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ADVANCED REVIEW

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Bioenergy potential in Nigeria, how to advance knowledge and deployment to enable SDG 7

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Abstract

Biomass is currently the main energy source in Nigeria, but it is being used and managed unsustainably, resulting in significant health and environmental risks. To support Nigeria's transition to an affordable, reliable, and low-emission future, there is a need to shift from traditional biomass use to modern bioenergy applications. The research reviews the existing knowledge on themes relevant to developing sustainable modern bioenergy for Nigeria in the context of agri-residues. It synthesizes the key findings on the themes from 161 scientific literature published between 2010 and 2021 on Nigeria and Sub-Saharan Africa. The findings show that most literature focused on agri-residues potentially available in large amounts but highly disaggregated, such as cassava and palm residues. Furthermore, the literature highlighted the importance of understanding agri-residue aggregation, technological, economic, socio-economic, governance framework of bioenergy, and the interactions with other sectors to unlock the full potential of modern bioenergy. While research acknowledged that bioenergy could enhance energy security, economic growth, and social co-benefits, there has been less focus on the benefits of novel bioenergy solutions co-created by relevant stakeholder groups in Nigeria. Involving relevant stakeholders in developing novel bioenergy solutions would address the missing link between resource assessment, appropriate technology deployment, and end-user demand. It would also enhance the analysis of the bioenergy market and nonmarket benefits and ensure that bioenergy solutions in Nigeria are aligned with community needs and foster inclusivity.

This article is categorized under:
Sustainable Energy > Bioenergy
Policy and Economics > Governance and Regulation

Abbreviations: AD, Anaerobic digestion; AER, Absorption Enhanced Reforming; FAO, Food and Agriculture Organization; GDP, Gross Domestic Product; GHG, Greenhouse gas; IEA, International Energy Agency; LCOE, Levelized cost of electricity; LMIC, Low- and middle-income countries; LUT, Look-up table; ML/day, Million liters per day; Mtoe, Million tons; MW, Megawatt; NREEEP, National Renewable Energy and Energy Efficiency Policy; OECD, Organization for Economic Co-operation and Development; POME, Palm oil mill effluent; PRF, Policy and regulatory framework; SDGs, Sustainable Development Goals; SEA, Socio-economic assessment; SSA, Sub-Sahara Africa; SuM4All, Sustainable Mobility For All; TEA, Techno-economic assessment.

KEYWORDS
biomass and bioenergy, conversion technologies, Nigeria, techno-economic and socio-economic assessment

1 | INTRODUCTION

The development of any nation is determined by its access to energy and finance (IEA et al., 2020). To better the quality of life and livelihoods, a nation needs access to clean energy (IEA et al., 2020). Access to clean and affordable energy in low- and middle-income countries can enable economic growth, availability and access to food, good health and well-being, quality education, and other related SDGs (IEA, 2019; IEA et al., 2020; SuM4All, 2017). However, in Nigeria, over 90 million people do not have access to electricity (IEA, 2019; IEA et al., 2020). At the same time, more than 170 million of the population cook using traditional biomass and other unclean cooking solutions (IEA, 2019; IEA et al., 2020). Nigeria targets to increase electricity access, clean cooking access, and conditional emission reduction to 80%, 28%, and 45%, respectively, in 2030 (IEA, 2019). To achieve its energy access and emission reduction targets, Nigeria's National Renewable Energy and Energy Efficiency Policy (NREEEP) outlined plans to integrate various renewable energy sources into its energy mix by 2030. These include hydroelectric power capacity of 12,801 MW; Solar electricity capacity of 6831 MW; Wind electricity capacity of 3211 MW; Biomass electricity capacity of 292 MW; Bio-ethanol production of 24.2 ML/day; and Biodiesel production of 11.7 ML/day. These targets reflect Nigeria's commitment to diversifying its energy sources and reducing emissions through the adoption of renewable energy technologies (Foundation & AllOn, 2015). But Nigeria's population lacking access to sustainable energy will likely increase due to continuing population growth and a low energy access rate. Over the last decade, Nigeria's energy access rate has been low. Access to electricity increased by an annual average of just 0.7% and access to cooking gas rose by 2% (IEA, 2019; IEA et al., 2020; SuM4All, 2017). The low energy access rate in Nigeria can undermine the country's efforts to attain its Sustainable Development Goals (SDGs) because of the co-benefits energy access offers (IEA et al., 2020). Figure 1 (IEA, 2019) shows Nigeria's major energy demand and Gross Domestic Product (GDP) in the stated policy scenario, 2010–2040. The forecast was developed considering reductions in greenhouse gas (GHG) emissions, fossil fuel exports, percentage federal capital expenditure deployment and population, GDP, electricity, and clean cooking growths. Nigeria's energy demand from its primary energy sources is around 150 Mtoe and is forecasted to rise to more than 200 Mtoe by 2040 (IEA, 2019). Traditional biomass and other wastes contribute up to 74% of Nigeria's energy demand. In comparison, the contribution of oil products and natural gas is 17% and 9%, respectively (IEA, 2019).

Biomass demand is anticipated to increase from 125 Mtoe in 2030 to 137 Mtoe by 2040 (IEA, 2019). The consumption of biomass is largely for domestic cooking, as over 80% of energy for cooking comes from wood fuel, charcoal, and other agricultural residues (Power, 2016). The health and environmental risks of using wood and agricultural residues

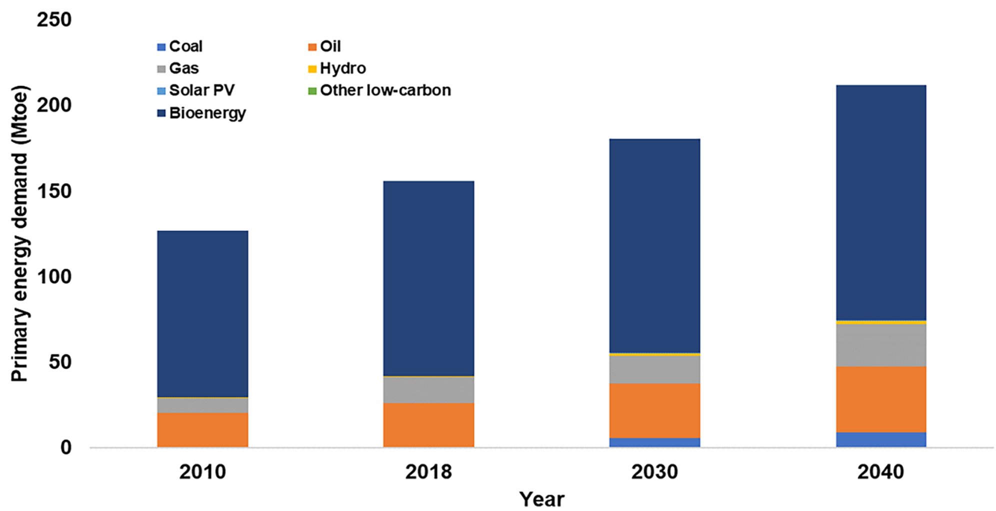

FIGURE 1 Projected primary energy demand of Nigeria (IEA, 2019).

are established and well-documented (Chen et al., 2017; Ranius et al., 2018). Furthermore, the use of wood fuel and charcoal as a source of energy has led to indiscriminate cutting down of trees, which leads to deforestation and carbon stock reduction (FAO, 2021a). As such, there is a need for a change from unsustainable biomass use to a more sustainable modern bioenergy approach. There has been a lack of political will to initiate and implement national energy policies that would engineer a change from conventional biomass use to modern bioenergy applications (Power, 2016). Where such policies exist, transitioning has been slow due to poverty, inadequate support (IEA et al., 2020; Power, 2016), and paucity of data-centered research on bioenergy to inform policy, industry, and society on the benefits of sustainable modern bioenergy solutions in Nigeria (Elsevier, 2021).

An integrated system approach is urgently needed to fully realize the prospect of sustainable modern bioenergy systems in Nigeria for heat, electricity, and transportation fuel production. This approach can involve the combination of fundamental and applied research, knowledge transfer, investment, stakeholder and end-user participation, and supportive government frameworks. It is important to review the trends in bioenergy to assess the status of bioenergy development and deployment in Nigeria to pave the way for novel modern bioenergy solutions for the country. Bioenergy offers unique benefits including versatility, flexibility, economic development, energy security, and renewable source of carbon. Small- and medium-scale applications, in particular, provide great flexibility and can help to balance fluctuation in energy demand (Welfle et al., 2023). This article provides evidence of the existing knowledge on advances in bioenergy in Nigeria in the context of agri-residues. Agri-residues include rice straw, wheat straw, rice husk, palm kernel shell, corn cob, and cassava peel which are usually left on the fields after harvests and in processing facilities. 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 embedded energy content, known as bioenergy potential. The agri-residues can produce various forms of energy that can facilitate economic and socio-economic development and growth in Nigeria. The study synthesizes key findings from 161 pieces of scientific literature on using agri-residues for energy production in Nigeria and other Sub-Saharan African countries. The article focuses on the key findings and themes relevant to developing and deploying modern bioenergy solutions in Nigeria. These include (a) biomass and bioenergy, (b) technology development, (c) techno-economic assessment (TEA), (d) socio-economic assessments (SEAs), and (e) policy and regulatory frameworks (PRFs). While the research fields and themes covered in the 161 literature are not exhaustive, they provide an overview of the current research and knowledge for bioenergy development in Nigeria and other Sub-Saharan African countries.

This review presents an innovative approach to the research of bioenergy production from agri-residues in Nigeria, showing not only the level of bioenergy penetration but also future research that could enable Nigeria's transition to low carbon future.

2 | METHODOLOGY

This section describes the focus of the review and how it was conducted using a literature review tool. The review focused on existing knowledge on bioenergy in Sub-Saharan Africa. The scope of the review includes but is not limited to:

1. Nigeria and other Sub-Saharan African countries including Ghana, Uganda, Egypt, South Africa, and so on.
2. The Sub-Saharan African regions that have similar characteristics and commonalities.
3. Understanding the trends in bioenergy within Sub-Saharan Africa region.
4. Checking possible knowledge transfer as Sub-Saharan Africa has similar commonalities.
5. Identifying potential knowledge gap(s).

2.1 | Building the bioenergy literature database

A comprehensive literature review was conducted to analyze the bioenergy trends in Nigeria. It was completed by focusing on peer-reviewed literature published on biomass and bioenergy development in the low- and middle-income countries (LMIC). The articles were collated on the Web of Science (Clarivate, 2022). The searches centered on bioenergy literature that referenced the keywords—(Biomass, "agri-residue," bioenergy, "developing countries" or "developing country," "Sub-Sahara Africa" or SSA, Nigeria, "low-carbon" or "low-carbon future" or "transition to a low-carbon future," "techno-economic," "socio-economic," "energy model" or "energy models," "Integrated Assessment Model," "Energy system model," "Specialist model," "energy vector"). The search captured 7931 pieces of literature on biomass and bioenergy in LMIC published from 2010 to 2021. This time frame was selected because 2010 marked the beginning of increased policy focus and attention on bioenergy in Nigeria and many Sub-Saharan African countries, and 2021 was the most recent year for which a complete publication record was available at the time of the review. The 7931 scientific outputs were added to Welfle et al. (2020) literature analysis tool. The tool was used to analyze the results systematically. Building on a methodology developed by Welfle et al. (2020), the analysis assumes that keywords describing the paper's content were included in the abstract.

The literature review tool was used to identify literature that focused on the context of Nigeria and Sub-Saharan Africa. This was achieved by searching for literature that referred to these keywords—Biomass, "agri-residue," bioenergy, "Sub-Saharan Africa" or "SSA" or Nigeria, "low-carbon" or "low-carbon future" or "transition to a low-carbon future," "techno-economic," "socio-economic," "policy" or "governance," "policy and regulatory framework." To ensure comprehensive coverage of relevant literature on agri-residues, all crops grown in Nigeria, as listed in the FAO database (FAO, 2022), were included in the literature review tool. Additionally, all countries in Sub-Saharan Africa were listed in the tool to capture literature investigating agri-residues in the region. The tool's output identified 161 relevant publications on biomass and bioenergy, focusing on agri-residues, published from 2010 to 2021 and addressing Nigeria and some Sub-Saharan African contexts. The key findings of the scientific literature were synthesized and discussed following this high-level categorization of five key themes—(a) biomass and bioenergy, (b) technology development, (c) TEA, (d) SEA, and (e) PRFs.

3 | SCIENTIFIC LITERATURE REVIEW

Given the focus on agri-residues in the review, it is essential to gain an understanding of the agricultural sector in Nigeria. Agriculture is a key sector of the Nigerian economy that employs about two-third of the national labor force and is the main livelihood base for many. The sector contributed about 21% of the total GDP of Nigeria in the second quarter of 2023 (Statistics, 2023).

3.1 | Agriculture in Nigeria

The Nigerian agricultural sector is dominated by small-scale farming (∼1.8 ha/household) and low productivity (1.2 t/ha for cereals). This applies across subsistence and commercial crops. For example, Nigeria is one of the top-10 palm oil producers globally and one of the most important economic sectors in the country, but about 50% of the fruit is collected from wild groves and grown on small scale. Compared with other main palm oil-producing countries the Nigerian yield is significantly lower with about 2.6 t/ha due to poorly and non-managed plantations, groves, and overaged trees (FAO, 2021b). The main agricultural crops in Nigeria are Cassava and Yams. Nigeria is the largest cassava producer globally (∼50 million tons and 3.7 million ha), but yields are low with about 8.6 t/ha (Average yield Africa ∼9 t/ha, average yield world ∼11.3 t/ha). Other key crops are maize, oil crops (oil palm fruit, groundnuts), vegetable, cereals (sorghum, rice), and fruits (FAO, 2022).

3.2 | Existing knowledge on biomass resource assessment

The literature review tool identified 23 pieces of scientific literature focusing on primary- and secondary-residue resource assessment and applications in Nigeria and some other Sub-Saharan African countries. Figure 2 shows that 39% of outputs specifically focused on Nigeria. Nigeria has considerable biomass potential from agricultural residues (Ezealigo et al., 2021; Olanrewaju et al., 2019; Simonyan & Fasina, 2013, 2015). Agriculture is the mainstay of Nigeria's economy and is characterized by small-scale farming, low productivity, and low income (FAO, 2021b). The sector produces large amounts of residues that is managed unsustainably. Ezealigo et al. (2021) and Jekayinfa et al. (2020) showed the theoretical potential of biomass resources from various crops in Nigeria like rice husk, cassava peels, and palm kernel shells. Using these residues for modern bioenergy applications can provide energy for industrial and community

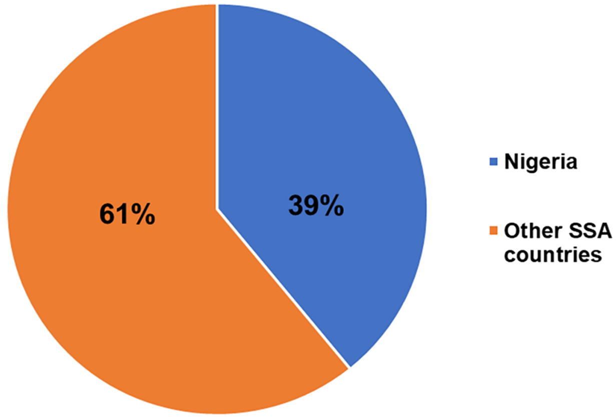

FIGURE 2 The percentage share of research outputs focused on biomass and bioenergy.

energy supply (Ejiofor et al., 2020; Toyese & Jibiri, 2016). The residues can be used for biofuel (Ishola et al., 2020) in transportation, a key sector of Nigeria's economy (SuM4All, 2017).

Literature on bioenergy in Nigeria focused mainly on largely available agri-residues that are highly disaggregated, like palm oil, rice, cassava, and sugar cane. Ishola et al. (2020) investigated how biodiesel produced from palm olein can support commercial applications. Similarly, Toyese and Jibiri (2016) showed how biogas generated from sugarcane bagasse can be used for combined heat and power applications in sugarcane industries. In locations where small-scale processing clusters exist, agricultural residues are more likely to accumulate over time, reducing mobilization challenges if enough high-quality processing residues are generated to meet the energy demand for the processing cluster. In such cases, bioenergy can offer an integrated solution by utilizing the agri-residues to meet the energy demand, thus contributing to sustainable resource utilization and supporting energy needs. Ejiofor et al. (2020) showed how electricity can be generated from rice husk for rice farming clusters and households in eastern Nigeria. Proper utilization of agri-residues in modern bioenergy applications in Nigeria can enhance energy supply and access at regional and national levels, minimize indiscriminate waste disposal, replace conventional biomass use or fossil-based energy, and make everyday living more resilient and sustainable. However, research has shown that improper siting of biomass plants poses many challenges and barriers to mobilizing biomass resources (Moustakas et al., 2020). Bioenergy plant location is crucial, as it plays an essential role in the success of bioenergy projects. Kyauta et al. (2021) used GIS technology for the optimal siting of a biomass gasification plant in a groundnut farming cluster in northern Nigeria. The optimal location of a biomass plant would contribute to reducing mobilization costs and plant downtime because of insufficient feedstock. While most biomass is sourced from agricultural residues in Nigeria, bioenergy can be produced from other sources like animal and food waste for distributed energy generation (Mohammed et al., 2014).

Figure 2 shows that 61% of the research output focused on other Sub-Saharan Africa countries. The agri-residues can produce various forms of energy that can facilitate economic and socio-economic development and growth in Africa (Gnansounou et al., 2020). Research in other countries in Sub-Saharan Africa is country-specific (Akbi et al., 2017; Balogun et al., 2014; Chitawo & Chimphango, 2017; Kilama et al., 2019; Mboumboue & Njomo, 2016; Mensah et al., 2021; Röder, Jamieson, & Thornley, 2020; van der Hilst & Faaij, 2012; Winkler et al., 2015) showing agri-residues potential and its applications. Mensah et al. (2021) showed how different agri-residues can be used to support Ghana's electricity sector. They used the bioenergy estimation method and look-up table (LUT) model for power sector transition modeling. The LUT model was applied to develop six alternative scenarios for the power sector. Their study reveals that with an electrical efficiency of 37.2%, bioenergy could contribute up to 16.9% of Ghana's electricity demand for grid balancing by 2050. Similarly, Chitawo and Chimphango (2017) investigated the potential of using rice waste for irrigation pumping. They found that irrigating rice farms during the off-season would increase annual rice production from 34,703 to 59,970 tons. Energy production from biomass comes with cost and mobilization barriers (Mensah et al., 2021). However, Röder, Jamieson, and Thornley (2020) proposed ways to address some of the barriers to biomass mobilization, such as cost and time, inadequate infrastructures, timing of availability, demand, quality of biomass, if biomass is generated in small scale, and often dispersed settings. They also showed the importance of stakeholders' engagement and the need for appropriate business models that enable biomass sourcing and collection to overcome such barriers and aid the utilization of agri-residues. While most of the produced and sourced biomass is land-based, bioenergy can be produced from water-based feedstocks for grid or off-grid applications (Akbi et al., 2017).

3.3 | Existing knowledge on technology assessment

The choice, efficiency, and performance of biomass technologies can be affected by the composition and characteristics of biomass. The range of feedstock, conversion technologies, and final energy vectors investigated in the scientific literature highlights the need to understand and address the interfaces between feedstock, technology, and demand. Figure 3 shows the output of the technology-focused research obtained from the literature review analysis tool.

3.3.1 | Anaerobic digestion (AD)

AD is suitable for feedstock with high moisture content for renewable energy production and waste management. Suitable feedstocks include fruit wastes such as mango, watermelon, and pawpaw (Anika & Akin-Osanaiye, 2020; Jensen et al., 2019). The efficiency of AD can be improved by feedstock pretreatment, co-digestion, and user operational practices (Sawyerr et al., 2019; Wasajja et al., 2021). Figure 3 shows that AD technology gained the highest research interest in Nigeria. The high research interest could be attributed to the technology's relatively low cost and simplicity (Adams et al., 2018; Daoutidis et al., 2013; Kaltschmitt, 2017). Between 2010 and 2021, 28 articles on biomass AD technology in Nigeria and other Sub-Saharan African countries were published. Out of the 28 research outputs, 36% focused on Nigeria. Hosseini and Wahid (2015) investigated energy production from palm oil mill effluent (POME) biogas. A 3 MW electricity demand was modeled in Aspen Plus. From the results, it was found that ultra-lean POME biogas could generate 10.8 MW of power. One of the ingredients of POME biogas is hydrogen. When 2% hydrogen was added to the biogas, the rate of power generation increased to around 0.7 MW. Aisien and Aisien (2020), Odekanle et al. (2020), and Jekayinfa and Scholz (2013) showed that co-digestion of different feedstocks can improve the biogas yield and the quality of the produced bio-fertilizer to support both household and industrial energy supply and improve soil quality. An animal farm that generates large amounts of animal waste can use AD technology for combined heat and power for process heat and electricity supply to farm machinery (Lamidi et al., 2016). Biogas can be utilized in a hybrid energy system to substitute batteries, provide energy in the absence of sunshine and when there is high fluctuation in grid supply (Sanni et al., 2021).

Research output on AD technology in other Sub-Saharan African countries constitutes 64% of the total research theme. They highlighted the status of AD research in several African countries, including Egypt (Elagroudy et al., 2020; Ezz et al., 2021), Ghana (Arthur et al., 2011), Zambia (Makai & Molinas, 2013), and others (Fito et al., 2019; Kerroum

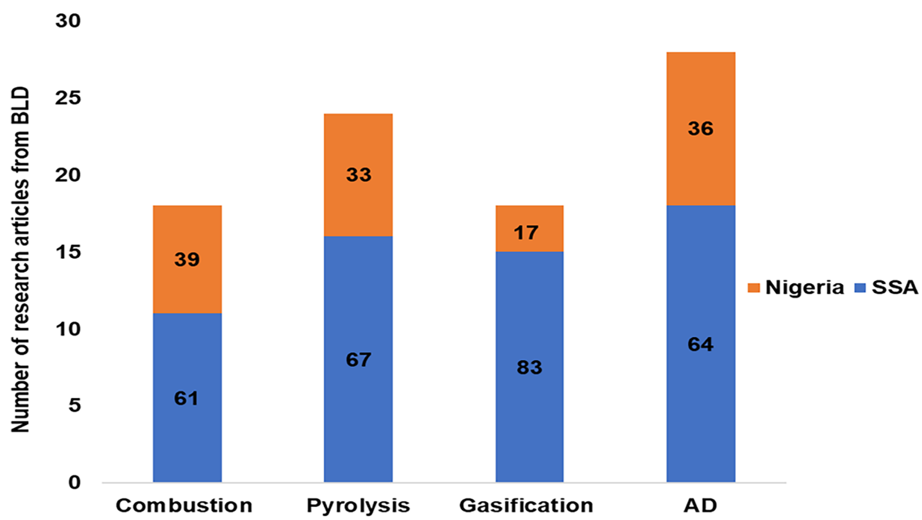

FIGURE 3 Percentage shares of existing knowledge on technology assessment.

et al., 2014; Okoro & Sun, 2021). The literature is not exhaustive and shows opportunities and challenges of AD in Africa (Mouftahi et al., 2023; Roopnarain & Adeleke, 2017; Surendra et al., 2014). The major challenges identified in implementing AD technology include investment cost, communication gap, leadership challenges, and negative perceptions resulting from past failures (Roopnarain & Adeleke, 2017). To increase the uptake of biogas technology in Africa, there would be a need for soft loans, subsidies, stakeholder engagement, and local fabrication of digesters (Jiang et al., 2012; McHenry et al., 2014; Roopnarain & Adeleke, 2017). Feedstock-technology-energy match is important to reduce the risk of failure of bioenergy projects. Chala et al. (2018) assessed methane production from husk, pulp, parchment, and mucilage in a coffee processing company in Ethiopia. The study found that pulp, husk, and mucilage had similar cellulose contents and could generate significant amounts of methane through AD. However, parchment showed low anaerobic performance and was deemed unsuitable for fermentation. Elsayed et al. (2020), Kra et al. (2020), and Vintila et al. (2019) assessed biofuel production from different agri-residues. They found that co-digestion and pretreament of the feedstocks increased the biofuel yield and proposed the use of the biofuel for household, industrial, and transport energy supply. McCord et al. (2020) assessed biogas production from seven digesters in Uganda. They found that the digesters failed to meet the standards for wastewater discharge for practical application. They suggested that micro-scale biogas systems can improve waste handling and meet standards associated with practical application. Similarly, Mugodo et al. (2017) assessed biogas production from industrial and agro-processing waste in South Africa using AD technology. They found that the liquor industry demonstrated the highest biogas production, while pig farming exhibited the least production. The produced biogas from the assessment exceeded the set 2030 target for biogas production in South Africa.

3.3.2 | Combustion

Between 2010 and 2021, 18 articles on biomass combustion technology in Nigeria and other Sub-Saharan African countries where published. A total of 39% of the papers focus on Nigeria as shown in Figure 3. Pretreatment can improve the combustion rate and efficiency of biomass for both household and industrial applications (Balogun et al., 2014; Sotannde et al., 2010). The studies by Arewa et al. (2016), Kuhe et al. (2013), and Umar et al. (2018) assessed the benefits of pretreating agri-residues for combustion applications. They found that briquettes made by pretreating the agri-residues offer better performance than untreated residues. Their result also showed that the combustion rate of the briquettes decreased as the density and moisture content increased. Additionally, hollow briquettes have a higher combustion rate than solid briquettes. The results show that briquettes could be a viable alternative to fuel wood and kerosene stove for household and industrial applications. Kareem et al. (2018) investigated 5 kW grate furnace with a palm kernel shell additive mixture. They aimed at optimizing the combustion features of the agri-residue mixtures to produce a fuel mixture that has a low ash yield and higher heating value. They found that pretreating palm kernel shells reduced the ash generated in the furnace during combustion. The ash reduction improved the boiler thermal performance and can prevent unscheduled plant shutdown. Balogun et al. (2021) investigated energy production from invasive species of grass using combustion and pyrolytic technologies. Combustion shows more suitability for bioenergy applications for electricity and heat generation while pyrolytic technology shows more suitability for biofuels production. Apart from these energy vectors, the invasive grass demonstrated huge capability for biochemical extraction.

Existing knowledge on combustion technology in other Sub-Saharan African countries has a share of 61% of the research output as shown in Figure 3. They are country-specific and targeted different applications. Some of the applications include using briquettes from different agri-residues for domestic heating in Burkina Faso (Sawadogo et al., 2018), Kenya (Njenga et al., 2013), and Ghana (Obeng et al., 2017). Like that of feedstock pretreatment research in Nigeria, El-Sayed and Mostafa (2021), Malika et al. (2019), Prempeh et al. (2021), and Lubwama and Yiga (2017, 2018) showed that agri-residue pretreatment for combustion application can improve the combustion efficiency, flexibility, and diversified application. Ramamurthi et al. (2016) assessed a 5 MW rice straw combustion technology for grid application in Ghana. They found that rice straw combustion is a viable grid-connected option in all regions of the country. However, Abdulrahman and Huisingh (2018) identified some barriers that can limit the application of direct firing routes for electricity generation using different agri-residues. The major barriers identified are fouling and slagging. They recommended assessing the rate of fouling and slagging for feedstock with high ash, alkali, and chlorine content to reduce corrosion on the heat transfer surface. Nsaful et al. (2013) compared combustion and pyrolysis technologies for energy production in the sugar industry. Bagasse was converted to steam and electricity via combustion. The same pathway was also modeled for partial and fast pyrolysis. The pathways were simulated in AspenPlus to assess if they can meet the energy demand of two sugar mill scenarios: more efficient mill and less efficient mill. The results showed that both pathways met the energy demand. However, pyrolysis technology showed better process efficiencies than the most efficient combustion process. But the combustion process was the most economically viable option.

3.3.3 | Pyrolysis

Between 2010 and 2021, 24 articles on biomass pyrolysis technology in Nigeria and other Sub-Saharan African countries were published. Out of the 24 research outputs, 33% focused on Nigeria as shown in Figure 3. Existing knowledge focused mostly on the production of bio-oil, bio-char (Adeniyi et al., 2019; Majhi et al., 2015; Nwajiaku et al., 2018; Ogunjobi & Lajide, 2015), and biofuels (Balogun et al., 2018; Mohammed et al., 2019; Salman et al., 2019) from different agri-residues, as well as their potential applications in energy generation and agricultural sustainability (Ayodele et al., 2020; Nomanbhay et al., 2017). The study by Nomanbhay et al. (2017), Majhi et al. (2015), and Ogunjobi and Lajide (2015) showed how biofuel can be produced from different agri-residues in Nigeria to replace fossil fuel in an existing diesel engine or to generate electricity using a gas engine. They found that the bio-fuel produced can be used for both applications with little modification of the engines. Feedstocks like plastic waste can be used in combination with agri-residues to diversify energy production. Combining agricultural waste with plastic waste in pyrolysis processes offers a promising approach to sustainable waste management, energy production, and resource utilization. Salman et al. (2019) and Ayodele et al. (2020) investigated bio-oil production from oil palm empty fruit bunch and plastic waste using pyrolysis technology. They showed that the solution can contribute to energy security and other co-benefits like a cleaner environment. However, pyrolysis technology comes with high capital costs due to instrumentation requirements (Mohammed et al., 2019; Nomanbhay et al., 2017; Salman et al., 2019). One of the ways to reduce the cost is by transitioning from a fully automated model to a semi-automated solution (Mohammed et al., 2019).

Existing knowledge on pyrolysis technology from other Sub-Saharan African countries is wider in scope and application compared with Nigeria. Some examples include biofuel production in South Africa (Nsaful et al., 2013; van Schalkwyk et al., 2020), Morocco (Malika et al., 2019); bio-oil production in Zimbabwe (Charis et al., 2019) and Tunisia (Jeguirim et al., 2014; Saadi et al., 2019) and other African countries (Gratitude et al., 2019; Ren & Zhao, 2015). Temperature is a major contributing factor in energy yield from pyrolysis technology (Saadi et al., 2019). Bio-oil and bio-gas yields are higher in flash pyrolysis. Furthermore, the biogas obtained by flash pyrolysis can have higher methane production and quality than the one obtained by conventional pyrolysis (Saadi et al., 2019). The study by Aboagye et al. (2017) and Adjin-Tetteh et al. (2018) showed how bio-oil can be produced from cocoa pod husks and orange peels using fast pyrolysis in Ghana. They found that Ghana can replace up to 0.09% of its diesel and petroleum demand in 2020 and 0.07% in 2030 after processing 10% of the total oranges produced. Additionally, an increase in the area of cultivation of oranges to the same area occupied by cocoa in 2013 can replace total diesel and petrol demand by 8.73%. Deployment of pyrolysis technology often comes with high capital costs, which present a challenge to its widespread adoption. However, Ezz et al. (2021) presented an innovative dual biogas/bio-char production technique, demonstrating the economic feasibility of pyrolysis technology. This approach highlights the possibility of integrating multiple outputs to enhance the economic viability of pyrolysis processes.

3.3.4 | Gasification

Between 2010 and 2021, 18 articles on biomass gasification technology in Nigeria and other Sub-Saharan African countries were published. Out of the 18 research outputs, 17% focused on Nigeria as shown in Figure 3. Ejiofor et al. (2020), Mohammed et al. (2019), and Ugbebor et al. (2012) designed a gasification system for off-grid electricity generation using rice husk as input fuel. They showed that the solution can provide electricity for commercial and household applications, especially in farming clusters in Nigeria.

Other Sub-Saharan African countries have 83% share of the research output on gasification technology as shown in Figure 3. The research centered mostly on bioelectricity for both grid and off-grid applications (Abd El-Sattar et al., 2019; Abdulrahman & Huisingh, 2018; Ansari & Liu, 2018; Arranz-Piera et al., 2018; Commeh et al., 2019; Garrido et al., 2016; Nwokolo et al., 2014; Ramamurthi et al., 2016), bioheat for household and industrial application (Bailis et al., 2020; Diedhiou et al., 2019; Gitau et al., 2019; Stafford et al., 2013; Sundberg et al., 2020) and syngas production (Amigun et al., 2010; Radenahmad et al., 2021) from different agri-residues across different countries. Studies by Commeh et al. (2019), Arranz-Piera et al. (2018), and Radenahmad et al. (2021) showed how gasification technology can be used to offer decentralized electrification using different agri-residues. The findings demonstrate the technical viability of utilizing gasification technology in rural communities, where agriculture is a predominant livelihood activity. Bailis et al. (2020), Sundberg et al. (2020), and Gitau et al. (2019) showed that biochar can be used as a feedstock in a gasifier cookstove for bioheat application to improve energy efficiency and indoor air quality in rural households. Diedhiou et al. (2019) and Stafford et al. (2013) investigated the use of gasification technology to convert various agricultural residues, such as cashew nut shells, palm nut shells, and peanut shells, to provide heat for industrial application and clay brick firing units. The gasification tests were conducted in a fixed bed reactor under steam and carbon dioxide at three different temperatures to assess the experimental conditions of feedstocks. They found that temperature has a positive effect on gasification reaction and quality of product gas. Carbon dioxide showed that the reactivity of the different chars depends on the increase of steam concentration in the mixture. Amigun et al. (2010) used an enhanced gasification process to convert Temer Musa and non-woody plants into syngas and methanol. They find that Absorption Enhanced Reforming (AER) process offers higher biomass conversion efficiency. Abdulrahman and Huisingh (2018) investigated the role of agri-residues as a cleaner energy source in Egypt's energy mix. The study assesses four different pathways, with biomass gasification for chemical production identified as the optimal waste-to-energy pathway. This finding underscores the potential of gasification technology in converting waste biomass into valuable chemicals, emphasizing its versatility and efficiency.

3.4 | Existing knowledge on TEA and SEA

TEA and SEA provide a holistic view of projects, technologies, and policies (Lansche & Mueller, 2017). They facilitate evidence-based decision-making by considering not only the technical and financial aspects but also the broader societal implications (Bamwesigye et al., 2020). Bioenergy systems and innovation should be economically feasible to compete with other sources of renewable energy. Figure 4 shows the output of the existing knowledge on techno-economic, socio-economic, and PRF research obtained from the literature review tool.

3.4.1 | Techno-economic assessment

The literature review tool identified 22 scientific publications that focused on this theme, with Nigeria having a share of 36% as shown in Figure 4. Ejiofor et al. (2020) and Ogorure et al. (2018), assessed the feasibility of integrated agricultural waste-to-energy solutions for the rice farming community in Nigeria. They compared the levelized cost of

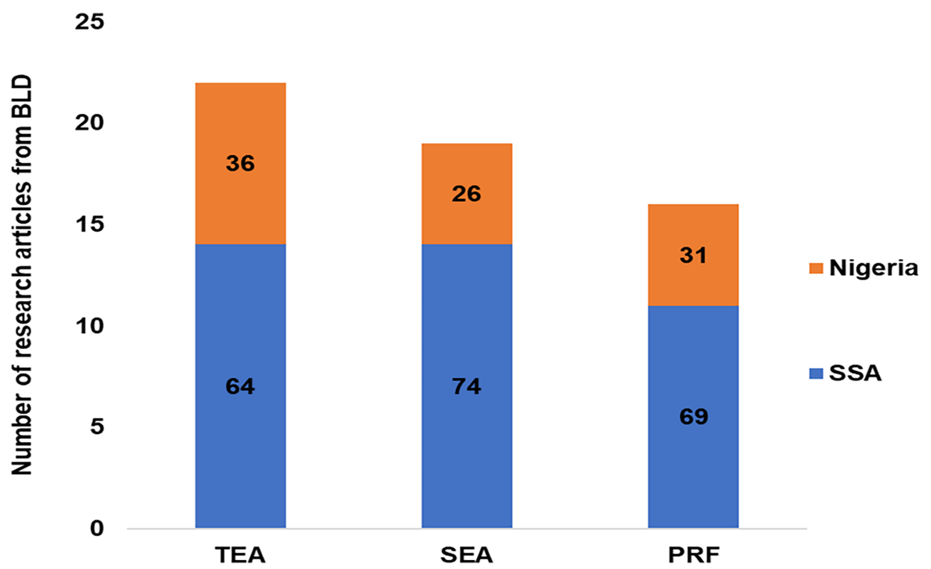

FIGURE 4 Percentage shares of research that focused on TEA, SEA, and PRF.

electricity (LCOE) of the system to the national power grid. The results show that the gasifier system offered a lower LCOE and could serve as an alternative energy source for agricultural clusters in Nigeria. Mohammed et al. (2019) and Somorin and Kolios (2017) investigated the economic viability of energy production from Napier grass bagasse and Jatropha in Nigeria. Bioenergy modeling was used to assess the capital and operating costs. The minimum selling price of the Jatropha-driven plant is lower than the cost of self-generated electricity in Nigeria but Napier grass bagasse driven plant is a bit higher than the current cost of fossil fuel. They proposed the use of process optimization to reduce the system cost. Research that focused on TEA in Nigeria mainly investigated hybrid energy systems consisting of solar PV, biogas, wind, and diesel-generator for electricity generation (Jumare et al., 2020; Oyewo et al., 2018; Sanni et al., 2019; Sanni et al., 2021). Biogas integrated in hybrid systems can offer better economic benefits, support unstable grid and solar fluctuation (Jumare et al., 2020; Sanni et al., 2021). Furthermore, their energy cost was lower than the grid system and that of the Napier grass bagasse case study (Mohammed et al., 2019) and could be due to optimized process. Apart from agri-residues, biogas can be generated from animal waste at lower LCOE to supply the energy demand of the animal farm (Lamidi et al., 2016).

Existing knowledge in TEA research in other Sub-Saharan countries accounts for 64% of the research theme, as shown in Figure 4. The literature is country-specific, assessing the economic viability of different bioenergy case studies. Some examples include the bioenergy optimization model for Ethiopia (Tesfamichael et al., 2021), biomass for clean cooking (Chen et al., 2021), and rice residues to electricity generation in Ghana (Ramamurthi et al., 2016) and Egypt (Abdelhady et al., 2018; Ezz et al., 2021). These studies show how energy can be produced from different agri-residues at a lower minimum selling cost of energy. The study by Burman et al. (2020) and El Shimi and Moustafa (2018) predicted the feasibility of bioethanol and biodiesel projects. They assessed the process equipment, capital and production costs, and profitability of the solutions. They found that biodiesel production would be profitable but bioethanol may be unprofitable due to high capital cost. Similarly, Branca et al. (2016), investigated the profitability and competitiveness of producing biodiesel and ethanol in Tanzania using a value-chain approach. They evaluated the potential trade-offs between different scales of biofuel production. The assessment showed that only sunflower biodiesel is profitable when produced in large-scale estate farming systems. Manhongo et al. (2021) evaluated the economic feasibility of biorefinery modeled in different scenarios—bioethanol production, recovery of pectin, and recovery of pectin and polyphenols from mango peel. Scenario 1 showed the least capital-intensive but not economically attractive. Scenario 3 showed the most attractive in terms of profitability. Most research on household cooking focused on cookstoves; however, Wiskerke et al. (2010) assessed the economic feasibility of using agri-residues to provide households energy supply. Rotational woodlots showed the highest economic benefit while Jatropha oil showed high cost as an alternative to fuelwood. However, the Jatropha performed economically better when used as a diesel substitute. Research by Abdulah et al. (2016), Manjong et al. (2021), and Yimen et al. (2018) showed that bioenergy as part of a hybrid system can enhance the economic benefits of the system.

3.4.2 | Socio-economic assessment

SEA seems to be the least researched of all sustainability topics in bioenergy-related research, not receiving the same amount of attention as the environmental or economic aspects (Kamali et al., 2018). A balance in energy production, food security, and feedstock availability can reduce food insecurity, sustainable production, and job creation in Nigeria (Abila, 2014). Between 2010 and 2021, 19 articles on biomass SEA in Nigeria and other Sub-Saharan African countries were captured in the review tool. Out of the 19 research outputs, 26% focused on Nigeria (Figure 4). Fakinle et al. (2017) assessed air emissions from the open burning of some common biomass to inform the choice of appropriate air pollution control for Nigeria. Of all the assessed gaseous pollutants, they discovered that *Gliricidia sepium* had the minimum emission factor, except for SO_2. Similarly, Mohammed et al. (2019) and Ugbebor et al. (2012) assessed the fuel efficiency, environmental performance, and sustainability of biofuel and crude oil. From an environmental performance comparison, the study showed that 100% biofuel will contribute to a reduction in greenhouse gases and health issues. Agri-residues can be used in coal mining industries in Nigeria to reduce the negative impact on the environment. Waheed and Akogun (2021) investigated the co-firing of cornhusks and cassava peels for combined heat and power applications in Nigeria. Considering the capital-intensive nature of technology innovation, public infrastructures, and services, the utilization of existing facilities and infrastructure such as coal power plants could provide cost benefits (Waheed & Akogun, 2021). For application in Nigeria, co-firing of agricultural residues could be an option in states with substantial coal deposits, such as Enugu state.

Existing knowledge on socio-economic benefits of bioenergy in other Sub-Saharan Africa is more diverse in scope compared with Nigeria. Research in different countries like Ghana (Kemausuor et al., 2016; Obeng et al., 2017), Kenya (Hamid & Blanchard, 2018), Senegal (de la Sota et al., 2018), and Bangladesh (Rahman et al., 2019) showed that household cooking using sustainable bioenergy can reduce emission, health issues, and time women and children spend in fetching firewood. Brinkman et al. (2020) used the computable general equilibrium model in combination with a household and a nutrition module to quantify 13 food security indicators in Ghana. The results indicate that the largest food security effects of the biofuel mandate are that it has an adverse effect on the prices of food, other consumer goods, and increases import dependency. The studies by Stafford and Blignaut (2017), Romijn et al. (2014), and Branca et al. (2016), investigated barriers of bioenergy projects in Mozambique, Tanzania, and Mali. Capital, unreliable crop maturation, lack of experience, inadequate utilization of by-products, and competition from other fuels are barriers to bioenergy projects. However, the projects contributed to food security, positive gender effects, improved income, and employment. They proposed that establishing out-grower schemes (or similar arrangements), rather than estate farms for biofuel production would improve the rural economy. The involvement of policymakers, industry stakeholders, and societal actors is crucial for the development and deployment of bioenergy solutions to realize the full benefits of bioenergy and reduce project failure. Röder, Mohr, and Liu (2020) and Hamid and Blanchard (2018) showed the importance of demand-driven bioenergy systems co-designed by relevant stakeholders, which can contribute to energy access, human and economic development. Furthermore, while centralized bioenergy pathways can offer significant benefits to national energy supplies, research by Röder et al. (2017) highlighted the importance of investing in community-scale bioenergy. Community-scale bioenergy projects can directly target the development and empowerment of communities, improve energy security, and generate wider socio-economic benefits (Röder et al., 2017). The scientific literature by Fito et al. (2019) assessed the environmental effects of effluent from the sugarcane industry. They found that the presence of different varieties of pollutants in the effluent is challenging for conventional treatment methods. Physicochemical and biological treatment methods were not effective. However, AD showed an effective approach of treating the effluent from the sugarcane industry.

3.4.3 | Policy and regulatory framework

Bioenergy policies can provide a framework for investment, regulation, and incentives that enable the growth of the bioenergy industry and its positive impacts on energy security, climate change mitigation, rural development, and environmental sustainability (Ohimain, 2013). Between 2010 and 2021, 16 articles on biomass PRF in Nigeria and other Sub-Saharan African countries where published. Out of the 16 research outputs, 31% focused on Nigeria (Figure 4). Dick and Wilson (2018) and Okoro et al. (2018) examined the land-energy-food dilemma of Nigeria's biofuels policy. They found that expanding the bioethanol program to double current consumption levels would significantly impact land-use change, negatively affecting domestic food production and increasing food prices. The authors recommend a carefully articulated land-use policy to balance bioethanol production, food production, and meeting emission reduction targets. Similarly, Ogundari et al. (2010) examined the issues in Jatropha biofuel enterprise development in Nigeria. They found that the feedstock has great potential for biodiesel production in Nigeria with high demand for diesel and recommended enabling policies that can facilitate biodiesel production in Nigeria. Additionally, Ohimain (2015) evaluated bioethanol projects in Nigeria following the implementation of the Nigerian Biofuel Policy and Incentives. They found that some projects were misevaluated in terms of feedstock requirements to achieve the desired ethanol output. They provided realistic estimates to guide project proponents and enhance the evaluation of bioethanol projects.

The existing knowledge on bioenergy PRF in other countries in Sub-Saharan Africa is wider in scope and reach compared with Nigeria. Bioenergy policy can reduce fuel imports and traditional biomass consumption, empower rural development, facilitate the transition toward the green economy, empower women, and increase energy access in rural areas in Sub-Saharan Africa (Janssen & Rutz, 2015; Schut et al., 2013; Schut et al., 2014). Mainstreaming gender in bioenergy systems is essential for promoting gender equality and aligning with global development agendas. Molony (2011) investigated the importance of gender mainstreaming into bioenergy policies in African countries. They found that there is a lack of empirical evidence on gender issues related to biofuels and emphasized the importance of integrating gender equity into national bioenergy policies. Doku and Di Falco (2012) investigated the role of comparative advantage in biofuel policy adoption. They found that different countries have distinct drivers for creating biofuel policies, with GDP being more significant for the Organization for Economic Co-operation and Development (OECD) countries. Non-OECD countries consider factors like arable land availability and feedstock prices. Jingura and Kamusoko (2018), Tufa et al. (2018), and Ahmed et al. (2017) accessed the drivers of failure in Jatropha projects in Sub-Saharan Africa countries. They found that the major drivers of failures in Jatropha projects are poor planning, limited community involvement, and local chiefs. Ahmed et al. (2018) investigated the implications of not meeting the interests of chiefs in large-scale land acquisitions for bioenergy projects in Ghana. The study emphasized the need for deep land policy reforms within the land administration system to address conflicts and attract investors for sustainable bioenergy solutions. Lietaer et al. (2019) and Doggart et al. (2020) investigated the perceptions of local actors on private sector development in the clean cooking biomass market sector in Uganda and Tanzania. They found that charcoal is the cheapest and most widely used fuel and advised that energy policy needs to acknowledge the continued dominance of charcoal in urban energy use.

4 | DISCUSSION

Existing knowledge on bioenergy showed the status of bioenergy in Nigeria and other Sub-Saharan Africa countries. It provided valuable insights and identified various research needs and knowledge gaps but they are not fully comprehensive. However, the collection of the literature presents an opportunity for wider research and possible knowledge transfer in low- and middle-income countries.

4.1 | Advancing SDG 7 by enhancing the bioenergy potential in Nigeria

The agri-residues assessment in Nigeria is often conducted using aggregated method targeting mostly secondary residues that are potentially available in large amounts but highly disaggregated like cassava, palm, and rice residues (Alhassan et al., 2019; Ejiofor et al., 2020; Ezealigo et al., 2021; Giwaa et al., 2016; Ishola et al., 2020; Jekayinfa et al., 2020; Olanrewaju et al., 2019; Simonyan & Fasina, 2013, 2015; Toyese & Jibiri, 2016). The resource assessment did not consider losses like competing other uses, aggregation, and mobility. There is limited research on modern bioenergy deployment in Nigeria. To take off bioenergy deployment to support the agricultural and energy sectors of Nigeria, there is a need to consider the agricultural outlook of the country because it can play a vital role in determining the scale, application, and feed-stock-technology-energy fit. The agricultural sector of Nigeria is dominated by small-scale farming and processing (FAO, 2021b). As a result, agri-residues such as husks, and other by-products are mainly found in remote areas, scattered, and available in limited quantities (FAO, 2021b). Collection of these agri-residues can be challenging due to associated costs, time, and labor requirements. Therefore, assessing context and location-specific business models would be necessary to understand projects' economic feasibility and profitability. Additionally, well-established large-scale industries often have advanced infrastructures, supply chains, and business models that can allow them to effectively integrate agri-residue utilization into their operations by leveraging existing structures, assets, knowledge, and technology. Therefore, there is a need to investigate bioenergy business models that specifically show how bioenergy solutions can be integrated into large-scale businesses. 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. Furthermore, Nigeria has the potential to become a biomass exporter in the future. Research can look at how biomass export can contribute to Nigeria's foreign earnings and forex reserve. Such research could show whether Nigeria can achieve self-sufficiency or become a net importer from both local and wider regions.

4.2 | Advancing SDG 7 using novel bioenergy technologies in Nigeria

Existing knowledge on biomass technology focused mostly on AD and combustion technologies with a limited focus on pyrolysis and gasification. Furthermore, the research focused on less aggregated and largely available feedstocks giving rise to some miss match between availability assessment and application and feedstock-technology fit. Feedstock-technology match is an integral part of bioenergy system development because technology mismatch could potentially lead to the failure of a bioenergy project. Technology research often misses the correlation to understanding the local context of services, knowledge, and capacities available to maintain long-term technology interventions. It also misses the importance of understanding the demand of end-users and the impact the technology intervention has on the wider system bioenergy becomes part of, which increases the risk of technology failure. To pave the way for novel bioenergy technologies in Nigeria, there is a need to understand the demand of end-users and available feedstocks to gain insight into resource assessment, appropriate technology deployment, and end-user demand. The novel bioenergy technologies can drive innovation and create significant societal co-benefits in Nigeria that have high biomass potential.

4.3 | Evaluating TEA and SEA of bioenergy to advance SDG 7 in Nigeria

TEA of previous studies focused mostly on hybrid energy systems (Jumare et al., 2020; Oyewo et al., 2018; Sanni et al., 2019; Sanni et al., 2021) and limited studies in bioenergy (Ejiofor et al., 2020). These studies used levelized cost of energy to predict the economic viability of energy systems. A detailed TEA of bioenergy solutions of different scales and applications is needed in Nigeria. The economic benefits of an integrated gasification system supporting the energy supply of a cereal milling cluster can be different from that of an AD system providing the same service in a vegetable market. An analysis covering the full breadth of TEA that includes the costs and benefits associated with bioenergy projects in Nigeria can provide evidence-based decisions to developers, investors, policy, and society.

Socio-economic studies of modern bioenergy in Nigeria focused on opportunities related to biomass resources in promoting energy (SDG 7) and food security (SDG 2) (Abila, 2014). Bioenergy business models should include broader societal, economic, sustainability, and environmental aspects. To achieve this, there is a need to involve relevant stakeholders in co-creating bioenergy business models for Nigeria. Stakeholders' involvement can reduce the risk of the project failure because the project would satisfy the interest of the stakeholders and end-users. Socio-economic benefits of a well-established industry using the waste generated in the company to support its energy needs can be different from a small-scale milling cluster that uses waste from its milling process to support its energy needs. Understanding the social co-benefits and evaluating the life cycle assessment of bioenergy is crucial in Nigeria. The outcome of the assessment can provide evidence for non-monetary social benefits and support commercial and institutional decision-making.

4.4 | Evaluating PRF of bioenergy to advance SDG 7 in Nigeria

Research that focused on bioenergy policy in Nigeria is limited and they analyzed the implication of bioenergy policies on land use and environmental impacts of deforestation (Okoro et al., 2018). With advancements in technology, policy development, and market dynamics, bioenergy deployment is expected to grow in Nigeria. It is crucial to understand the interconnections between different sectors involved in bioenergy to prevent any adverse effects on other industries and end-users. Evaluation of the effects of policy and investment decisions in the short-, medium-, and long-term of bioenergy business models is important as innovation and development are dynamic processes that also lead to changes in societal needs and behavior. This helps ensure that decisions are made with a broader perspective, considering the interests of all stakeholders involved as well as assists in prioritizing investments and allocating resources in a manner that maximizes social welfare and economic development. Additionally, assessing the impact of policy framework can help policymakers and planners identify sustainable and economically viable solutions for addressing societal challenges, such as energy transition, environmental sustainability, and economic development. Research can also evaluate the Nigeria Energy Policy, highlighting relevant themes and objectives. The findings of such research can provide insight into Nigeria's energy goals and ambitions. And can potentially foster collaboration on energy system development and deployment, both domestically and internationally. Additionally, it could promote collaborative research efforts on an international scale.

5 | CONCLUSION

The existing knowledge showed examples of how modern bioenergy systems can significantly contribute to energy access and promote human and economic development in Nigeria. Additionally, it was found that Nigeria has substantial biomass potential from agri-residues that can be utilized for sustainable modern bioenergy. The agri-residues can produce various forms of energy that can facilitate economic and socio-economic development and growth in Africa.

The abundant biomass in Nigeria can facilitate domestic and international bioenergy system development and deployment for different scales and applications. Also, the biomass can be exported, contributing to Nigeria's foreign earnings and forex reserve. To ensure that bioenergy systems in Nigeria are in line with the needs of the community and promote inclusivity, it is vital to understand the interconnections and synergies among different factors, including agri-residue aggregation, technical, environmental, economic, socio-economic, and socio-cultural aspects, as well as social structures, dynamics, and governance framework. Furthermore, involving relevant stakeholder groups in developing bioenergy business models can help identify both technical and non-technical obstacles, mitigate the risk of failure, and support a wide range of SDGs.

Therefore, to enable the transition from the use of traditional biomass to modern and sustainable bioenergy including changes in customary practices, demonstration of gains is the use of sophisticated systems is necessary in taking a holistic approach to assessing the technical and non-technical challenges and the synergies between different implications. This is evident among extant literature, which has overtime shown the inter-disciplinary and multi-disciplinary links and synergies between different research themes. While there is wide consensus that bioenergy can provide energy security, economic, and social co-benefits, research has focused less on bioenergy business models co-created by relevant stakeholder groups and novelty technologies like gasification and pyrolysis in Nigeria. In addition, the environmental and sustainability dimensions of bioenergy are not yet well considered in Nigeria. TEA research in Nigeria has mainly centered on the levelized cost of energy of hybrid energy systems, while SEA focuses on opportunities related to biomass resources. TEA and SEA of bioenergy systems should consider all aspects of predicting the economic feasibility and the co-benefits bioenergy solutions can offer. Research can examine whether and how bioenergy business models co-designed by relevant stakeholders in Nigeria can contribute to achieving different SDGs. This would strengthen the analysis of non-monetary values and support institutional and commercial decision-making beyond renewable energy, energy access and ensure that bioenergy systems in Nigeria align with community needs and encourage inclusion.

AUTHOR CONTRIBUTIONS

Prince Anthony Okoro: Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (equal); software (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Katie Chong:** Conceptualization (equal); funding acquisition (equal); resources (equal); software (equal); supervision (equal); validation (equal); writing – review and editing (equal). **Mirjam Röder:** Conceptualization (equal); funding acquisition (equal); resources (equal); software (equal); supervision (equal); validation (equal); visualization (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data are available from Web of science database: https://www.webofscience.com/wos/alldb/basic-search.

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REFERENCES

Abd El-Sattar, H., Kamel, S., Tawfik, M. A., Vera, D., & Jurado, F. (2019). Modeling and simulation of corn stover gasifier and micro-turbine for power generation. *Waste and Biomass Valorisation*, *10*(10), 3101–3114. https://doi.org/10.1007/s12649-018-0284-z

Abdelhady, S., Borello, D., & Shaban, A. (2018). Techno-economic assessment of biomass power plant fed with rice straw: Sensitivity and parametric analysis of the performance and the LCOE. *Renewable Energy*, *115*, 1026–1034. https://doi.org/10.1016/j.renene.2017.09.040

Abdulah, M., Matlokotsi, T., & Chowdhury, S. (2016). Techno-economic feasibility study of solar PV and biomass-based electricity generation for rural household and farm in Botswana. In 2016 IEEE PES PowerAfrica conference.

Abdulrahman, A. O., & Huisingh, D. (2018). The role of biomass as a cleaner energy source in Egypt's energy mix. *Journal of Cleaner Production*, *172*, 3918–3930. https://doi.org/10.1016/j.jclepro.2017.05.049

Abila, N. (2014). Biofuels adoption in Nigeria: Attaining a balance in the food, fuel, feed and fibre objectives. *Renewable & Sustainable Energy Reviews*, *35*, 347–355. https://doi.org/10.1016/j.rser.2014.04.011

Aboagye, D., Banadda, N., Kiggundu, N., & Kabenge, I. (2017). Assessment of orange peel waste availability in Ghana and potential bio-oil yield using fast pyrolysis. *Renewable & Sustainable Energy Reviews*, *70*, 814–821. https://doi.org/10.1016/j.rser.2016.11.262

Adams, P., Bridgwater, T., Lea-Langton, A., Ross, A., & Watson, I. (2018). Biomass conversion technologies. In P. Thornley & P. Adams (Eds.), *Greenhouse gas balances of bioenergy systems*. Academic Press.

Adeniyi, A. G., Ighalo, J. O., & Abdulsalam, A. (2019). Modeling of integrated processes for the recovery of the energetic content of sugar cane bagasse. *Biofuels, Bioproducts & Biorefining (Biofpr)*, *13*(4), 1057–1067. https://doi.org/10.1002/bbb.1998

Adjin-Tetteh, M., Asiedu, N., Dodoo-Arhin, D., Karam, A., & Amaniampong, P. N. (2018). Thermochemical conversion and characterisation of cocoa pod husks a potential agricultural waste from Ghana. *Industrial Crops and Products*, *119*, 304–312. https://doi.org/10.1016/j.indcrop.2018.02.060

Ahmed, A., Campion, B. B., & Gasparatos, A. (2017). Biofuel development in Ghana: Policies of expansion and drivers of failure in the jatropha sector. *Renewable & Sustainable Energy Reviews*, *70*, 133–149. https://doi.org/10.1016/j.rser.2016.11.216

Ahmed, A., Kuusaana, E. D., & Gasparatos, A. (2018). The role of chiefs in large-scale land acquisitions for jatropha production in Ghana: Insights from agrarian political economy. *Land Use Policy*, *75*, 570–582. https://doi.org/10.1016/j.landusepol.2018.04.033

Aisien, F. A., & Aisien, E. T. (2020). Biogas from cassava peels waste. *Detritus*, *10*, 100–108. https://doi.org/10.31025/2611-4135/2020.13910

Akbi, A., Saber, M., Aziza, M., & Yassaa, N. (2017). An overview of sustainable bioenergy potential in Algeria. *Renewable & Sustainable Energy Reviews*, *72*, 240–245. https://doi.org/10.1016/j.rser.2017.01.072

Alhassan, E. A., Olaoye, J. O., Olayanju, T. M. A., & Okonkwo, C. E. (2019). An investigation into some crop residues generation from farming activities and inherent energy potentials in Kwara State, Nigeria. *IOP Conference Series: Materials Science and Engineering*, *640*, 1–10.

Amigun, B., Gorgens, J., & Knoetze, H. (2010). Biomethanol production from gasification of non-woody plant in South Africa: Optimum scale and economic performance. *Energy Policy*, *38*(1), 312–322. https://doi.org/10.1016/j.enpol.2009.09.020

Anika, O. C., & Akin-Osanaiye, B. C. (2020). Effect of the nutritional composition of fruit wastes on methane gas production and energy potential. *Environmental Engineering and Management Journal*, *19*(7), 1097–1104.

Ansari, S. H., & Liu, X. (2018). ASPEN plus simulation study of concentrated solar power and biomass gasification for co-production of power and liquid fuel. In AIP conference proceedings [Solarpaces 2018: International conference on concentrating solar power and chemical energy systems] (SolarPACES), Casablanca, MOROCCO.

Arewa, M. E., Daniel, I. C., & Kuye, A. (2016). Characterisation and comparison of rice husk briquettes with cassava peels and cassava starch as binders. *Biofuels*, *7*(6), 671–675. https://doi.org/10.1080/17597269.2016.1187541

Arranz-Piera, P., Kemausuor, F., Darkwah, L., Edjekumhene, I., Cortes, J., & Velo, E. (2018). Mini-grid electricity service based on local agricultural residues: Feasibility study in rural Ghana. *Energy*, *153*, 443–454. https://doi.org/10.1016/j.energy.2018.04.058

Arthur, R., Baidoo, M. F., & Antwi, E. (2011). Biogas as a potential renewable energy source: A Ghanaian case study. *Renewable Energy*, *36*(5), 1510–1516. https://doi.org/10.1016/j.renene.2010.11.012

Ayodele, T. R., Ogunjuyigbe, A. S. O., Durodola, O., & Munda, J. L. (2020). Electricity generation potential and environmental assessment of bio-oil derivable from pyrolysis of plastic in some selected cities of Nigeria. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *42*(10), 1167–1182. https://doi.org/10.1080/15567036.2019.1602226

Bailis, R., Ghosh, E., O'Connor, M., Kwamboka, E., Ran, Y. V., & Lambe, F. (2020). Enhancing clean cooking options in peri-urban Kenya: A pilot study of advanced gasifier stove adoption. *Environmental Research Letters*, *15*(8), 084017. https://doi.org/10.1088/1748-9326/ab865a

Balogun, A. O., Adeleke, A. A., Ikubanni, P. P., Adegoke, S. O., Alayat, A. M., & McDonald, A. G. (2021). Physico-chemical characterisation, thermal decomposition and kinetic modeling of *Digitaria sanguinalis* under nitrogen and air environments. *Case Studies in Thermal Engineering*, *26*, 101138. https://doi.org/10.1016/j.csite.2021.101138

Balogun, A. O., Lasode, O. A., & McDonald, A. G. (2014). Thermo-analytical and physico-chemical characterisation of woody and non-woody biomass from an agro-ecological zone in Nigeria. *Bioresources*, *9*, 5099–5113.

Balogun, A. O., Lasode, O. A., & McDonald, A. G. (2018). Thermochemical and pyrolytic analyses of Musa spp. residues from the rainforest belt of Nigeria. *Environmental Progress & Sustainable Energy*, *37*(6), 1932–1941. https://doi.org/10.1002/ep.12869

Bamwesigye, D., Kupec, P., Chekuimo, G., Pavlis, J., Asamoah, O., Darkwah, S. A., & Hlavackova, P. (2020). Charcoal and wood biomass utilisation in Uganda: The socioeconomic and environmental dynamics and implications. *Sustainability*, *12*, 1–18. https://doi.org/10.3390/su12208337

Branca, G., Cacchiarelli, L., Maltsoglou, I., Rincon, L., Sorrentino, A., & Valle, S. (2016). Profits versus jobs: Evaluating alternative biofuel value-chains in Tanzania. *Land Use Policy*, *57*, 229–240. https://doi.org/10.1016/j.landusepol.2016.05.014

Brinkman, M., Levin-Koopman, J., Wicke, B., Shutes, L., Kuiper, M., Faaij, A., & van der Hilst, F. (2020). The distribution of food security impacts of biofuels, a Ghana case study. *Biomass & Bioenergy*, *141*, 105695. https://doi.org/10.1016/j.biombioe.2020.105695

Burman, N. W., Sheridan, C. M., & Harding, K. G. (2020). Feasibility assessment of the production of bioethanol from lignocellulosic biomass pretreated with acid mine drainage (AMD). *Renewable Energy*, *157*, 1148–1155. https://doi.org/10.1016/j.renene.2020.05.086

Chala, B., Oechsner, H., Latif, S., & Mueller, J. (2018). Biogas potential of coffee processing waste in Ethiopia. *Sustainability*, *10*(8), 2678. https://doi.org/10.3390/su10082678

Charis, G., Danha, G., Muzenda, E., & Nkosi, N. P. (2019). Bio-oil from pine residues—yields, quality and potential applications: A case study on the valorisation of Zimbabwe's timber residues. In International renewable and sustainable energy conference IRSEC [Proceedings of 2019 7th international renewable and sustainable energy conference (IRSEC)], Agadir, MOROCCO.

Chen, J., Li, C., Ristovski, Z., Milic, A., Gu, Y., Islam, M. S., Wang, S., Hao, J., Zhang, H., He, C., Guo, H., Fu, H., Miljevic, B., Morawska, L., Thai, P., Lam, Y. F., Pereira, G., Ding, A., Huang, X., & Dumka, U. C. (2017). A review of biomass burning: Emissions and impacts on air quality, health and climate in China. *Science of the Total Environment*, *579*, 1000–1034. https://doi.org/10.1016/j.scitotenv.2016.11.025

Chen, K. C., Leach, M., Black, M. J., Tesfamichael, M., Kemausuor, F., Littlewood, P., Marker, T., Mwabonje, O., Mulugetta, Y., Murphy, R. J., Diaz-Chavez, R., Hauge, J., Saleeby, D., Evans, A. W., & Puzzolo, E. (2021). BioLPG for clean cooking in sub-Saharan Africa: Present and future feasibility of technologies, feedstocks, enabling conditions and financing. *Energies*, *14*(13), 3916. https://doi.org/10.3390/en14133916

Chitawo, M. L., & Chimphango, A. F. A. (2017). A synergetic integration of bioenergy and rice production in rice farms. *Renewable & Sustainable Energy Reviews*, *75*, 58–67. https://doi.org/10.1016/j.rser.2016.10.051

Clarivate. (2022). Web of science. https://www.webofscience.com/wos/woscc/basic-search

Clean Tech Incubation and Acceleration Foundation, & All On. (2015). National renewable energy and energy efficiency policy (NREEEP).

Commeh, M. K., Kemausuor, F., Badger, E. N., & Osei, I. (2019). Experimental study of ferrocement downdraft gasifier engine system using different biomass feedstocks in Ghana. *Sustainable Energy Technologies and Assessments*, *31*, 124–131. https://doi.org/10.1016/j.seta.2018.12.016

Daoutidis, P., Marvin, W. A., Rangarajan, S., & Torres, A. I. (2013). Engineering biomass conversion processes: A systems perspective. *AICHE Journal*, *59*(1), 3–18. https://doi.org/10.1002/aic.13978

de la Sota, C., Lumbreras, J., Perez, N., Ealo, M., Kane, M., Youm, L., & Viana, M. (2018). Indoor air pollution from biomass cookstoves in rural Senegal. *Energy for Sustainable Development*, *43*, 224–234. https://doi.org/10.1016/j.esd.2018.02.002

Dick, N. A., & Wilson, P. (2018). Analysis of the inherent energy-food dilemma of the Nigerian biofuels policy using partial equilibrium model: The Nigerian energy-food model (NEFM). *Renewable & Sustainable Energy Reviews*, *98*, 500–514. https://doi.org/10.1016/j.rser.2018.09.043

Diedhiou, A., Ndiaye, L.-G., Bensakhria, A., & Sock, O. (2019). Thermochemical conversion of cashew nut shells, palm nut shells and peanut shells char with CO2 and/or steam to aliment a clay brick firing unit. *Renewable Energy*, *142*, 581–590. https://doi.org/10.1016/j.renene.2019.04.129

Doggart, N., Ruhinduka, R., Meshack, C. K., Ishengoma, R. C., Morgan-Brown, T., Abdallah, J. M., Spracklen, D. V., & Sallu, S. M. (2020). The influence of energy policy on charcoal consumption in urban households in Tanzania. *Energy for Sustainable Development*, *57*, 200–213. https://doi.org/10.1016/j.esd.2020.06.002

Doku, A., & Di Falco, S. (2012). Biofuels in developing countries: Are comparative advantages enough? *Energy Policy*, *44*, 101–117. https://doi.org/10.1016/j.enpol.2012.01.022

Ejiofor, O. S., Okoro, P. A., Ogbuefic, C., Victor Nabuike, C., & Okedu, K. (2020). Off-grid electricity generation in Nigeria based on rice husk gasification technology. *Cleaner Engineering and Technology*, *1*, 100009.

El Shimi, H. I., & Moustafa, S. S. (2018). Biodiesel production from microalgae grown on domestic wastewater: Feasibility and Egyptian case study. *Renewable & Sustainable Energy Reviews*, *82*, 4238–4244. https://doi.org/10.1016/j.rser.2017.05.073

Elagroudy, S., Radwan, A. G., Banadda, N., Mostafa, N. G., Owusu, P. A., & Janajreh, I. (2020). Mathematical models comparison of biogas production from anaerobic digestion of microwave pretreated mixed sludge. *Renewable Energy*, *155*, 1009–1020. https://doi.org/10.1016/j.renene.2020.03.166

Elsayed, M., Ran, Y., Ai, P., Azab, M., Mansour, A., Jin, K. D., Zhang, Y. L., & Abomohra, A. (2020). Innovative integrated approach of biofuel production from agricultural wastes by anaerobic digestion and black soldier fly larvae. *Journal of Cleaner Production*, *263*, 121495. https://doi.org/10.1016/j.jclepro.2020.121495

El-Sayed, S. A., & Mostafa, M. E. (2021). Kinetics, thermodynamics, and combustion characteristics of Poinciana pods using TG/DTG/DTA techniques. *Biomass Conversion and Biorefinery*, *13*, 11583–11607. https://doi.org/10.1007/s13399-021-02021-8

Elsevier. (2021). Science direct. https://www.sciencedirect.com/

Ezealigo, U. S., Ezealigo, B. N., Kemausuor, F., Achenie, L. E. K., & Onwualu, A. P. (2021). Biomass valorisation to bioenergy: Assessment of biomass residues' availability and bioenergy potential in Nigeria. *Sustainability*, *13*(24), 13806. https://doi.org/10.3390/su132413806

Ezz, H., Ibrahim, M. G., Fujii, M., & Nasr, M. (2021). Dual biogas and biochar production from rice straw biomass: A techno-economic and sustainable development approach. *Biomass Conversion and Biorefinery*, *13*, 10807–10821. https://doi.org/10.1007/s13399-021-01879-y

Fakinle, B. S., Okedere, O. B., Seriki, O., Adesanmi, A. J., & Sonibare, J. A. (2017). An estimation of a trace gaseous emission factor from combustion of common fuelwood species in South-western Nigeria. *Energy Sources Part A: Recovery, Utilization, and Environmental Effects*, *39*(12), 1298–1306. https://doi.org/10.1080/15567036.2017.1327998

FAO. (2021a). *Global, Forest resources assessment*. FAO.

FAO. (2021b). Nigeria agriculture at a glance. https://www.fao.org/nigeria/fao-in-nigeria/nigeria-at-a-glance/en/

FAO. (2022). Nigeria crop production. https://www.fao.org/countryprofiles/index/en/?iso3=NGA

Fito, J., Tefera, N., & Van Hulle, S. W. H. (2019). Sugarcane biorefineries wastewater: Bioremediation technologies for environmental sustainability. *Chemical and Biological Technologies in Agriculture*, *6*, 6. https://doi.org/10.1186/s40538-019-0144-5

Garrido, H., Vendeirinho, V., & Brito, M. C. (2016). Feasibility of KUDURA hybrid generation system in Mozambique: Sensitivity study of the small-scale PV-biomass and PV-diesel power generation hybrid system. *Renewable Energy*, *92*, 47–57. https://doi.org/10.1016/j.renene.2016.01.085

Gitau, J. K., Sundberg, C., Mendum, R., Mutune, J., & Njenga, M. (2019). Use of biochar-producing gasifier cookstove improves energy use efficiency and indoor air quality in rural households. *Energies*, *12*(22), 4285. https://doi.org/10.3390/en12224285

Giwaa, A., Alabia, A., Yusufa, A., & Olukanb, T. (2016). A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. *Renewable and Sustainable Energy Reviews*, *69*, 620–641.

Gnansounou, E., Pachon, E. R., Sinsin, B., Teka, O., Togbe, E., & Mahamane, A. (2020). Using agricultural residues for sustainable transportation biofuels in 2050: Case of West Africa. *Bioresource Technology*, *305*, 123080. https://doi.org/10.1016/j.biortech.2020.123080

Gratitude, C., Danha, G., & Muzenda, E. (2019). Waste valorisation opportunities for bush encroacher biomass in savannah ecosystems: A comparative case analysis of Botswana and Namibia. In Procedia manufacturing [2nd international conference on sustainable materials processing and manufacturing (smpm 2019)], South Africa.

Hamid, R. G., & Blanchard, R. E. (2018). An assessment of biogas as a domestic energy source in rural Kenya: Developing a sustainable business model. *Renewable Energy*, *121*, 368–376. https://doi.org/10.1016/j.renene.2018.01.032

Hosseini, S. E., & Wahid, M. A. (2015). Utilisation of biogas released from palm oil mill effluent for power generation using self-preheated reactor. *Energy Conversion and Management*, *105*, 957–966. https://doi.org/10.1016/j.enconman.2015.08.058

IEA. (2019). Nigeria energy outlook. https://www.iea.org/articles/nigeria-energy-outlook

IEA, IRENA, UNSD, World Bank, & WHO. (2020). Tracking SDG 7: The energy progress report. https://trackingsdg7.esmap.org/

Ishola, F., Adelekan, D., Mamudu, A., Abodunrin, T., Aworinde, A., Olatunji, O., & Akinlabi, S. (2020). Biodiesel production from palm olein: A sustainable bioresource for Nigeria. *Heliyon*, *6*, 1–12. https://doi.org/10.1016/j.heliyon.2020.e03725

Janssen, R., & Rutz, D. (2015). Policies for sustainable biofuels in Southeast Africa. Papers of the 23rd European biomass conference: Setting the course for a biobased economy, Vienna, Austria.

Jeguirim, M., Elmay, Y., Limousy, L., Lajili, M., & Said, R. (2014). Devolatilisation behavior and pyrolysis kinetics of potential Tunisian biomass fuels. *Environmental Progress & Sustainable Energy*, *33*(4), 1452–1458. https://doi.org/10.1002/ep.11928

Jekayinfa, S. O., Orisaleye, J. I., & Pecenka, R. (2020). An assessment of potential resources for biomass energy in Nigeria. *Resources*, *9*, 1–41.

Jekayinfa, S. O., & Scholz, V. (2013). Laboratory scale preparation of biogas from cassava tubers, cassava peels, and palm kernel oil residues. *Energy Sources Part A: Recovery, Utilization, and Environmental Effects*, *35*(21), 2022–2032. https://doi.org/10.1080/15567036.2010.532190

Jensen, C. D., Olugbemide, A. D., Akpa, F. A. O., & Oladipo, A. (2019). Pretreatment chemometrics in holistic biogas life cycle assessment: Framing case study with *Carica papaya*. *Waste and Biomass Valorisation*, *11*(12), 7029–7042. https://doi.org/10.1007/s12649-019-00635-8

Jiang, Y., Heaven, S., & Banks, C. J. (2012). Strategies for stable anaerobic digestion of vegetable waste. *Renewable Energy*, *44*, 206–214. https://doi.org/10.1016/j.renene.2012.01.012

Jingura, R. M., & Kamusoko, R. (2018). Experiences with Jatropha cultivation in sub-Saharan Africa: Implications for biofuels policies. *Energy Sources Part B: Economics, Planning, and Policy*, *13*(4), 224–230. https://doi.org/10.1080/15567249.2012.675014

Jumare, I. A., Bhandari, R., & Zerga, A. (2020). Assessment of a decentralised grid-connected photovoltaic (PV)/wind/biogas hybrid power system in northern Nigeria. *Energy Sustainability and Society*, *10*(1), 30. https://doi.org/10.1186/s13705-020-00260-7

Kaltschmitt, M. (2017). *Biomass as renewable source of energy*. Possible Conversion Route. https://doi.org/10.1007/978-1-4939-2493-6_244-3

Kamali, F. P., Rossi Borges, J. A., Osseweijer, P., & Posada, J. A. (2018). Towards social sustainability: Screening potential social and governance issues for biojet fuel supply chains in Brazil. *Renewable & Sustainable Energy Reviews*, *92*, 50–61. https://doi.org/10.1016/j.rser.2018.04.078

Kareem, B., Oladosu, K. O., Alade, A. O., & Durowoju, M. O. (2018). Optimisation of combustion characteristics of palm kernel-based biofuel for grate furnace. *International Journal of Energy and Environmental Engineering*, *9*(4), 457–472. https://doi.org/10.1007/s40095-018-0277-5

Kemausuor, F., Bolwig, S., & Miller, S. (2016). Modelling the socio-economic impacts of modern bioenergy in rural communities in Ghana. *Sustainable Energy Technologies and Assessments*, *14*, 9–20. https://doi.org/10.1016/j.seta.2016.01.007

Kerroum, D., Mossaab, B. L., & Hassen, M. A. (2014). Production of bio-energy from organic waste: Effect of temperature and substrate composition. *International Journal of Energy Research*, *38*(2), 270–276. https://doi.org/10.1002/er.3044

Kilama, G., Lating, P. O., Byaruhanga, J., & Biira, S. (2019). Quantification and characterisation of cocoa pod husks for electricity generation in Uganda. *Energy Sustainability and Society*, *9*, 1–11. https://doi.org/10.1186/s13705-019-0205-4

Kra, E. K. F., Yao, L., & Akichi, A. (2020). 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*, *10*(4), 647–656. https://doi.org/10.31407/ijees10.410

Kuhe, A., Ibiang, F. A., & Igbong, D. I. (2013). Potential of low pressure agricultural waste briquettes: An alternative energy source for cooking in Nigeria. *Journal of Renewable and Sustainable Energy*, *5*(1), 013109. https://doi.org/10.1063/1.4781048

Kyauta, E. E., Adisa, A. B., Habou, I., Ejilah, R. I., & Ibrahim, E. S. (2021). The application of GIS model as a location selector for biomass gasification plant in Bogoro Local Government Area, Bauchi, Nigeria. *International Journal of Scientific & Engineering Research*, *12*, 534–543.

Lamidi, R. O., Wang, Y. D., Pathare, P. B., & Roskily, A. P. (2016). Evaluation of CHP for electricity and drying of agricultural products in a nigerian rural community. In Energy procedia [8th international conference on applied energy (ICAE2016)], Beijing Inst Technol, Beijing.

Lansche, J., & Mueller, J. (2017). Life cycle assessment (LCA) of biogas versus dung combustion household cooking systems in developing countries: A case study in Ethiopia. *Journal of Cleaner Production*, *165*, 828–835. https://doi.org/10.1016/j.jclepro.2017.07.116

Lietaer, S., Zaccai, E., & Verbist, B. (2019). Making cooking champions: Perceptions of local actors on private sector development in Uganda. *Environmental Development*, *32*, 100452. https://doi.org/10.1016/j.envdev.2019.07.002

Lubwama, M., & Yiga, V. A. (2017). Development of groundnut shells and bagasse briquettes as sustainable fuel sources for domestic cooking applications in Uganda. *Renewable Energy*, *111*, 532–542. https://doi.org/10.1016/j.renene.2017.04.041

Lubwama, M., & Yiga, V. A. (2018). Characteristics of briquettes developed from rice and coffee husks for domestic cooking applications in Uganda. *Renewable Energy*, *118*, 43–55. https://doi.org/10.1016/j.renene.2017.11.003

Majhi, A., Sharma, Y. K., Naik, D. V., & Chauhan, R. (2015). The production and evaluation of bio-oil obtained from the *Jatropha curcas* cake. *Energy Sources Part A: Recovery, Utilization, and Environmental Effects*, *37*(16), 1782–1789. https://doi.org/10.1080/15567036.2011.645120

Makai, L., Molinas, M., & IEEE. (2013). Biogas – An alternative household cooking technique for Zambia. In Proceedings of the third 2013 IEEE global humanitarian technology conference (GHTC 2013), San Jose, CA.

Malika, A., Mohammed, A., & Guhel, Y. (2019). Energetic combustion characteristics and environmental impact of Moroccan biomass wastes and their solid biofuel. *Waste and Biomass Valorisation*, *10*(5), 1311–1322. https://doi.org/10.1007/s12649-017-0128-2

Manhongo, T., Chimphango, A., Thornley, P., & Röder, M. (2021). Techno-economic and environmental evaluation of integrated mango waste biorefineries. *Journal of Cleaner Production*, *325*, 129335. https://doi.org/10.1016/j.jclepro.2021.129335

Manjong, N. B., Oyewo, A. S., & Breyer, C. (2021). Setting the pace for a sustainable energy transition in Central Africa: The case of Cameroon. *IEEE Access*, *9*, 145435–145458. https://doi.org/10.1109/Access.2021.3121000

Mboumboue, E., & Njomo, D. (2016). Potential contribution of renewables to the improvement of living conditions of poor rural households in developing countries: Cameroon's case study. *Renewable & Sustainable Energy Reviews*, *61*, 266–279. https://doi.org/10.1016/j.rser.2016.04.003

McCord, A. I., Stefanos, S. A., Tumwesige, V., Lsoto, D., Kawala, M., Mutebi, J., Nansubuga, I., & Larson, R. A. (2020). Anaerobic digestion in Uganda: Risks and opportunities for integration of waste management and agricultural systems. *Renewable Agriculture and Food Systems*, *35*(6), 678–687. https://doi.org/10.1017/S1742170519000346

McHenry, M. P., Doepel, D., & de Boer, K. (2014). 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), 103–113. https://doi.org/10.1002/bbb.1433

Mensah, T. N. O., Oyewo, A. S., & Breyer, C. (2021). The role of biomass in sub-Saharan Africa's fully renewable power sector: The case of Ghana. *Renewable Energy*, *173*, 297–317. https://doi.org/10.1016/j.renene.2021.03.098

Mohammed, I. Y., Abakr, Y. A., & Mokaya, R. (2019). Integrated biomass thermochemical conversion for clean energy production: Process design and economic analysis. *Journal of Environmental Chemical Engineering*, *7*(3), 103093. https://doi.org/10.1016/j.jece.2019.103093

Mohammed, Y. S., Mustafa, M. W., Bashir, N., Ogundola, M. A., & Umar, U. (2014). Sustainable potential of bioenergy resources for distributed power generation development in Nigeria. *Renewable & Sustainable Energy Reviews*, *34*, 361–370. https://doi.org/10.1016/j.rser.2014.03.018

Molony, T. (2011). Bioenergy policies in Africa: Mainstreaming gender amid an increasing focus on biofuels. *Biofuels, Bioproducts & Biorefining (Biofpr)*, *5*(3), 330–341. https://doi.org/10.1002/bbb.293

Mouftahi, M., Tlili, N., Hidouri, N., Bartocci, P., & Fantozzi, F. (2023). Bioenergy recovery from Southern Tunisia's organic wastes: Analysis and kinetic modeling study of biomethane production. *Biomass Conversion and Biorefinery*, *13*(7), 6345–6361. https://doi.org/10.1007/s13399-021-01684-7

Moustakas, K., Loizidou, M., Rehan, M., & Nizami, A. S. (2020). A review of recent developments in renewable and sustainable energy systems: Key challenges and future perspective. *Renewable & Sustainable Energy Reviews*, *119*, 109418. https://doi.org/10.1016/j.rser.2019.109418

Mugodo, K., Magama, P. P., & Dhavu, K. (2017). Biogas production potential from agricultural and agro-processing waste in South Africa. *Waste and Biomass Valorisation*, *8*(7), 2383–2392. https://doi.org/10.1007/s12649-017-9923-z

National Bureau of Statistics. (2023). Nigerian gross domestic product report Q2 2023.

Njenga, M., Karanja, N., Jamnadass, R., Kithinji, J., Sundberg, C., & Jirjis, R. (2013). Quality of cooking fuel briquettes produced locally from charcoal dust and sawdust in Kenya. *Journal of Biobased Materials and Bioenergy*, *7*(3), 315–322. https://doi.org/10.1166/jbmb.2013.1355

Nomanbhay, S., Salman, B., Hussain, R., & Ong, M. Y. (2017). Microwave pyrolysis of lignocellulosic biomass: A contribution to power Africa. *Energy, Sustainability and Society*, *7*, 1–24. https://doi.org/10.1186/s13705-017-0126-z

Nsaful, F., Goergens, J. F., & Knoetze, J. H. (2013). Comparison of combustion and pyrolysis for energy generation in a sugarcane mill. *Energy Conversion and Management*, *74*, 524–534. https://doi.org/10.1016/j.enconman.2013.07.024

Nwajiaku, I. M., Olanrewaju, J. S., Sato, K., Tokunari, T., Kitano, S., & Masunaga, T. (2018). Change in nutrient composition of biochar from rice husk and sugarcane bagasse at varying pyrolytic temperatures. *International Journal of Recycling of Organic Waste in Agriculture*, *7*, 269–276. https://doi.org/10.1007/s40093-018-0213-y

Nwokolo, N., Mamphweli, S., Meyer, E., & Tangwe, S. (2014). Electrical performance evaluation of Johansson biomass gasifier system coupled to a 150 kVA generator. *Renewable Energy*, *71*, 695–700. https://doi.org/10.1016/j.renene.2014.06.018

Obeng, G. Y., Mensah, E., Ashiagbor, G., Boahen, O., & Sweeney, D. J. (2017). Watching the smoke rise up: Thermal efficiency, pollutant emissions and global warming impact of three biomass cookstoves in Ghana. *Energies*, *10*(5), 641. https://doi.org/10.3390/en10050641

Odekanle, E. L., Odejobi, O. J., Dahunsi, S. O., & Akeredolu, F. A. (2020). Potential for cleaner energy recovery and electricity generation from abattoir wastes in Nigeria. *Energy Reports*, *6*, 1262–1267. https://doi.org/10.1016/j.egyr.2020.05.005

Ogorure, O. J., Oko, C. O. C., Diemuodeke, E. O., & Owebor, K. (2018). Energy, exergy, environmental and economic analysis of an agricultural waste-to-energy integrated multigeneration thermal power plant. *Energy Conversion and Management*, *171*, 222–240. https://doi.org/10.1016/j.enconman.2018.05.093

Ogundari, I. O., Oladipo, O. G., Famurewa, A. J., Ali, G. A., Aladesanmi, O. T., Ogunkanmbi, D. A., & Siyanbola, W. O. (2010). Strategic issues in Jatropha biofuel enterprise development in Nigeria. In Picmet 2010: Technology management for global economic growth. Portland International Center for Management of Engineering and Technology (PICMET 10), National Electronics and Computer Technology Center (NECTEC), National Science and Technology Development Agency (NSTDA, Portland, OR).

Ogunjobi, J. K., & Lajide, L. (2015). The potential of cocoa pods and plantain peels as renewable sources in Nigeria. *International Journal of Green Energy*, *12*(4), 440–445. https://doi.org/10.1080/15435075.2013.848403

Ohimain, E. I. (2013). Can the Nigerian biofuel policy and incentives (2007) transform Nigeria into a biofuel economy? *Energy Policy*, *54*, 352–359. https://doi.org/10.1016/j.enpol.2012.11.051

Ohimain, E. I. (2015). The evaluation of pioneering bioethanol projects in Nigeria following the announcement and implementation of the Nigerian biofuel policy and incentives. *Energy Sources, Part B: Economics, Planning, and Policy*, *10*(1), 51–58. https://doi.org/10.1080/15567249.2010.512904

Okoro, O. V., & Sun, Z. (2021). The characterisation of biochar and biocrude products of the hydrothermal liquefaction of raw digestate biomass. *Biomass Conversion and Biorefinery*, *11*(6), 2947–2961. https://doi.org/10.1007/s13399-020-00672-7

Okoro, S. U., Schickhoff, U., & Schneider, U. A. (2018). Impacts of bioenergy policies on land-use change in Nigeria. *Energies*, *11*(1), 152. https://doi.org/10.3390/en11010152

Olanrewaju, F. O., Andrews, G. E., Li, H., & Phylaktou, H. N. (2019). Bioenergy potential in Nigeria. *Chemical Engineering Transactions*, *74*, 61–66. https://doi.org/10.3303/CET1974011

Oyewo, A. S., Aghahosseini, A., Bogdanov, D., & Breyer, C. (2018). Pathways to a fully sustainable electricity supply for Nigeria in the midterm future. *Energy Conversion and Management*, *178*, 44–64. https://doi.org/10.1016/j.enconman.2018.10.036

Power, N. M. O. (2016). sustainable energy for all action agenda (SE4ALL-AA).

Prempeh, C. O., Formann, S., Schliermann, T., Dizaji, H. B., & Nelles, M. (2021). Extraction and characterisation of biogenic silica obtained from selected agro-waste in Africa. *Applied Sciences-Basel*, *11*(21), 10363. https://doi.org/10.3390/app112110363

Radenahmad, N. R., Bakar, M. S., Abu, M. S., Shams, S., Tesfai, A., Taweekun, J., Khalilpoor, N., Azad, A. K., & Issakhov, A. (2021). Evaluation of the bioenergy potential of temer musa: An invasive tree from the African desert. *International Journal of Chemical Engineering*, *2021*, 1–10. https://doi.org/10.1155/2021/6693071

Rahman, K. M., Edwards, D. J., Melville, L., & El-Gohary, H. (2019). Implementation of bioenergy systems towards achieving United Nations' sustainable development goals in rural Bangladesh. *Sustainability*, *11*(14), 3814. https://doi.org/10.3390/su11143814

Ramamurthi, P. V., Fernandes, M. C., Nielsen, P. S., & Nunes, C. P. (2016). Utilisation of rice residues for decentralised electricity generation in Ghana: An economic analysis. *Energy*, *111*, 620–629. https://doi.org/10.1016/j.energy.2016.05.116

Ranius, T., Hämäläinen, Egnell, G., Olsson, B., Eklöf, K., Stendahl, J., Rudolphi, J., Sténs, A., & Felton, A. (2018). The effects of logging residue extraction for energy on ecosystem services and biodiversity: A synthesis. *Journal of Environmental Management*, *209*, 409–425. https://doi.org/10.1016/j.jenvman.2017.12.048

Ren, Q., & Zhao, C. (2015). Evolution of fuel-N in gas phase during biomass pyrolysis. *Renewable & Sustainable Energy Reviews*, *50*, 408–418. https://doi.org/10.1016/j.rser.2015.05.043

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

Röder, M., Mohr, A., & Liu, Y. (2020). Sustainable bioenergy solutions to enable development in low- and middle-income countries beyond technology and energy access. *Biomass & Bioenergy*, *143*, 105876. https://doi.org/10.1016/j.biombioe.2020.105876

Röder, M., Stolz, N., & Thornley, P. (2017). Sweet energy – Bioenergy integration pathways for sugarcane residues. A case study of Nkomazi, district of Mpumalanga, South Africa. *Renewable Energy*, *113*, 1302–1310. https://doi.org/10.1016/j.renene.2017.06.093

Romijn, H., Heijnen, S., Colthoff, J. R., de Jong, B., & van Eijck, J. (2014). Economic and social sustainability performance of Jatropha projects: Results from field surveys in Mozambique, Tanzania and Mali. *Sustainability*, *6*, 6203–6235. https://doi.org/10.3390/su6096203

Roopnarain, A., & Adeleke, R. (2017). Current status, hurdles and future prospects of biogas digestion technology in Africa. *Renewable & Sustainable Energy Reviews*, *67*, 1162–1179. https://doi.org/10.1016/j.rser.2016.09.087

Saadi, W., Rodriguez-Sanchez, S., Ruiz, B., Souissi-Najar, S., Ouederni, A., & Fuente, E. (2019). Pyrolysis technologies for pomegranate (*Punica granatum* L.) peel wastes. Prospects in the bioenergy sector. *Renewable Energy*, *136*, 373–382. https://doi.org/10.1016/j.renene.2019.01.017

Salman, B., Ong, M. Y., Nomanbhay, S., Salema, A. A., Sankaran, R., & Show, P. L. (2019). Thermal analysis of Nigerian oil palm biomass with sachet-water plastic wastes for sustainable production of biofuel. *Pro*, *7*(7), 475. https://doi.org/10.3390/pr7070475

Sanni, S. O., Ibrahim, M., Mahmud, I., Oyewole, T. O., & Olusuyi, K. O. (2019). Potential of off-grid solar PV/biogas power generation system: Case study of Ado Ekiti slaughterhouse. *International Journal of Renewable Energy Research*, *9*(3), 1309–1318.

Sanni, S. O., Oricha, J. Y., Oyewole, T. O., & Bawonda, F. I. (2021). Analysis of backup power supply for unreliable grid using hybrid solar PV/diesel/biogas system. *Energy*, *227*, 120506. https://doi.org/10.1016/j.energy.2021.120506

Sawadogo, M., Tanoh, S. T., Sidibe, S., Kpai, N., & Tankoano, I. (2018). Cleaner production in Burkina Faso: Case study of fuel briquettes made from cashew industry waste. *Journal of Cleaner Production*, *195*, 1047–1056. https://doi.org/10.1016/j.jclepro.2018.05.261

Sawyerr, N., Trois, C., & Workneh, T. (2019). Identification and characterisation of potential feedstock for biogas production in South Africa. *Journal of Ecological Engineering*, *20*(6), 103–116. https://doi.org/10.12911/22998993/108652

Schut, M., van Paassen, A., & Leeuwis, C. (2013). Beyond the research-policy interface. Boundary arrangements at research-stakeholder interfaces in the policy debate on biofuel sustainability in Mozambique. *Environmental Science & Policy*, *27*, 91–102. https://doi.org/10.1016/j.envsci.2012.10.007

Schut, M. S., Cunha, N., van de Ven, G., & Slingerland, M. (2014). Multi-actor governance of sustainable biofuels in developing countries: The case of Mozambique. *Energy Policy*, *65*, 631–643. https://doi.org/10.1016/j.enpol.2013.09.007

Simonyan, K. J., & Fasina, O. (2013). Biomass resources and bioenergy potentials in Nigeria. *African Journal of Agricultural Research*, *8*, 4975–4989.

Simonyan, K. J., & Fasina, O. (2015). A comprehensive review of biomass resources and biofuel production in Nigeria: Potential and prospects. *De Gruyter*, *30*, 143–162. https://doi.org/10.1515/reveh-2015-0015

Somorin, T. O., & Kolios, A. J. (2017). Prospects of deployment of jatropha biodiesel-fired plants in Nigeria's power sector. *Energy*, *135*, 726–739. https://doi.org/10.1016/j.energy.2017.06.152

Sotannde, O. A., Oluyege, A. O., & Abah, G. B. (2010). Physical and combustion properties of charcoal briquettes from neem wood residues. *International Agrophysics*, *24*(2), 189–194.

Stafford, W., & Blignaut, J. (2017). Reducing landscape restoration costs: Feasibility of generating electricity from invasive alien plant biomass on the Agulhas Plain, South Africa. *Ecosystem Services*, *27*, 224–231. https://doi.org/10.1016/j.ecoser.2017.04.008

Stafford, W., Cohen, B., Pather-Elias, S., von Blottnitz, H., van Hille, R., Harrison, S. T. L., & Burton, S. G. (2013). Technologies for recovery of energy from wastewaters: Applicability and potential in South Africa. *Journal of Energy in Southern Africa*, *24*(1), 15–26.

SuM4All. (2017). Global mobility report 2017: Tracking sector performance. https://openknowledge.worldbank.org/bitstream/handle/10986/28542/120500.pdf?sequence=6&isAllowed=y

Sundberg, C., Karltun, E., Gitau, J. K., Katterer, T., Kimutai, G. M., Mahmoud, Y., Njenga, M., Nyberg, G., de Nowina, K. R., Roobroeck, D., & Sieber, P. (2020). Biochar from cookstoves reduces greenhouse gas emissions from smallholder farms in Africa. *Mitigation and Adaptation Strategies for Global Change*, *25*(6), 953–967. https://doi.org/10.1007/s11027-020-09920-7

Surendra, K. C., Takara, D., Hashimoto, A. G., & Khanal, S. K. (2014). Biogas as a sustainable energy source for developing countries: Opportunities and challenges. *Renewable & Sustainable Energy Reviews*, *31*, 846–859. https://doi.org/10.1016/j.rser.2013.12.015

Tesfamichael, B., Montastruc, L., Negny, S., & Yimam, A. (2021). Designing and planning of Ethiopia's biomass-to-biofuel supply chain through integrated strategic-tactical optimisation model considering economic dimension. *Computers & Chemical Engineering*, *153*, 107425. https://doi.org/10.1016/j.compchemeng.2021.107425

Toyese, O., & Jibiri, B. E.-Y. (2016). Design and feasibility study of a 5MW bio-power plant in Nigeria. *International Journal of Renewable Energy Research*, *6*, 1496–1505.

Tufa, F. A., Amsalu, A., & Zoomers, E. B. (2018). Failed promises: Governance regimes and conflict transformation related to jatropha cultivation in Ethiopia. *Ecology and Society*, *23*(4), 26. https://doi.org/10.5751/es-10486-230426

Ugbebor, J. N., Membere, E. A., & Joel, O. J. (2012). A comparative study of biofuel and fossil fuel: A case study of palm oil and crude oil. In Advanced materials research [Advances in materials and systems technologies IV]. 4th International Conference on Engineering Research and Development (ICERD 2012), Univ Benin, Benin, Nigeria.

Umar, A. A., Hamzah, K., Saleh, M. A. M., Fagge, N. I., Muhammad, M. R., & Dalladi, J. B. (2018). Poverty sequestration using sawdust biomass energy in Nigeria. *Malaysian Journal of Fundamental and Applied Sciences*, *14*, 485–491.

van der Hilst, F., & Faaij, A. P. C. (2012). Spatiotemporal cost-supply curves for bioenergy production in Mozambique. *Biofuels, Bioproducts & Biorefining (Biofpr)*, *6*(4), 405–430. https://doi.org/10.1002/bbb.1332

van Schalkwyk, D. L., Mandegari, M., Farzad, S., & Görgens, J. F. (2020). Techno-economic and environmental analysis of bio-oil production from forest residues via non-catalytic and catalytic pyrolysis processes. *Energy Conversion and Management*, *213*, 112815. https://doi.org/10.1016/j.enconman.2020.112815

Vintila, T., Ionel, I., Fregue, T. T. R., Wachter, A. R., Julean, C., & Gabche, A. S. (2019). Residual biomass from food processing industry in Cameroon as feedstock for second-generation biofuels. *BioResources*, *14*(2), 3731–3745. https://doi.org/10.15376/biores.14.2.3731-3745

Waheed, M. A., & Akogun, O. A. (2021). Quality enhancement of fuel briquette from cornhusk and cassava peel blends for co-firing in coal thermal plant. *International Journal of Energy Research*, *45*(2), 1867–1878. https://doi.org/10.1002/er.5865

Wasajja, H., Al-Muraisy, S. A. A., Piaggio, A. L., Ceron-Chafla, P., Aravind, P. V., Spanjers, H., van Lier, J. B., & Lindeboom, R. E. F. (2021). Improvement of biogas quality and quantity for small-scale biogas-electricity generation application in off-grid settings: A field-based study. *Energies*, *14*(11), 3088. https://doi.org/10.3390/en14113088

Welfle, A., Thornley, P., & Röder, M. (2020). A review of the role of bioenergy modelling in renewable energy research & policy development. *Biomass & Bioenergy*, *136*, 105542. https://doi.org/10.1016/j.biombioe.2020.105542

Welfle, A. J., Almena, A., Arshad, M. N., Banks, S. W., Butnar, I., Chong, K. J., Cooper, S. G., Daly, H., Garcia Freites, S., Güleç, F., Hardacre, C., Holland, R., Lan, L., Lee, C. S., Robertson, P., Rowe, R., Shepherd, A., Skillen, N., Tedesco, S., … Röder, M. (2023). Sustainability of bioenergy – Mapping the risks & benefits to inform future bioenergy systems. *Biomass and Bioenergy*, *177*, 106919. https://doi.org/10.1016/j.biombioe.2023.106919

Winkler, B., Lemke, S., & Lewandowski, I. (2015). IREPA – Biomass for bioenergy potential assessment by a holistic and participatory approach. Papers of the 23rd European biomass conference: Setting the course for a biobased economy. In 23rd European biomass conference and exhibition (EU BC and E), Vienna, Austria.

Wiskerke, W. T., Dornburg, V., Rubanza, C. D. K., Malimbwi, R. E., & Faaij, A. P. C. (2010). Cost/benefit analysis of biomass energy supply options for rural smallholders in the semi-arid eastern part of Shinyanga region in Tanzania. *Renewable & Sustainable Energy Reviews*, *14*(1), 148–165. https://doi.org/10.1016/j.rser.2009.06.001

Yimen, N., Hamandjoda, O., Meva'a, L., Ndzana, B., & Nganhou, J. (2018). Analyzing of a photovoltaic/wind/biogas/pumped-hydro off-grid hybrid system for rural electrification in sub-Saharan Africa. Case study of Djounde in Northern Cameroon. *Energies*, *11*(10), 2644. https://doi.org/10.3390/en11102644

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