technology development	Environment implications	Socio-economics and governance
Azasi, et al.; Bioenergy from crop residues: a regional analysis for heat and electricity applications in Ghana. [6]	Crop residue availability and bioenergy potential to replace traditional biomass, LPG and fossil-based electricity	🟩			🟨
Brinkman, et al.; The distribution of food security impacts of biofuels, a Ghana case study [7]	Price development for food crops with increasing demand for biofuels and biofuel mandates	🟨			🟩
Chen, et al.; Production of renewable fuel and value-added bioproducts using pineapple leaves in Costa Rica [8]	Production of biofuels from crop residues supporting the biofuel mandate and replacing fossil-based fuels and materials		🟩		
Elias, et al.; Effects of Leucaena biochar addition on crop productivity in degraded tropical soils [9]	Application of biochar to tropical soils for soil conditioning and yield improvement		🟩		🟨
Garcia-Freites, et al.; Environmental trade-offs associated with bioenergy from agri-residues in sub-tropical regions: A case study of the Colombian coffee sector [10]	Environmental implications from residues and trade-offs of different energy applications and replacement of existing energy use			🟩	
Hughes, et al.; Strength in diversity? Past dynamics and future drivers affecting demand for sugar, ethanol, biogas and	Governance frameworks and policies approaches to enabling future industry development				🟩

bioelectricity from Brazil’s sugarcane sector [11]					🟩
Karthikeya, et al.; Exploring optimal strategies for aquatic macrophyte pre-treatment: Sustainable feedstock for biohydrogen production [12]	Enzymatic pre-treatment option to enhance hydrogen production from perennial aquatic plants		🟩		
Ordoñez-Frías, et al.; Bioenergy potential and technical feasibility assessment of residues from oil palm processing: a case study of Jalapa, Tabasco, Mexico [13]	Palm oil processing residues and potential for different energy applications to manage processing waste and improve energy access	🟩			🟨
Ozonoh, et al.; Optimization of process variables during torrefaction of coal/biomass/waste tyre blends: Application of Artificial Neural Network & Response Surface Methodology [14]	Conversion performance of pre-treatment and co-firing of biomass with coal to reduce cost and emissions		🟩	🟨	
Röder, et al.; (Stop) burning for biogas. Enabling positive sustainability trade-offs with business models for biogas from rice straw [15]	Socio-economic trade-offs from bioenergy integration in agricultural systems to manage waste residues and improve energy accesses				🟩
Sekoai, et al.; Revising the dark fermentative H2 research and development scenario – An Overview of the Recent Advances and Emerging Technological Approaches [16]	Review of approaches for dark fermentation to produce advanced biofuels		🟩		
Tomei, et al.; Assessing the relationship between sugarcane expansion and human development at the municipal level: a case study of Mato Grosso do Sul, Brazil [17]	Opportunities and limitations of co-benefits from regional sugar production (including biofuels) for human and municipal development				🟩
Traverso, et al.; Opportunities and constraints for implementation of cellulosic ethanol value chains in Europe [18]	Producing lingo-cellulosic energy crops on marginal land and ggovernance objectives and policies to enable future industry development	🟨			🟩
Welfle, et al.; Kenya’s Biomass Resource Potential & Modern Bioenergy Opportunities for the Domestic & Industry Sectors: Life Cycle GHG Assessment Gliricidia Sepium Production for Briquettes [19]	Replacing traditional biomass and fossil fuels with modern bioenergy and reducing emissions of domestic and productive energy uses	🟨		🟩	
Yang, et al.; Characterization on the aerobic denitrification process of Bacillus strains [20]	Reduction of nitrates run-off and waste waters, supporting energy crop production and treatment of organic fertilisers		🟩	🟨	

2. Sustainable bioenergy solutions

2.1. Biomass resources

Whilst having limited access, in particular to affordable and sustainable energy, many regions in LMICs have considerable biomass potential [21-23]. The Special Issue (SI) articles by Azasi et al. [6] and Ordoñez-Frías et al. [13], showed the theoretical potential of biomass resources from various agricultural harvest residues of the most common food crops in Ghana and agri-processing residues from the palm oil industry in Mexico respectively. In most LMICs, agriculture is a key economic sector that underpins growth in GDP, household incomes, employment and rural livelihoods. Biomass production and sourcing is closely related to the use of land and interfaces more closely with human livelihoods than any other renewable energy technologies. Azasi et al. [6] and Ordoñez-Frías et al. [13] showed how bioenergy production and waste management are closely linked and can create sustainable supply chains. Moreover, Brinkman et al. [7], Garcia-Freites et al. [10], Ordoñez-Frías et al. [13] and Welfle et al. [19] assessed how utilising biomass resources can provided sustainable approaches that address not only energy access, but also reduce greenhouse gas emissions and negative impacts on land, water and air, and additionally improve agricultural productivity and practices, enhance agricultural and forest management systems, diversify rural economic activities and income, create social benefits, and empower rural communities. Hence, biomass utilisation would not just improve energy supply and access at local and national level, but reduce waste disposal, replace traditional biomass use or fossil-based energy and make livelihoods more resilient and sustainable. However, experiences and research have also shown that there are many challenges and unevenly-distributed barriers to enable the mobilisation of biomass resources [24, 25]. The SI article by Röder et al. [15] addressed some of these barriers of biomass mobilisation, such as cost and time of collection, lacking infrastructures, quality of biomass and timing of availability and demand, if biomass is generated in smallholder and often dispersed settings. This SI article also showed the relevance of stakeholder participation and need for suitable business models that support biomass sourcing and collection to overcome such barriers and utilise biomass resources.

While most of the produced and sourced biomass is land-based, there are also opportunities for water-based feedstocks. The SI article by Karthikeya et al. [12] investigates how aquatic macrophyte that do not compete for land use or food production and can be suitable for the production of 2nd generation biofuels and hydrogen.

2.2. Technology development

Two of the main advantages of bioenergy are its versatility and flexibility. Any material of organic origin can be utilised to provide solid, gaseous or liquid biofuels [26]. Additionally, bioenergy systems are flexible as biomass and fuels can be more easily stored than other renewable energy forms [27]. Moreover, small and medium scale applications, in particular, provide high flexibility and can help to balance demand fluctuations [27]. Nonetheless, there can be various challenges related to the composition and characteristics of biomass that can affect and limit the performance, efficiency and choice of technologies. The breadth of feedstocks, conversion technologies and final energy vector covered in the SI articles showed the importance of understanding and addressing the interfaces between feedstock, technology, and demand. The SI articles by Azasi et al. [6], Chen et al. [8], Karthikeya et al. [12], Ordoñez-Frías et al. [13], Ozonoh et al. [14], Sekoai et al. [16] showed how thermal, mechanical and chemical pre-treatment of biomass can help to overcome some of these challenges and improve the versatility of feedstocks.

The focus of most bioenergy interventions in LMICs is on mature technologies such as combustion, gasification, and anaerobic digestion for the provision of heat and electricity as these provide the basic services needed for a minimally decent standard of living and human well-being. Electricity supply and grid expansion are important enablers for economic development and many LMICs are heavily dependent on fossil-based electricity. Considering the high costs of technology innovation and public infrastructures and services, the utilisation of existing facilities and infrastructure such as coal power plants could provide cost benefits as Ozonoh et al. [14] demonstrated in their SI article showing how co-firing can enable an important transition to a lower carbon energy sector in the longer term. Nevertheless, innovations and technology interventions beyond energy grid and large-scale infrastructures can be provide more targeted interventions for communities and offer more flexibility of energy supply and use. The SI articles by Azasi et al. [6], Garcia-Freites et al. [10], Ordoñez-Frías et al. [13] and Welfle et al. [19] investigated solutions that could improve energy supply and support the decarbonisation of off-grid electricity and heat generation through the replacement of fossil-based feedstocks as well as provide technical and economic advantages, directly addressing the energy demand of communities for domestic and productive uses.

Chen et al. [8], Karthikeya et al. [12], and Sekoai et al. [16] showed the high potential of advanced conversion technologies to produce hydrogens and alcohols, that have multiple applications including liquid biofuels for transport. The real cost and implementation of such bioenergy approaches is yet to be widely exploited even in advanced economies. However, the national emission profiles of many LMIC countries reveal the scale of the challenge of decarbonising transport systems [28]. At the same time, mobility is a key element of economic and inclusive development [29]. Providing low-carbon transport solutions, through utilising and maximising domestic biomass resources in LMICs and developing and deploying novel technologies, would facilitate the development of sustainable transportation systems, reduce dependence on imported fossil fuels and associated environmental impacts while creating new job and income opportunities in rural communities.

2.3. Environmental impacts

Bioenergy has an important role in decarbonising the energy and transport sector. In addition to replacing fossil fuels, in off-grid contexts, bioenergy has the added potential for improving energy access using local biomass feedstock as Azasi et al. [6] Garcia-Freites et al. [10], Röder et al. [15] and Welfle et al. [19] showed in their SI articles. Garcia-Freites et al. [10], Ordoñez-Frías et al. [13] and Röder et al. [15] also demonstrated how the use of residues can provide a valid waste management option as residues are often burned or disposed of in unmanaged manners, causing negative environmental and health impacts. In any of these cases, it is important to understand the environmental implications of bioenergy use to identify possible emission impacts and being able to mitigate emission risks or enable environmental benefits. Especially for bioenergy applications replacing or changing existing practices, it is important to understand the synergies and trade-offs between different environmental implications as these can vary for the same technology and supply chain within different contexts and counterfactuals, sometimes limiting the benefits from the technology intervention. The SI article by Garcia-Freites et al. [10] showed that replacing low-carbon grid electricity with bioenergy does not necessarily reduces GHG emissions, while it would when replacing off-grid electricity generated with diesel generators. Hence, understanding context and possible replacement effects of bioenergy deployment is key to avoid any negative impacts and enable benefits and sustainability.

Apart from airborne emissions and the reduction of greenhouse gases, emissions to soil and water are also an important consideration. While bioenergy from residual feedstocks is normally considered as low-carbon, purpose-grown biomass can lead to higher emissions from soil during biomass production as well as to land use competition [26, 30]. In their SI articles Traverso et al. [18] and Welfle et al. [19] investigated how growing lignocellulosic biomass on depleted, marginal or contaminated land may not only reduce these risks, but can also provide additional benefits, such as additional income and improved agricultural practices. In these cases, bioenergy can provide wider eco-system services, such as soil remediation, improved biodiversity, and water conservation.

Even though growing biomass on low-quality land can improve the soil quality, yields from such soils can be low. Elias et al. [9] showed in their SI article that one way of addressing this is through the application of biochar. As an agricultural soil amendment and conditioner, biochar can improve soil fertility and biomass yields, particularly on acidic and highly weathered and degraded soils across the humid tropics [9].

In more intensified agricultural systems, groundwater quality may be affected by irrigated and fertilised crops or the application of digestate or sewage sludge from anaerobic digestion, resulting in nitrification and water contamination. Yang et al. [20] investigated in their SI article methods to treat contaminated water and to pre-treat contaminated sewage and digestate, resulting in efficient denitrification and reducing the risk of nitrification significantly leading to wider eco-system benefits [20].

2.4. Socio-economic impacts and governance frameworks

Bioenergy systems innovation and implementation must be reflective of the demands and priorities of end-users and relevant stakeholders. Sustainable bioenergy solutions extend beyond mere technological fixes can enable wider societal, economic and environmental dimensions. This requires a deep understanding of system impacts to maximise potential benefits to stakeholders and end-users. Sustainable resource availability, robust technologies, low emissions and affordable prices alone, do not necessarily lead to successful bioenergy systems implementation if the demands of end-users are not met. Demand relates to more than just sufficient energy provision; energy is used not for its own sake but as part of the valued social, economic and environmental practices. The SI article by Röder et al. [15] analysed how bioenergy systems that are co-designed by the end-users and address broader livelihood benefits beyond energy access are more likely to be sustainable than applications that have a narrow focus on energy supply. Tomei, et al. [17] showed with their SI article that bioenergy related industry not necessarily enable municipal and human development, especially if transparent mechanisms targeting at human development and monitoring positive and negative impact are limited or lacking. Hence, without end-user participation bioenergy interventions do not guarantee successful uptake and benefits to the stakeholders.

Technological, policy and market innovations mean that bioenergy is likely to be increasingly deployed in the near- and long-term. Understanding the cross-sectoral interfaces of bioenergy is important to avoid negatively impacting adjacent sectors and their end-users. Brinkman, et al. [7] investigated how biofuel production can pose some risks and have adverse impacts on the food sector and food prices. Anticipating the consequences of resource and land use as well as the impacts on prices and markets is possible through the deployment of measures to responsibly govern these sectors, and the synergies between them [7].

Modern bioenergy is often more expensive and economically less feasible than other renewable energy sources. This should not be a barrier to pursuing it. The SI articles by Traverso, et al. [18] and Hughes, et al. [11] demonstrated the relevance of governance and policy measures that reduce uncertainties and support long-term investment to enable bioenergy intervention and enable their co-benefits. Often a change of perception, behaviour and institutional framework are needed to drive innovation, transition and enable benefits beyond short-term economics [11, 18]. Other renewable energies like PV are good examples showing how policy support and public funding lead to scale up and reduced cost. Hence, innovation in institutional frameworks is required that facilitate sustainable and just supply chains and bioenergy systems in the short-, medium- and long-term. However, policy frameworks in many countries currently do not support the competitiveness of modern bioenergy applications. The SI articles by Brinkman, et al. [7], Hughes, et al. [11], Röder et al. [15], Tomei, et al. [17] and Traverso, et al. [18] showed examples that sustainable bioenergy systems require clear policy and sustainability targets over the longer term to attract investment and facilitate market penetration, that deliver environmental, economic and social benefits. These SI articles also showed that in LMICs, the development of policies to attract investment has a further urgency beyond just ensuring local developmental benefits of these investments. Policy has a role to play in encouraging investment in bioenergy infrastructure outside of areas with higher levels of human development so that less developed regions with high bioenergy resource potential can also gain from developmental benefits [7, 11, 15, 17, 18].

2.5. Multi-disciplinarity of bioenergy in LMCIs supporting SDG targets

Figure 2 presents an overview of the SDGs addressed by the SI articles. As expected, the research of the SI articles support SDGs focussing on energy (SDG 7) and climate (SDG 13). The SI articles also address sustainable biomass sourcing and management of resources, support clean energy technology development and can encourage the adaptation of sustainable practices; such research evidence can directly support targets for sustainable production (SDG12). Several of the SI article also showed the relevance of governance frameworks to enable bioenergy deployment which directly links to SDG 16. Whilst not directly assessed in the SI articles, the discussed co-benefits from bioenergy can support SDGs supporting economic development (SDG 8), e.g., creating new income opportunities and diversifying agricultural systems and commercial activities; enabling innovation (SDG9), e.g., supporting the utilisation of residues and underutilised resources, introduction of modern and novel pre-treatment and conversion technologies or new business models; and supporting sustainable use of terrestrial ecosystems and land (SDG 15) e.g., restore degraded land and ecosystems, conserve vulnerable ecosystems, reduce deforestation.

The SI articles assessing the replacement of traditional bioenergy, integration of bioenergy in agricultural systems and community activities and governance frameworks showed additional benefits that are in line with SDGs focusing on poverty alleviation (SDG 1) and hunger alleviation (SDG 2) or improved health (SDG3). A small number of the SI articles also showed the relevance of gender (SDG 5), clean water (SDG 6), reducing inequalities (SDG 10), sustainable cities (SDG 11), and life below water (SDG 14).

The direct benefits and co-benefits from bioenergy evident from the SI articles showed the relevance of multi-disciplinarity research and approaches to capture the breadth of bioenergy and how bioenergy can contribute to various SDGs by enabling positive trade-offs beyond energy and climate change.

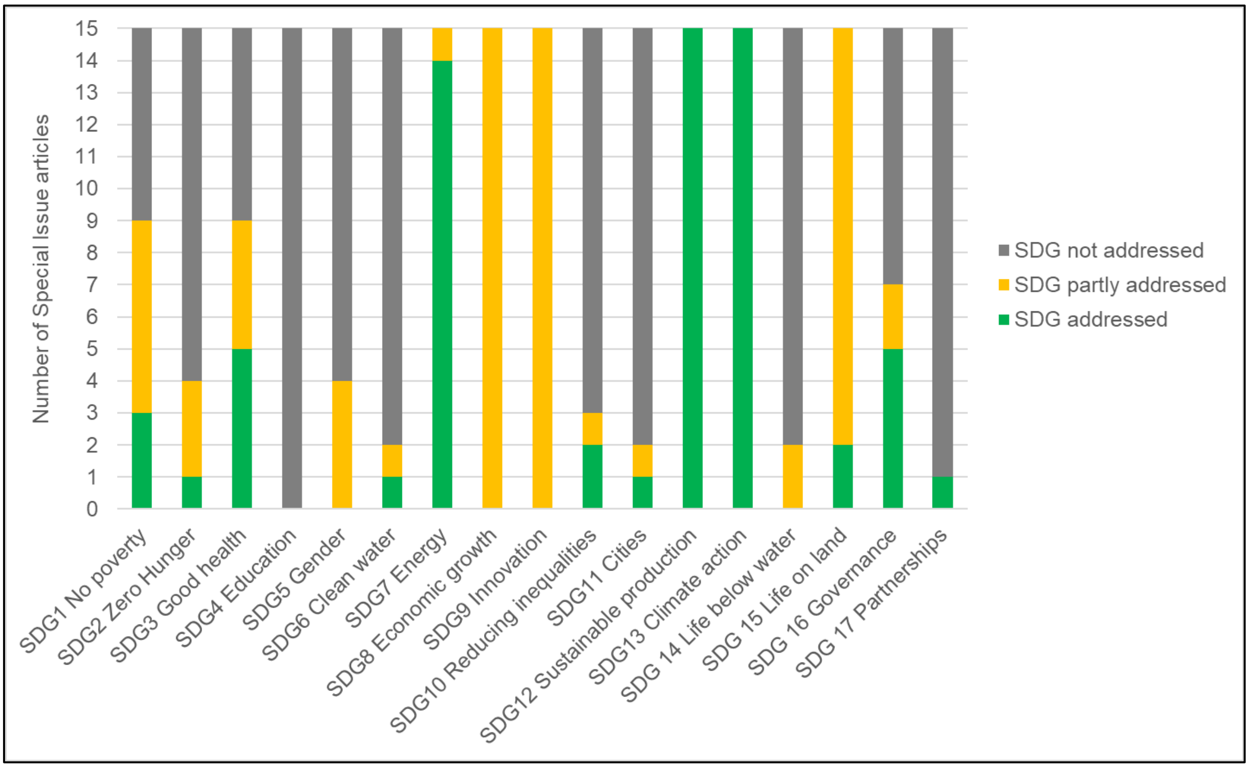

Figure 2: Special Issue articles underpinning the Sustainable Development Goals (SDG). Green = SDG directly addressed, yellow = SDG partly address (co-benefits), grey = SDG not addressed

3. Research and knowledge gaps

The articles of the SI “Development of modern bioenergy approaches in low- and middle-income countries” provide a snapshot of current research for bioenergy development in LMICs and are not exhaustive. Still, a number of wider research needs, knowledge gaps and lessons learnt can be drawn from the collection of SI articles.

3.1. Biomass resources research gaps

Biomass resource can be plentiful and are often underutilised as shown by a number of SI articles [6, 13, 18, 19], but especially harvest residues, often generated in small-scale farming systems, can be scattered and difficult to collect [15], have seasonal availability or are limited by other uses [6, 10, 19]. Work by others has shown that biomass resource assessment often focus on the energy trilemma, just considering decarbonisation, energy security and affordability [31]. Investigating resource availability needs to be considered within the wider concept of mobilisation including amount, aggregation and seasonality of resources and related technical, economic, financial and social barriers to avoid negative choices and enable benefits beyond SDGs 7, 8 and 13.

3.2. Technology development research gaps

The SI articles investigating the technical feasibility and development of bioenergy [8, 12, 13, 16, 20] showed possible application of different conversion technologies and utilisation of feedstocks as well as the optimisation through pre-treatment for different types of feedstock and conversion pathways. The research by Chen et al. [8], Karthikeya et al. [12], Sekoai et al. [16] and Traverso et al. [18], showed the need to address research and knowledge gaps for novel bioenergy technologies and approaches as these can enhance the bioenergy potential beyond currently mature applications and drive development in innovation in countries with high biomass potential. Especially in LMICs with a potentially lower rate of technology lock-ins, novel approaches could leap development and create significant societal co-benefits.

Whilst the feedstock-technology fit is an important aspect of bioenergy, especially technology focused research often misses the link to understanding the local context of services, knowledge and capacities available to maintain technology interventions in the long term as has been shown by others [32]. Additionally, technology focused research needs to consider the real-life energy demand of bioenergy end-users to enable benefits for all user groups, enabling benefits beyond SDGs 7, 9 and 12, ensuring that the overarching aim of the SGDs of “leaving no one behind” is addressed.

3.3. Environmental impacts research gaps

Environmental implications of bioenergy are well research especially in terms of GHG emissions and climate change mitigation potential. A number of the SI articles [10, 19] demonstrated that most bioenergy systems are context specific and showed the need for understanding impacts of a specific business model and system specific replacement effects and that these should be part of comprehensive sustainability assessment. Additionally, environmental impacts from bioenergy during conversion and the disposal of end products like ash and digestate are often outside the research boundaries, but could have a significant environmental constraints. Similar knowledge gaps exist for the impact of water use and the impact of biomass production on surface and ground water. Especially in the context of bioenergy deployment in LMICs, understanding the synergies between climate and environmentally focused SDGs within wider societal implications can enable co-benefits for different stakeholders and help to avoid adverse environmental impacts on air, water and soil and minimise negative impacts for vulnerable groups and environments.

3.4. Socio-economic impacts and governance frameworks research gaps

The SI articles showed that enabling wider socio-economic benefits from bioenergy must be understood beyond energy and technology [13, 15, 17]. Understanding the links and synergies between wider technical, environmental, socio-economic, and socio-cultural implications, including social structure and dynamics and different levels of governance, is important to ensure their alignment with community needs and inclusion. Business models developed together with the relevant stakeholder groups can help identifying technical and non-technical challenges and reduce the risk of failure and support a wide range of SDGs. While there can be commonalities between regions, knowledge transfer can be a valuable way of engagement but business model approaches need to consider context specific factors of the whole system including the relevant stakeholders, end-users and beneficiaries.

The SI articles also showed the need for transparent policy and sustainability targets to attract investment and facilitate market penetration, that deliver environmental, economic and social benefits [7, 11, 15, 17, 18]. Research can help to inform the design of enabling policy environments, but research is also needed to evaluate the impact of policy and investment decisions in a short-, medium- and long-term as development and innovation are dynamic processes that also lead to changes in societal needs and behaviour.

3.5. Research gaps supporting the breadths of SDG targets

Figure 2 showed how the research published in the SI could support the SDGs and how bioenergy enables co-benefits across different SDGs, in particular for those related to energy, environmental, economic and socio-economic targets. However, it became apparent that less or even none research evidence was provided supporting SDGs on education and skill development (SDG 4), equality (SDG 5 and 10) and global partnerships (SDG 17). The topics and foci of the SI articles are not exhaustive and not every bioenergy systems would be expected to support all SDGs, however, understanding whether and how bioenergy deployment in LMICs could potentially support SDGs that currently receive less attention in bioenergy research could support wider societal benefits and ensure that bioenergy interventions do not create new barriers. These could become particularly important for bioenergy applications in off-grid settings and local bioenergy for productive uses at domestic and community scale as these can significantly affect the social networks of supply chain actors and beneficiaries. Understanding co-benefits like skill, capacity building and education, equality and global partnerships and knowledge transfer can be particularly important when providing evidence for non-monetary social benefits and support commercial and institutional decision making.

4. Conclusion

The research articles published in the special issues “Development of modern bioenergy approaches in low- and middle-income countries” in Biomass & Bioenergy showed examples of how modern bioenergy systems can make an important contribution to energy access and human and economic development in LMICs. Energy has always been a mix of different fuels and vectors. The versatility and flexibility of bioenergy offers a large array of technical options to supply clean energy. However, to enable the full potential of sustainable bioenergy it is necessary to understand its technical environmental, economic and social implications and the synergies with the wider system bioenergy interventions will be part of. For this, business models for bioenergy need to consider the wider implications and co-benefits of the intervention for different stakeholder groups and supporting governance frameworks are necessary.

Therefore, to enable the transition to modern and sustainable bioenergy including changes in practices and behaviour, demonstration of advanced systems is needed that take a holistic approach investigating technical and non-technical challenges and the synergies between different implications. This reflects across all SI articles, by repeatedly showing the multi-disciplinary links and synergies between different research themes and the benefits of bioenergy systems that can provide solutions that enable multiple benefits beyond a single challenge. However, assessments not always capture the full breadth of sustainability and often focus on the most obvious environmental and economic benefits. The synthesis of the SI research highlighted the need for further evaluation of synergies between the different SDGs. In particularly, including less visible co-benefits in the evaluation of bioenergy systems would allow to analyse non-monetary values in more depths and would provide a comprehensive assessment and support commercial and institutional decision making particularly under the overarching concept of the SDGS of “leaving no one behind”.

Acknowledgements

This paper synthesises the key findings of research published in the special issue “Development of modern bioenergy approaches in low- and middle-income countries” published in Biomass and Bioenergy. The authors want to thank all contributing authors of the Special Issue for providing an interesting and multi-disciplinary range of research. The authors also thank the team of Biomass and Bioenergy for providing a platform for this Special Issue.

References

[1] Fuso Nerini, F., Tomei, J., To, L.S., et al. Mapping synergies and trade-offs between energy and the Sustainable Development Goals. Nature Energy 2018; 3:10-5. 10.1038/s41560-017-0036-5

[2] IEA. Renewables Information 2019, IEA, Paris https://www.iea.org/reports/renewables-information-2019. 2019

[3] Ritchie, H., Roser, M. CO_2 and Greenhouse Gas Emissions. Published online at OurWorldInDataorg Retrieved from: 'https://ourworldindataorg/co2-and-other-greenhouse-gas-emissions. 2017

[4] Parikh, J. Hardships and health impacts on women due to traditional cooking fuels: A case study of Himachal Pradesh, India. Energy Policy 2011; 39:7587-94. https://doi.org/10.1016/j.enpol.2011.05.055

[5] Pope, D., Bruce, N., Dherani, M., et al. Real-life effectiveness of ' improved ' stoves and clean fuels in reducing PM2.5 and CO: Systematic review and meta -analysis. Environment International 2017; 101:7-18. 10.1016/j.envint.2017.01.012

[6] Azasi, V.D., Offei, F., Kemausuor, F., et al. Bioenergy from crop residues: A regional analysis for heat and electricity applications in Ghana. Biomass and Bioenergy 2020; 140:105640. https://doi.org/10.1016/j.biombioe.2020.105640

[7] Brinkman, M., Levin-Koopman, J., Wicke, B., et al. The distribution of food security impacts of biofuels, a Ghana case study. Biomass and Bioenergy 2020; 141:105695. https://doi.org/10.1016/j.biombioe.2020.105695

[8] Chen, A., Guan, Y.J., Bustamante, M., et al. Production of renewable fuel and value-added bioproducts using pineapple leaves in Costa Rica. Biomass and Bioenergy 2020; 141:105675. https://doi.org/10.1016/j.biombioe.2020.105675

[9] Elias, D.M.O., Ooi, G.T., Ahmad Razi, M.F., et al. Effects of Leucaena biochar addition on crop productivity in degraded tropical soils. Biomass and Bioenergy 2020; 142:105710. https://doi.org/10.1016/j.biombioe.2020.105710

[10] Garcia-Freites, S., Röder, M., Thornley, P. Environmental trade-offs associated with bioenergy from agri-residues in sub-tropical regions: A case study of the Colombian coffee sector. Biomass and Bioenergy 2020; 140:105581. https://doi.org/10.1016/j.biombioe.2020.105581

[11] Hughes, N., Mutran, V.M., Tomei, J., et al. Strength in diversity? Past dynamics and future drivers affecting demand for sugar, ethanol, biogas and bioelectricity from Brazil's sugarcane sector. Biomass and Bioenergy 2020; 141:105676. https://doi.org/10.1016/j.biombioe.2020.105676

[12] Karthikeya, K., Sarma, M.K., Ramkumar, N., et al. Exploring optimal strategies for aquatic macrophyte pre-treatment: Sustainable feedstock for biohydrogen production. Biomass and Bioenergy 2020; 140:105678. https://doi.org/10.1016/j.biombioe.2020.105678

[13] Ordoñez-Frías, E.J., Azamar-Barrios, J.A., Mata-Zayas, E., et al. Bioenergy potential and technical feasibility assessment of residues from oil palm processing: A case study of Jalapa, Tabasco, Mexico. Biomass and Bioenergy 2020; 142:105668. https://doi.org/10.1016/j.biombioe.2020.105668

[14] Ozonoh, M., et al, Optimization of process variables during torrefaction of coal/biomass/waste tyre blends: Application of Artificial Neural Network & Response Surface Methodology. Biomass and Bioenergy 2020:(accepted). .

[15] Röder, M., Jamieson, C., Thornley, P. (Stop) burning for biogas. Enabling positive sustainability trade-offs with business models for biogas from rice straw. Biomass and Bioenergy 2020; 138:105598. https://doi.org/10.1016/j.biombioe.2020.105598

[16] Sekoai, P.T., Daramola, M.O., Mogwase, B., et al. Revising the dark fermentative H2 research and development scenario – An overview of the recent advances and emerging technological approaches. Biomass and Bioenergy 2020; 140:105673. https://doi.org/10.1016/j.biombioe.2020.105673

[17] Tomei, J., Lyrio de Oliveira, L., de Oliveira Ribeiro, C., et al. Assessing the relationship between sugarcane expansion and human development at the municipal level: A case study of Mato Grosso do Sul, Brazil. Biomass and Bioenergy 2020; 141:105700. https://doi.org/10.1016/j.biombioe.2020.105700

[18] Traverso, L., Colangeli, M., Morese, M., et al. Opportunities and constraints for implementation of cellulosic ethanol value chains in Europe. Biomass and Bioenergy 2020; 141:105692. https://doi.org/10.1016/j.biombioe.2020.105692

[19] Welfle, A., Chingaira, S., Kassenov, A. Decarbonising Kenya's domestic & industry Sectors through bioenergy: An assessment of biomass resource potential & GHG performances. Biomass and Bioenergy 2020; 142:105757. https://doi.org/10.1016/j.biombioe.2020.105757

[20] Yang, T., Xin, Y., Zhang, L., et al. Characterization on the aerobic denitrification process of Bacillus strains. Biomass and Bioenergy 2020; 140:105677. https://doi.org/10.1016/j.biombioe.2020.105677

[21] IEA. Africa Energy Outlook 2019. IEA Webstore. 2019; 288 p.

[22] IRENA. Biofuel potential in Sub-Saharan Africa: Raising food yields, reducing food waste and utilising residues. 978-92-9260-041-9. 2017

[23] Stecher, K., Brosowski, A., Thrän, D. Biomass Potential in Africa. IRENA, IEA Bioenergy, DBFZ. 2013

[24] Moustakas, K., Loizidou, M., Rehan, M., et al. A review of recent developments in renewable and sustainable energy systems: Key challenges and future perspective. Renewable & Sustainable Energy Reviews 2020; 119:6. 10.1016/j.rser.2019.109418

[25] Thornley, P., Gilbert, P. Biofuels: balancing risks and rewards. Interface Focus 6 2013; 3http://dx.doi.org/10.1098/rsfs.2012.0040

[26] Röder, M., Welfle, A. 12 - Bioenergy. In: Letcher, Trevor M., editor. Managing Global Warming: Academic Press; 2019. p. 379-98

[27] Purkus, A., Gawel, E., Szarka, N., et al. Contributions of flexible power generation from biomass to a secure and cost-effective electricity supply—a review of potentials, incentives and obstacles in Germany. Energy, Sustainability and Society 2018; 8:18. 10.1186/s13705-018-0157-0

[28] R. Sims, R. Schaeffer, F. Creutzig, et al. Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovern-mental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.; 2014

[29] SuM4All. Sustainable Mobility for All. Global Mobility Report 2017: Tracking Sector Performance. Washington DC. 2017

[30] Gilbert, P., Thornley, P., Riche, A.B. The influence of organic and inorganic fertiliser application rates on UK biomass crop sustainability. Biomass and Bioenergy 2011; 35:1170-81. http://dx.doi.org/10.1016/j.biombioe.2010.12.002

[31] Welfle, A., Holland, R.A., Donnison, I., Thornley, P.(2020). UK Biomass Availability Modelling Scoping Report. Supergen Bioenergy Hub Report No. 02/2020.Available from: https://www.supergen-bioenergy.net/wp-content/uploads/2020/10/Supergen-Bioenergy-Hub-UK-Biomass-Availability-Modelling-Scoping-Report-Published-Final.pdf. Hub, Supergen Bioenergy. 77 p.

[32] Röder, M., Stolz, N., Thornley, P. Sweet energy – Bioenergy integration pathways for sugarcane residues. A case study of Nkomazi, District of Mpumalanga, South Africa. Renewable Energy 2017; 113:1302-10. http://dx.doi.org/10.1016/j.renene.2017.06.093