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A Review of Biomass Valorization for Bioenergy and Rural Electricity Generation in Nigeria

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Abstract

Nigeria is confronted with a notable energy shortfall, despite its substantial population and ample access to both conventional and renewable energy sources. Around 40% of the population lacks reliable, affordable, and sustainable energy and electricity, leading to economic, social, and political issues. The government has implemented several energy and electricity policy reforms, including liberalization, removal of subsidies, promotion of renewable energy, and transition from fossil fuels to renewable fuels, including biomass. However, Nigeria's energy landscape transformation success relies on identifying technological gaps, developing and deploying technologies economically, and prioritizing sustainability in energy policies. This review provides comprehensive information on biomass valorization to bioenergy and electricity, facilitating the successful implementation of government policies, research findings, and private sector interventions. Feedstocks have been evaluated for biomass conversion, including crop residues, forestry residues, livestock waste, algae and aquatic plants, energy crops, oil seeds, and domestic and industrial waste. These feedstocks can be converted into heat, electricity, liquid fuels, biogas, and solid fuels. However, the contribution of biomass to Nigeria's energy mix is still insignificant compared to other sources. Barriers identified include uncertainty with feedstock availability, land availability and conflict with food security, access to technology, poor technological skills, absence of good business models, a low level of investments, inadequate policy implementation, and high initial costs. Recommendations for promoting biomass conversion include developing and implementing policy for biomass utilization; assessing biomass resources; identifying legislative, regulatory, and institutional frameworks; identifying appropriate technologies; sensitizing stakeholders; developing skills and capacity; setting national targets; fostering regional and international cooperation; harmonizing with other sectoral policies; and conducting product-driven research and development.

Categories: Renewable Energy Systems, Bioprocess Engineering, Materials Engineering
Keywords: biomass valorization, bioenergy, rural electrification, off-grid electricity, pyrolysis, biogas, biofuel, energy policies, nigeria

Introduction And Background

Achieving a net-zero transition is important in reducing the impacts of climate change and global warming [1]. Nigeria, being confronted with these impacts, needs to address the resulting critical issues, including lifting over 100 million people from multi-dimensional poverty, fostering economic growth, and ensuring universal access to modern energy services [2]. Presently, ~175 million Nigerians lack access to clean cooking solutions, and ~92 million are without electricity [3], constituting 70% and 36.8% of the population, respectively. Rural communities, particularly vulnerable due to heavy dependence on climate-sensitive resources, face increased exposure to climate change risks. These dependencies have led to the emission of greenhouse gases (GHGs) through the use of wood biomass for making charcoal for cooking purposes [4]. These challenges can be solved through a well-implemented rural electrification scheme.

Rural electrification is an essential factor in the development of any country. It is critical in rural parts of Nigeria, where ~92 million people do not have access to electricity, and this is one of the highest globally [5]. Biomass valorization to energy has been identified as a potential solution to Nigeria's rural electrification problem [6]. This involves converting biomass, especially agricultural waste, into energy using combustion, gasification, and pyrolysis [7]. Biomass valorization offers several advantages for rural electrification in Nigeria. For instance, it is a renewable energy source, ensuring a continuous supply without depleting finite resources, which is crucial in reducing dependence on fossil fuels. Biomass valorization can generate jobs and economic opportunities in rural areas. It offers various opportunities to advance rural electrification in any developing country. One method involves establishing small-scale biomass power plants in a rural area, utilizing locally available biomass like agricultural waste and wood chips [7]. Under the power distribution program, these power plants can supply electricity to rural communities. Another approach involves using biomass, such as animal manure and food waste, for intermediate energy production, such as biogas production, by an anaerobic digestion system [8]. Biogas could serve as a clean and affordable energy source for cooking and electricity in rural households. Communal cooking and heating centers can be established using biogas from central biodigesters installed in public places such as local abattoirs, fish smoking, and local food processing centers.

Additionally, biomass can be harnessed to produce other biofuels like ethanol and biodiesel [9], reducing dependence on imported fossil fuels and enhancing energy security. The significance of biomass energy (bioenergy) is growing, making it a crucial element in the future energy landscape of the global world. The exploration aims to emphasize the importance of biomass energy in the context of Nigeria's energy needs and rural electrification initiatives. Harnessing biomass valorization for energy is critical in advancing rural electrification in developing countries. It offers a renewable, locally abundant, and sustainable energy source, fostering job creation and economic opportunities in rural regions. To realize the potential benefits of bioenergy, there is a requirement for policies and incentives that encourage the adoption of biomass valorization technologies and facilitate the growth of a biomass-based energy sector.

Biomass valorization encompasses the conversion of organic matter from living or recently living organisms into valuable products like fuels, chemicals, and materials. Utilizing technologies such as pyrolysis, gasification, fermentation, and hydrolysis, this process aims to extract beneficial compounds from biomass. The ultimate objective is to establish a sustainable, renewable energy source and product alternative to conventional fossil fuels, contributing to diminished GHG emissions and consequently aiding in waste reduction and fostering circular economy practices [10].

Approximately 5 billion tonnes of crop residues are globally generated annually, with about 47%, 29%, and 7% produced in Asia, America, and Africa, respectively [11], and ~2 billion tonnes of municipal solid waste (MSW) [12]. Waste generation varies from region to region and is influenced by socioeconomics, technological advancement, etc. Waste generation is increasing steadily. Without suitable treatment, the waste constitutes environmental challenges and adversely affects human health and well-being and the planet Earth [13]. Many studies have been conducted on biomass utilization for energy production in Nigeria [14]. Rural communities in sub-Saharan Africa, including Nigeria, face significant challenges related to energy poverty [15]. A substantial portion, approximately 52.3% of this population, lacks access to electricity. Moreover, over 80% of these rural households rely on traditional firewood for cooking and utilize non-conventional methods and kerosene for lighting. According to a study [16], electricity access in Nigeria was ~55.4% in 2020. This marks a continued decrease from 56.5% in 2018 [17]. As Nigeria's population is anticipated to reach ~400 million by 2050 [18], there will be an inevitable surge in energy and electricity demands. A substantial portion of this growing population resides in rural areas, emphasizing the need for deliberate efforts to develop renewable energy and enhance energy efficiency to alleviate energy poverty [19].

There is a need to increase the contribution of biomass and agro-waste to bioenergy and electricity in the

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energy mix to harness biomass wastes. Not much has been done regarding comprehensive and implementable studies to combine the knowledge available for rural electrification using biomass. There is a lack of robust government policy, programs, research, private sector interventions, etc. Bioenergy must be considered and deployed to define a sustainable path toward achieving significant rural electrification using off-grid electricity. Through research and development activities, academic institutions like the African University of Science and Technology have conducted studies on the potential of biomass for rural electrification in Nigeria [20].

Existing knowledge on biomass-based rural electrification is often fragmented across different sources, making it challenging for stakeholders to access comprehensive and up-to-date information. Furthermore, there is a lack of synthesis and analysis of existing data and experiences, hindering the identification of best practices, lessons learned, and gaps in knowledge. Nigeria's renewable energy and rural electrification landscape is dynamic, with new policies, technologies, and interventions emerging regularly. A comprehensive and systematic review can help capture these changes and provide insights for future planning and decision-making.

This work aims to provide a systematic and consolidated review of biomass valorization to bioenergy in Nigeria to facilitate alignment between government policies, research findings, and private sector interventions and ensure more coherent and effective strategies for achieving 100% electrification of rural areas, with biomass making a significant contribution.

Research methods

This study used information from two primary sources, the Google Scholar database and the websites of pertinent Nigerian government agencies, in accordance with the systematic literature review approach (Figure *1*). A total of 321 papers from Google Scholar and 35 records from government agencies' websites were identified. After screening for duplicates, it was reduced to 283 records. Some of the records did not further address the subject. Further screening reduced the record to 130. Ninety-one out of the 130 records were used for qualitative synthesis, and 54 out of the 91 were used for quantitative synthesis.

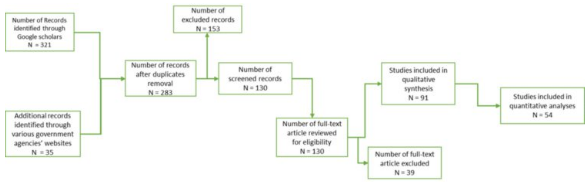

FIGURE 1: Systematic Literature Selections and Reviews

Google Scholar was used to identify peer-reviewed articles, books, reports, and conference proceedings related to biomass valorization, bioenergy, and off-grid rural electricity generation in Nigeria. These keywords were used in the search engines. Also, information was sought out from the relevant government agencies' websites. Literature published within the last 10 years (2014-2024) was considered to ensure relevance. Non-peer-reviewed and unrelated studies to biomass valorization, bioenergy, or rural electrification in Nigeria were excluded. For data collection, the study objectives, methodologies, findings, and recommendations from relevant literature were extracted, gathered, and organized for crucial information. The thematic analyses were done based on the key themes and sub-themes related to biomass valorization for bioenergy and rural electrification in Nigeria. The themes included Energy Framework and Landscapes in Nigeria, Energy from Biomass, Biomass Resources and Classification, Biomass Valorization to Energy in Nigeria, Biomass Energy Production Technologies, Feedstock Types, Bioenergy Conversion Technologies, Barriers and Challenges of Biomass Production for Energy in Nigeria, Policy Frameworks and Existing Policies, Development Needs, and Way Forward.

The synthesis and critical evaluation of the findings from the literature were done to identify common trends, challenges, and opportunities in biomass valorization and off-grid rural electricity generation in Nigeria. The implications of the findings were discussed in the bioenergy development and rural electrification initiatives in Nigeria. Gaps were identified, and insights were provided into future research directions and policy implications based on the gaps identified in the literature. Potential strategies for enhancing biomass valorization, promoting sustainable bioenergy development, and improving access to off-grid electricity in rural Nigeria were discussed. Finally, the key findings of the literature review were summarized, and the importance of biomass valorization for bioenergy production and rural electrification in Nigeria was highlighted.

Review

Nigeria's electricity framework and landscape

The Federal Government of Nigeria (FGN), supported by the 36 state governments, the Federal Capital Territory, and the associated offices, such as the Presidential Task Force on Power, play a pivotal role in overseeing the energy sector. This collaboration involves coordination with ministries, departments, commissions, programs, and other stakeholders (Figure *2*). Many Ministries, Departments, and Agencies (MDAs) in the country's energy sector oversee a variety of tasks. These MDAs include the Federal Ministries of Power (FMP), Water Resources, Petroleum, Environment, Innovation, Science, and Technology. With its network of interconnected institutions, this all-encompassing strategy guarantees efficient governance and management of Nigeria's energy landscape (Figure *2*). Following the sector's liberalization and privatization, there are currently 6 generating companies and 11 distribution companies (DisCos).

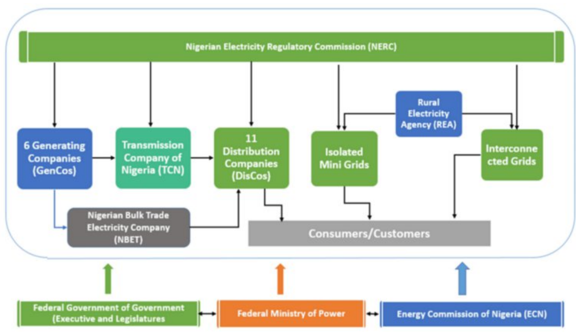

FIGURE 2: Institutional Framework for Electricity in Nigeria

The Rural Electrification Policy (REP), which was unveiled in 2005 and formally introduced in 2009, outlines the policies, goals, and objectives of the federal government with regard to rural areas. The rules governing the rural energy market are defined by this policy, which also provides guidelines and rights for energy actors. In order to implement policies effectively, it promotes cooperation between government organizations, including the Rural Electrification Agency (REA) and the Nigerian Electricity Regulatory Commission (NERC). Along with outlining their respective roles and processes for giving subsidies, the REP emphasizes how important it is for them to support solar mini- and off-grid systems in order to increase energy access rather than consumption [21]. In the meantime, the government, the FMP, and the Nigerian Energy Commission provide advice on how to formulate and carry out the policy.

Nigeria's Biomass (Bioenergy) Policies, as stated in Nigeria's National Energy Masterplan (NEMP), aim to efficiently harness non-fuel wood biomass energy resources and integrate them with other energy sources. Therefore, one of the most important objectives and metrics to support initiatives is to promote efficient technologies for biomass conversion, lessening the amount of biomass used for energy, ensuring that it coexists with other land demands, such as food production and biodiversity conservation, thoroughly mapping out energy crops suitable for agroecology, conducting a thorough life cycle analysis of all biomass feedstocks to determine their relative benefits in light of climate change, and offering a regional perspective on production potentials to guide decisions about handling and processing facilities [22].

The task of developing policies for the provision of electricity falls to the FMP through its guiding policies under the National Electric Power Policy (NEPP) of 2001, the Electric Power Sector Reform Act of 2005, the Roadmap for Power Sector Reform of August 2010, and, lastly, the Nigerian Electricity Act of 2023 [23]. They carry out this function in cooperation with the NERC, Electricity Management Services Limited, and the REA [24]. In order to address inadequate generation capacity, poor infrastructure and investment, and restricted access to electricity in rural areas, a number of reforms (Table *1*) have been put into place since 2001. They have also sought to encourage private sector participation, promote renewable energy deployment, and enhance regulatory oversight. The Energy Commission of Nigeria (ECN) has a multifaceted and statutory mandate encompassing the field of energy in all its ramifications. The government extended its responsibilities to include developing standards for electrical equipment and devices to mitigate these incidents [25]. It significantly influences how Nigeria's energy landscape is shaped. As the apex energy agency in the country, it is responsible for coordinating and supervising all activities in the energy sector, driving policy formulation, research, capacity building, regulation, and international cooperation to advance the country's energy development goals [26].

S/N	Reform Policies	Year	Strategic Intents
1	National Electric Power Policy (NEPP)	2001	To liberalize the electricity sector, attract private investment, and improve efficiency and reliability in power generation, transmission, and distribution [27].
2	National Energy Policy (NEP)	2003	To ensure the sustainable development and utilization of Nigeria's energy resources, including electricity, to meet its national development goals [26].
3	Electric Power Sector Reform Act (EPSRA)	2005	To establish a legal framework for restructuring the Nigerian electricity industry, promote competition, and create a conducive environment for private sector participation [28].
4	Rural Electrification Strategy and Implementation Plan (RESIP)	2005	To extend electricity access to rural areas through off-grid and mini-grid solutions, improve livelihoods, and reduce poverty [29].
5	National Integrated Power Project (NIPP)	2005	To fast-track the development of new electricity generation capacity, construct gas-fired power plants across the country, increase the overall power supply, and reduce reliance on hydroelectricity [30].
6	Nigerian Electricity Regulatory Commission (NERC) Establishment Act	2005	To create an independent regulatory body responsible for setting tariffs, ensuring fair competition, and promoting investor confidence in the electricity sector [31].
7	Power Sector Reform Roadmap	2010	To outline the government's strategy for privatization of the power sector, including the unbundling and sale of state-owned generation and distribution assets to private investors [32].
8	Nigerian Electricity Supply Industry (NESI) Roadmap	2013	To address the challenges in the electricity sector, improve service delivery, and achieve universal access to electricity by 2020 [32].
9	National Renewable Energy and Energy Efficiency Policy (NEP)	2015	To promote the development of renewable energy sources such as solar, wind, and biomass, as well as energy efficiency measures, to diversify the energy mix, increase access to electricity, and reduce greenhouse gas emissions [33].
10	Nigerian Electricity Market Stabilization Facility (NEMSF)	2015	To address financial challenges in the electricity sector and stabilize operations by providing financial support to market participants, addressing revenue shortfalls, and improving liquidity in the sector [34].
11	Power Sector Recovery Program (PSRP)	2017	To address the challenges facing the power sector, including inadequate generation capacity, poor transmission infrastructure, and financial viability issues among distribution companies, through targeted reforms and investments [35].
12	Nigerian Electricity Regulatory Commission (NERC) Mini-Grid Regulation	2017	To facilitate the development of off-grid and mini-grid electricity systems to increase access to electricity in rural and underserved areas [36].
13	Rural Electrification Strategy and Implementation Plan (RESIP)	2018	To accelerate rural electrification, and underserved areas through off-grid deployment, mini-grid solutions, leveraging renewable energy sources, and fostering public-private partnerships [37].
14	National Mass Metering Program (NMMP)	2020	To address the issue of estimated billing, improve metering in the electricity sector, deploy prepaid meters to customers across distribution companies, reduce losses, enhance revenue collection, and improve customer satisfaction [38].
15	Nigerian Electricity Act	2023	Aims to address persistent challenges in the electricity sector, such as inadequate generation capacity, transmission and distribution losses, tariff affordability, regulatory oversight, etc. [23,39].

TABLE 1: Electricity Reform Policies in Nigeria and Their Strategic Intents

The Rural Electrification Strategy, in conjunction with the REP, constitutes the framework to facilitate the extension of electricity services to rural areas. The objective (Table *2*) of the FGN was to enhance electricity accessibility, aiming for 75% and 90% coverage by 2020 and 2030, respectively. The focus is on integrating renewable energy sources to constitute at least 10% of the energy mix by 2025, as outlined in the NEPP of 2001 and the REP of 2005. To meet the 75% national target, urban electrification needs to achieve 95% coverage, while rural electrification must reach 60% by 2020. This necessitates connecting over 10 million additional rural households, based on an average of seven persons per household [40]. At the time of this review, there were no progress reports in the public domain on the targets.

Goal	Target Year	Target Achievement
Increase access to electricity	2020	75%
Increase access to electricity	2030	90%
Renewable energy contribution	2025	≥10%
Urban electrification	2020	95%
Rural electrification	2020	60%
Additional rural households connected	2020	>10,000,000

TABLE 2: Goals of the Federal Government of Nigeria Regarding Electricity Access and Renewable Energy Contribution

Refs. [41,42]

The FMP, through its Renewable and Rural Power Access department, has achieved 650 electrical installations, inspections, and testing of various generation, transmission, and distribution power projects. Among these, 450 installations were certified fit for use. NERC, as an autonomous regulatory agency, plays a crucial role in overseeing Nigeria's electric power industry. Its primary functions include enforcing compliance with market regulations and operational guidelines. Additionally, NERC is dedicated to safeguarding consumer interests by establishing customer service standards, implementing fair pricing rules, and offering effective dispute resolution mechanisms. The commission is also responsible for tariff regulation through the Multi-Year Tariff Order, promoting fair pricing, encouraging competition, and facilitating private sector participation [43].

Generally, electricity access has been poor. The World Energy Outlook 2020 database by the International Energy Agency revealed that as of 2019, electricity access in Nigeria stood at 61.6% (Figure 3), leaving approximately 77 million people without power [44].

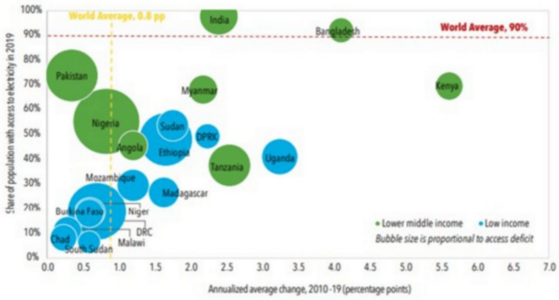

FIGURE 3: Electricity Access in Top 20 Access Deficit Countries, 2010-19

Ref. [44]

Nevertheless, the key metrics for the electricity sector in Nigeria are shown in Table 3, namely, total customer numbers, metered customers, estimated customers, revenue collected by DisCos, and electricity supply in Q1 2023. They show positive change percentages compared to the previous quarter (Q1) and a year-on-year percentage change.

Metric	Q1 2023	Q4 2022	Change (%)	Year-on-Year (%)
Total Customer Numbers	11.27 million	11.06 million	1.89	5.99
Metered Customers	5.31 million	5.13 million	3.61	10.86
Estimated Customers	5.96 million	5.93 million	0.40	1.99
Revenue Collected (Naira)	247.33 billion	232.32 billion	6.46	20.81
Electricity Supply (GWh)	5,852	5,611	4.29	−1.74

TABLE 3: Nigeria's Electricity Report Adopted from the Nigerian Bureau Statistics Q1 2023 Report

Ref. [45]

Furthermore, the NERC is saddled with the approval of operating codes, standards regulation, licensing, and regulation of entities involved in generation (>1 MW), transmission, distribution, and trading. Its mandates extend to monitoring electricity market activities and overseeing market amendments [46,47]. The ECN is tasked with strategic planning and coordination of national energy policies. Operating under the ECN Act, it advises the federal or state government on funding allocations for the energy sector, covering research and development, production, and distribution. The ECN actively monitors the energy sector's performance in line with government energy policies and serves as a central hub for gathering and disseminating information related to national energy policy [48]. The Federal Ministry of Power is entrusted with initiating, formulating, coordinating, and implementing comprehensive policies and programs to foster electricity generation from diverse energy sources in Nigeria. The ministry is expected to guide other MDAs that play in the country's power sector [21,24].

The NERC Guidelines on Distribution Franchising in the Nigerian Electricity Supply Industry 2020 will empower DisCos to adapt to evolving business structures and technology. This adaptation is crucial for providing secure and reliable services to end-user consumers. The Franchising Guidelines enable DisCos to engage in franchising arrangements with third parties, allowing them to perform specific functions within the DisCos' licensed area. The rise of distributed energy resources (DERs) was anticipated to contribute significantly to an integrated grid, fostering efficiency and consumption [49,50]. This is attributed to the ability of DERs to operate independently from local distribution licensees. Support for mini-grid development has increased recently, enhancing commercial viability and recognizing co-benefits such as national economic development. The evolving mix of DERs facilitates a two-way energy flow, accommodating new connected technologies for power generation. The completion of the Nigeria Electrification Roadmap (NER) is expected to alleviate challenges in power supply, positively impacting industrial, agricultural, and mining sectors by increasing operational capacity to 25 GW [49,50]. Privatization efforts concerning the National Integrated Power Projects and selected government midand downstream energy assets aim to address transmission and transportation issues, contingent on connected customers paying for consumed power promptly to ensure the flourishing of the generation sector.

The current electricity generation in Nigeria falls short of meeting the demands of households and businesses, leading to a low per capita consumption of electricity (Figure 4). The FGN has established ambitious goals in both the NEPP and the REP. These targets aim to provide reliable electricity access to 75% and 90% of the population (urban and rural) by 2020 and 2030, respectively. At the time of the review, no progress reports on the targets were in the public domain, hence the need to strengthen the capacity of the relevant institution toward information dissemination. Furthermore, the government intends to achieve at least a 10% share of renewable energy in the energy mix by 2025 [51]. At an installed capacity of 13.5 GW, generation has fluctuated between 3 MW and 5 MW [52]. Over the years, many power plants operated below their optimal capacity, resulting in a significant loss of electricity during transmission. For instance, although the electricity capacity was 5,600 MW in 2001, actual power generation plummeted to as low as ~1,750 MW [53]. Therefore, these shortfalls can be closed by introducing and scaling up bioenergy into the energy mix, especially for off-grid systems in rural areas. By 2030, biomass energy contribution (Table 4) is expected to hit 800 MW compared to 2015 records. The entire renewable energy capacity is expected to contribute ~36% of the total energy [54]. However, with more investments, research, and developments in biomass valorization for energy, the capacity and contribution of biomass energy will advance. In turn, this will address the issue of 80% and 28% of Nigerians not having access to electricity or clean cooking by 2030, respectively [55].

Resources	2010 (MW)	Contributions (%)	2015 (MW)	Contributions (%)	2030 (MW)	Contributions (%)
Large hydro	1,930	94.79	5,930	19.77	48,000	25
Small hydro	100	4.91	734	2.45	19,000	9.90
Solar PV	5	0.25	120	0.40	500	0.26
Solar Thermal	0	0	1	0.003	5	0.003
Wind	1	0.05	20	0.07	40	0.02
Biomass	0	0	100	0.33	800	0.42
Total Renewable Energy	2,036		6,905	23.02	68,345	35.60
Total Energy	16,000		30,000		192,000	
Renewable Energy Percentage		12.73		23.02		35.60

TABLE 4: Nigeria’s Electricity Generation from Renewable Energy Sources

Refs. [54,56]

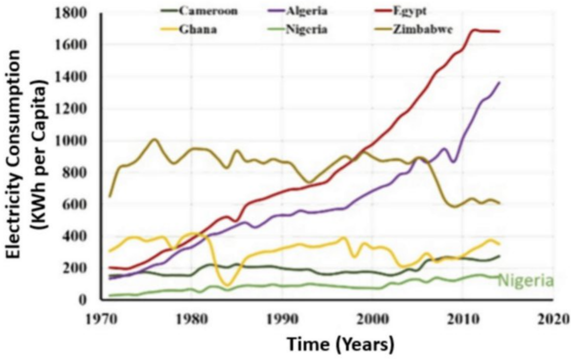

FIGURE 4: Electricity Consumption Per Capita for Different Countries in Africa

Ref. [52]

Nigeria has taken several initiatives in the past toward rural electrification. One primary approach was establishing the REA in 2006 to facilitate the electrification of rural and underserved communities in the country. The REA implements various programs and projects to provide access to electricity in rural areas through grid extension, mini-grid systems, and standalone solar solutions. Progress has been made in increasing electrification rates in rural areas through these initiatives (Figure 5a). The government has collaborated with development partners and private sector stakeholders to mobilize funding and technical expertise for rural electrification projects. However, bioenergy is not reflected in the energy mix, and despite these efforts, significant gaps still exist in rural electrification schemes, with many remote communities existing without access to reliable electricity, thereby hindering socio-economic development and quality of life in those communities. A further result of this misnomer is the continual urban migration and anti-social behavior of middle-aged and able-bodied youths. Challenges such as inadequate funding, technical capacity limitations, and policy inconsistencies continue to impede rural electrification. Figure 5a shows electrified communities with high density in southern Nigeria, while Figure 5b shows power distribution infrastructures with low footprints in the northeastern part of Nigeria. There is a need to improve the existing mini-grids (Figure 5c) to reach wider communities and address chronic energy poverty in Nigeria. Figure 5e shows the transmission lines, most of which are obsolete and often lead to the collapse of the grid system. There is a need for more independent power plants (Figure 5d) geographically spread to reduce the load on the existing aged transmission substation (Figure 5f).

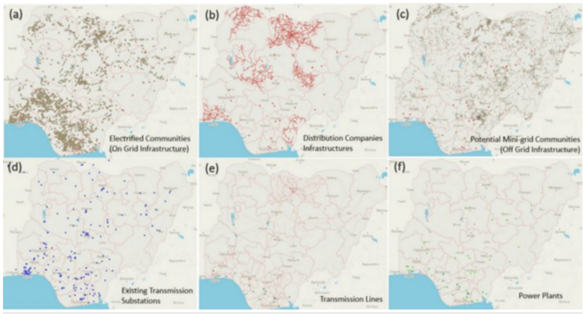

FIGURE 5: Nigeria's Electricity Coverage Showing (a) Electrified Communities (On-Grid Infrastructure), (b) Distribution Companies Infrastructures, (c) Potential Minigrid Communities (Off-Grid Infrastructure), (d) Existing Transmission Substations, (e) Transmission Lines, and (f) Power Plants

Ref. [57]

Energy from biomass

Biomass Resources and Classification

Biomass resources can be of plant or animal origin. They are renewable materials because they can be grown and regrown. They include agricultural residue, forest residue, energy crops, and animal waste, as seen in Figure 6.

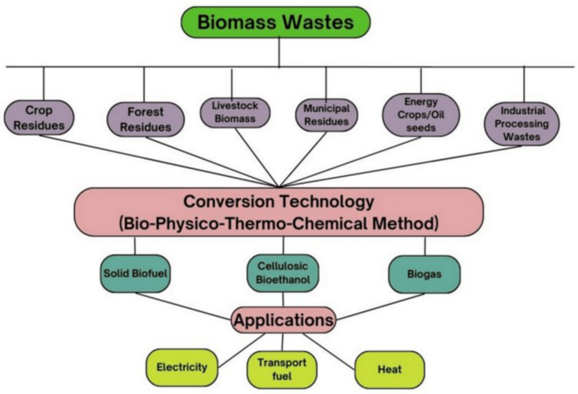

FIGURE 6: Biomass Classifications and Conversion Technologies to Bioenergy

These biomass materials present sustainable energy resources with significant potential for addressing global energy needs while mitigating environmental challenges and promoting rural development. By understanding their diverse sources and classification based on composition, origin, and application, stakeholders can identify optimal biomass valorization pathways and contribute to a more sustainable energy future. Figure 7 shows diverse sources of biomass waste, each with its own unique composition and potential for energy recovery or other valuable applications. By-products like crop residues (stalks, leaves, husks, corn cobs, and stover), straw (rice, wheat, and barley), and sugarcane bagasse are generated from agricultural production. Animal manure, such as droppings from cows, pigs, poultry, poultry litter, and fish wastes, is generated from animal wastes, while algae is an aquatic biomass from algae and aquatic plants.

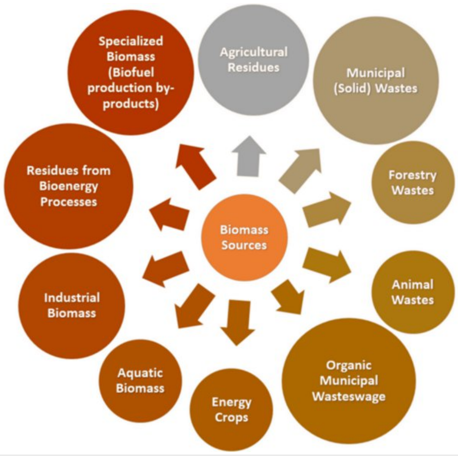

FIGURE 7: Categories of Biomass Wastes Based on Their Origin, Composition, and Characteristics

Biomass Valorization to Energy in Nigeria

Inconsistent policies, technology limitations, and poor waste management form part of the issues hindering the adaptation of biofuels in Nigeria. The Nigerian Biofuel Policy and Incentives released in 2007 were reviewed [58]. The policy was recommended to be upgraded as it classified biofuel as only including bioethanol and biodiesel and primary food sources as the main feedstock, neglecting second-generation feedstocks. To have effective energy structures, Nigeria needs to review its programs and policies [59]. Nigeria has explored adopting a 100% renewable energy supply by 2050 [60]. The country has experienced setbacks in renewable energy usage due to poorly utilized renewable resources and improper adoption of relevant policies. Efficient and effective policy formulation is critical, and with no global agreement, each nation's political decisions are essential in crafting an effective policy [59]. The urban population in Nigeria currently generates 20.5 million tons of MSW, which includes more than 50% of organics highly suitable for energy valorization [61]. Climate change and environmental issues are issues that are pushing many countries to adopt biofuels. By 2030, the Nigerian Renewable Energy and Energy Efficiency Policy aspires to add 23,000 MW of renewable energy capacity, with agricultural and MSW being the primary bioenergy sources [61].

Various authors have outlined (Table *5*) the potential of biomass valorization by assessing the agricultural residues and municipal solid and liquid waste available for producing biofuels, cellulosic ethanol biogas, and other industrial applications [6]. According to a study [62], the bioenergy potential of Nigeria's forest residue is estimated to generate ~101 TWh of electricity and bioenergy, which can reduce the pump price of petroleum products.

These studies conclude that Nigeria's biomass and agro-waste resources have the potential to significantly contribute to its energy and electricity mix. However, these potentials can only be realized if the policy and institutional framework, technological skills, and socio-economic landscape are right.

Topic	Objective	Methodology	Findings	Conclusion/Implications	Ref
Biomass Valorization to Bioenergy: Assessment of Biomass Residues' Availability and Bioenergy Potential in Nigeria	To investigate the bioenergy potential of agricultural residues and municipal solid and liquid waste in Nigeria	Applied a computational and analytical approach with mild assumptions using data from 2008 to 2018	It showed higher energy generation from biogas than cellulosic ethanol for the same type of residue	Biogas has diverse applications, including heat and electric power generation, and holds great potential in addressing Nigeria's electricity crisis	[6]
Preliminary characterization and valorization of Ficus benjamina fruits for biofuel application	To explore the potential of Ficus benjamina (FB) fruits, typically considered waste, as a biofuel feedstock	The study utilized various biochemical methods to characterize the physical, thermal, and chemical properties of pulverized Ficus benjamina fruits (PFB)	The moisture, ash, volatile matter, and fixed carbon contents are 9.29%, 6.26%, 64.35%, and 20.10%, respectively. The higher and lower heating values were determined to be 19.74 MJ/kg and 18.55 MJ/kg, respectively	The results indicate that PFB possesses properties comparable to other biomass feedstocks, suggesting its potential as a solid biofuel. This valorization of FB fruits could contribute to waste reduction and the development of sustainable biofuel sources	[63]
Biomass utilization for energy production in Nigeria: A review	To conduct a systematic review to assess the progress and major themes in biomass energy recovery in Nigeria, as well as identify challenges facing its utilization for energy production	A systematic search using Boolean-operator keywords was conducted on SCOPUS and Google Scholar databases	Major themes driving biomass valorization in Nigeria include climate change, energy diversification, waste management, and policies. Challenges include poor waste management, resource limitations, and inconsistent policies	Nigeria has significant energy potential from crop residues and municipal solid waste. Efforts should focus on developing agriculture and waste management systems and addressing fuel subsidies to make renewable energy ventures more attractive	[61]
Bio-Fuel Properties and Elemental Analysis of Bio-Oil Produced from Pyrolysis of Gmelina Arborea	To determine affordable processes for producing sustainable energy using waste materials	Pyrolysis conducted in a fixed bed pilot-scale reactor using Gmelina arborea biomass	Physicochemical properties and ultimate analysis of bio-oil determined	Gmelina arborea sawdust biomass shows favorable properties for bio-oil production with low sulfur content	[64]
Valorization of waste cassava peel into biochar: An alternative to electrically-powered process	To convert waste cassava peels into biochar using a biomass-powered reactor, addressing the environmental burden caused by increased cassava	Top-lit updraft reactor with retort heating for the conversion process was used, designed to be cheap, simple, and environmentally friendly	The study achieved a biochar yield of 55.13%, with FTIR analysis indicating similar functional groups in the biochar compared to the precursor, but with more oxygenated functional groups	The study demonstrates the feasibility of converting waste cassava peels into biochar using a biomass-powered reactor, offering an environmentally friendly solution for managing cassava peel waste. The biochar produced exhibited desirable properties for various applications	[65]

	consumption				
Valorization of pineapple peel and poultry manure for clean energy generation	To assess energy production from anaerobic co-digestion of pineapple peels (PPs) and poultry manure (PM)	Pretreatment of PPs using sulfuric acid and alkaline hydrogen peroxide (H_2O_2)	Alkaline H_2O_2 pretreatment removed 71.34% of lignin, reduced hemicellulose by 61%, and increased cellulose content by 39%	Alkaline pretreatment of PPs before digestion is recommended for biogas production and quality digestate, useful as biofertilizers or soil enhancers, particularly in regions with significant pineapple production	[66]
Biomass valorization for energy applications: A preliminary study on millet husk	To investigate the effect of particle sizes, compaction pressures, and binder concentrations on briquette characteristics and assess the economic viability of millet husk briquettes as fuel	Particle sizes of 0.3, 0.4, 0.6, and 1.7 mm; compaction pressures of 10, 15, 20, and 25 MPa; and binder concentrations (gum Arabic) of 25, 30, 35, and 40% were used	Density, impact resistance index, and compressive strength increased with compaction pressures and binder concentrations and decreased with particle size	Millet husk briquettes show potential as an efficient and cost-effective alternative for domestic cooking, leading to fuel savings, reduced deforestation, and improved profitability of millet cultivation in Northern Nigeria	[67]
Mechanical and Thermomechanical Properties of Clay-Cowpea (Vigna Unguiculata Walp.) Husks Polyester Bio-Composite for Building Applications	To investigate the feasibility of clay polymer-based composite with cowpea husk filler for roof tile production	Fabrication of polymeric composites by mixing unsaturated polyester resin with cowpea husk at varying filler weights and curing	Morphological analysis shows rough, coarse, inhomogeneous surfaces with voids in the mono-reinforced composites, while clay uniformly fills voids in hybrid composites	Composite combination suitable for roof tile production and applications requiring low strength	[68]
Physical-Mechanical properties of wood-based composite reinforced with recycled polypropylene and cowpea (Vigna unguiculata Walp.) husk	To produce eco-friendly panels from agro and industrial wastes for various applications	Panels produced from cowpea husk (CPH), wood chips (WC), and recycled polypropylene (rPP)	Optimal performance achieved with 80% WC and 20% CPH, meeting ANSI A 208.1 standard for physical properties	The CPH, WC, and rPP mixture can be utilized for board production with good dimensional stability, suitable for applications like ceiling boards and wall claddings where load-bearing is not crucial	[69]
Bioenergy Potential of Under-Utilized Solid Waste Residues from Oil Palm Mills in Nigeria	Estimate bioelectricity potentials of under-utilized oil palm processing solid wastes in Nigeria	Employ a quantitative approach to data generation	Bioelectricity potentials ranged from 3.234 to 5.175 MWh in 2004, increasing to 3.796 to 6.073 MWh in 2013	Technological, policy/political, and economic challenges identified as hurdles for bioelectricity generation	[70]
The potential of lignocellulosic fiber reinforced polymer composites for automobile parts production: Current knowledge, research needs, and future direction	To provide a comprehensive overview of the potential applications and sustainability of lignocellulosic-based natural fiber-reinforced polymer composites (NFRPCs) in the automobile industry	The paper examines the current state of knowledge, identifies research needs and existing limitations, and provides insights into future perspectives regarding using NFRPCs in the automotive sector	The review highlights that lignocellulosic fibers offer several advantages over synthetic counterparts and hold promise as sustainable, high-performance, and cost-effective alternatives. However, continuous research is needed to address issues such as fiber-matrix compatibility, processing techniques, long-term durability concerns, and general property improvement	Advancements in NFRPCs are crucial to meet the increasing demand for eco-friendly, renewable, and energy-efficient materials in automotive design	[71]
Exploring Biogas and Biofertilizer Production from Abattoir Wastes in Nigeria Using a Multi-Criteria Assessment Approach	To assess the potential use of waste generated in the north-central region of Nigerian abattoirs for biogas and biofertilizer production	Data acquired from the study sites were used for computational estimation and integrated into a SWOT analysis to evaluate strengths, weaknesses, opportunities, and threats associated with the prospects of biogas and biofertilizer production	The study revealed that high investment costs and public subsidies for fossil fuels are key limiting factors. However, tapping into unexploited carbon markets and multiple socio-economic and environmental benefits favor investment in waste-to-energy technologies	Concluded that public support, in the form of national policy reforms leading to intervention programs, is essential for progress in harnessing waste streams from abattoirs for biogas, and biofertilizer production	[72]
Prospects for biodiesel production from Macrotermes nigeriensis: Process optimization and characterization of biodiesel properties	The objective of this study was to produce biodiesel from an insect feedstock (M. nigeriensis) and characterize its physicochemical properties, as well as assess its engine performance	Biodiesel was synthesized from M. nigeriensis oil using a three-step process involving lipid extraction, acid esterification, and alkaline transesterification. The acid-esterification process was optimized for reaction time, temperature, and methanol-oil molar ratio	The acid-esterification process resulted in a free fatty acid conversion of 96.58%. The biodiesel obtained from M. nigeriensis oil had a volumetric yield of 86.54 vol.% and contained 96.72% fatty acid methyl esters, with a composition of 48% saturated esters and 52% monosaturated esters	The study demonstrated the feasibility of producing biodiesel from M. nigeriensis oil and characterized its physicochemical properties. The biodiesel met ASTM standards and exhibited favorable properties for engine performance, including low viscosity and good oxidation stability. These findings highlight the potential of insect-based biodiesel as a sustainable alternative fuel source	[73]

TABLE 5: Various Assessments on Biomass Valorization for Energy in Nigeria

Biomass Energy Production Technologies

Biomass can be converted into valuable energy forms using several different processes. Various technologies are used for the valorization of biomass, and the factors that influence the choice of the conversion technologies are the type and quantity of biomass feedstock and the desired form of energy, i.e., end-use requirements, environmental standards, economic conditions, and project-specific factors [74]. Biomass can be converted into three main products: power and heat generation, transportation fuels, and chemical feedstock.

Biomass conversion to bioenergy is usually carried out using two primary process technologies: thermochemical and biochemical/biological processes [75], depending on waste composition and moisture content [76]. Low moisture content and less dense wastes are suitable substrates for thermochemical processes, including incineration, combustion, pyrolysis, and gasification. In contrast, more dense organic waste with high moisture content is a suitable substrate for biochemical conversion [76,77]. Figure 8 shows the processes for the valorization of biomass.

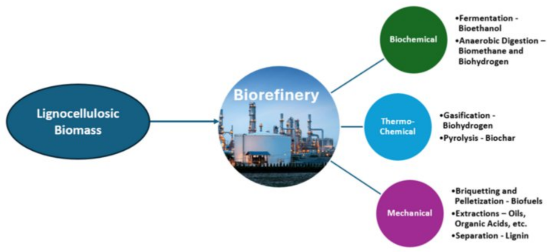

FIGURE 8: Valorization Routes for Biomass Waste to Value-Added Products

In thermochemical conversion processes, the carbonaceous, less dense organic waste undergoes high temperatures to produce heat energy, liquid fuel oil, gaseous fuels, and solids like charcoal [76]. The main thermochemical processes include direct combustion, gasification, and pyrolysis. Combustion is burning biomass in excess air or oxygen in a furnace at temperatures of 800°C-1,000°C, producing ash and hot gases at high temperatures that can be used for heating, i.e., in boilers [78]. Combustion reduces the volume of waste by 80-90% and mass by 70-80% [76], reducing landfill land space required and increasing the lifespan of existing landfill sites. Combustion also denatures hazardous materials. Hot flue gases generated from combustion heat high-pressure feed water to raise steam, which runs boilers, generating electricity [76]. Countries like Denmark and Sweden use this for power production. Co-combustion of biomass in coal-fired power plants has been explored as it increases the conversion efficiencies of these plants [79]. The major disadvantage of this process is that it generates hazardous pollutants that are detrimental to human health and the environment. Direct domestic combustion of biomass is used everywhere in the world, particularly in rural areas in Africa, where firewood is used in domestic stoves. Commercial applications of biomass involve use in heating and electricity generation [80].

Co-firing of coal and biomass is currently being used in more than 150 power plants, with the United States, Germany, and Sweden having more co-firing facilities globally [81]. Cofiring with biomass reduces GHG emissions by more than 40% since the combustion of 100% woody biomass can reduce the emissions by up to 76% [81]. Cofiring combines a primary fuel with a secondary fuel for combustion in power plants without alterations to the existing combustion equipment. Co-firing will also be a viable option for Nigeria, as it allows for the use of existing infrastructure and reduces capital investment [82]. Roni et al. [82] thoroughly review existing biomass co-firing conditions, policies, challenges, and opportunities worldwide. Pulverized combustion is used for co-firing, and it is divided into three categories: direct co-firing, indirect co-firing, and parallel combustion. Direct co-firing comprises feeding fossil fuel together with biomass in the same furnace. Indirect co-firing involves two stages: partial oxidation of woody biomass and syngas combustion to produce hot gases (i.e., heat) [82].

Parallel co-firing entails the installation of an additional boiler for the combustion of biomass to produce steam. This presents an expensive combustion option. Co-firing, which generates electricity, has an efficiency between 28% and 44% [81]. Industrial combustion technologies entail either a fixed bed, fluidized bed, or pulverized bed technologies. Studies have shown that the theoretical framework for the exergy analysis and advanced exergy analysis of real biomass boilers has been established [83]. Components to be considered for improvement and real fuel-saving potentials were reviewed. The combustion process needs to be highly optimized, and an increase in biomass moisture decreases the adiabatic flame temperature, decreasing the total boiler energy efficiency [84].

Fixed-bed boilers are the most commonly used combustion systems due to their low investment cost, energy consumption, and ease of assembly. They operate between 850°C and 1,400°C. In the first stage, air primarily goes through a fixed bed where partial combustion, drying, and gasification processes are developed. In the second stage, hot gases produced are completely burned above from a fixed fuel bed where the secondary air is supplied. This stream is greater than the primary air because of the high volatile content in biomass. The char produced provides enough heat to combust the new biomass supplied [81].

Fluidized bed boilers operate as a self-mixing suspension where biomass is mixed with silica sand, limestone, dolomite, or other non-combustible material, which acts as a bed. Biomass is burned around the combustion chamber while primary air enters from the bottom. Fluidized bed boilers operate between 700°C and 1,000°C to avoid ash sintering. Fluidized bed boilers are divided into bubbling fluidized beds (BFB) and circulating fluidized bed boilers (CFB), depending on the airspeed. Air demand in fluidized-bed boilers is low [81].

Pulverized fuel combustion boilers are similar to CFB and BFB, but the raw material must have a mean particle size of 20 mm. This technology offers a thermal capacity of 2 MW [81].

Pyrolysis: Pyrolysis is the thermal decomposition of biomass at temperatures of about 350-600°C, under pressure, in the total/partial absence of oxygen. It produces three fractions: a liquid fraction (bio-oil), a solid fraction (predominantly ash), and a gaseous fraction [81,85]. Pyrolysis can be carried out in an inert atmosphere created by hydrogen pressure or in an inert atmosphere [86].

Pyrolysis can be classified into slow, fast, and flash pyrolysis, considering the residence time of the feed and product vapors inside the reactor and the heating rate. The comparison of the processes is given in Table 6.

Classification of Pyrolysis	Heating rate °C/s	Products Yield/ %wt.	Advantages	Disadvantages
Slow pyrolysis	≤1.5	Biochar 30-40 Bio-oil 25-35 Non-condensable gases 25-35	Upgrade of low-quality feedstocks. Lower emissions of CO, CO_2, NO_x, and dust	Long residence time required to obtain the desired product
Intermediate pyrolysis	3-5	Biochar 25-35 Bio-oil 40-50 Non-condensable gases 25	Produces more biochar	Lower tar yield and viscosity in comparison to fast pyrolysis
Fast pyrolysis	10-200	Biochar 12-20 Bio-oil 60-75 Non-condensable gases 13-20	The mixture of insoluble organic compounds, i.e. bio-oil produces heat and power in boilers and turbines	High oxygen content in bio-oil compared to fossil fuels

TABLE 6: Comparisons of Classes of Pyrolysis

Refs. [87-91]

Bio-oil is a source of hydrocarbons that can be used for fuel applications after upgrading and is a rich source of functional chemicals such as phenolic compounds, aromatic ethers, furans, etc. Biochar is a solid product obtained by pyrolysis. It can be used for soil amendment and enrichment, as adsorbents, catalysts, and high-value applications such as supercapacitors, electrodes, etc. Pyrolysis reactor design affects the performance and selectivity of the process [81].

Gasification: This is the partial oxidation of biomass to produce a gaseous mixture known as syngas (synthetic gas), which can be further used for power generation or other thermal applications [92]. Syngas is composed of CO, H_2, CH_4, and CO_2, and its composition varies depending on the type of raw material (e.g., coal, pet coke, and biomass) as well as the gasifying agent (i.e., O_2, steam, CO_2, and air) [81]. Carbon-enriched fuels such as coal or MSW are decomposed at high temperatures of 550-1,600°C in low oxygen required for stoichiometric combustion [76]. Gasification can be classified as auto-thermal or also-thermal, where in auto-thermal gasification, the heat needed to gasify the feedstock is delivered by a part of the input feedstock (i.e., fuel). An example of auto-thermal gasification is where, in allo-thermal gasification, the heat required is delivered by an external source of heat energy, e.g., a plasma torch [76]. Gasification, compared to combustion processes, produces low emissions. Unfortunately, based on existing literature, Nigeria has no gasification plant. The above review shows that several technological routes can be used to produce different energy-related products, but it appears that there are only a few cases of application of such technologies in Nigeria. It is imperative to discover why these technologies are not currently deployed for economic benefit.

Biomass Conversion to Electricity

Nigeria should promote biomass power systems (BPSs) to address electricity issues and expand the energy mix. The vast agricultural sector and significant biomass resources present a substantial opportunity for biomass conversion to electricity. There are two ways to utilize biomass in electricity production. The first entails the dedicated use of biomass, while the other involves co-firing biomass with an existing fossil fuel plant. The technologies for directly using biomass in electricity production include direct combustion, gasification, pyrolysis, and biochemical degradation. These technologies have been discussed in the section of Biomass Energy Production Technologies. According to a study, a hybrid gas turbine cycle (GTC) and BPS with an absorption refrigeration system for combined cooling, heating, and power can be developed. This reduces CO_2 emissions by 30% less than standard GTC of the same capacity at a levelized electricity cost of $0.137/kWh [93]. This initiative can address the nation's energy deficits, particularly in rural areas, while promoting sustainable development and reducing GHG emissions. Direct combustion of biomass in a boiler to produce steam drives a steam turbine connected to an electricity generator. Also, by establishing pilot plants in local government areas (LGAs), this initiative can serve as a model for rural electrification, enhance local capacities, and contribute to the country's broader energy and environmental goals. Public-private partnerships (PPP) will play a crucial role in funding and implementing these projects, ensuring their success and scalability.

Barriers to biomass conversion to energy in Nigeria

The availability of arable land in Nigeria in a relatively large proportion indicates that biofuel production from biomass is feasible. The country has 7,85,000 km^2 of accessible farmland [94,95]. Cultivable land being lavishly available was earlier established by the Food and Agriculture Organization in the inventory of forest plantations from different states in Nigeria [96]. Ironically, these large expanses of land have not translated into an increased yield of agricultural products to match the population increase. The dwindling interest in the agricultural sector is a major factor in this scenario.

The trend of rural-urban migration, coupled with a large percentage of the employable population seeking white-collar jobs, poor/lack of access to loans, low wages, and inadequate equipment and facilities, amongst other factors, is responsible for the loss of interest. All of these have contributed to the low output of agricultural produce, which inevitably affects biomass availability for biofuel production in Nigeria [97].

The competition between biomass for renewable energy and food is a critical challenge in the country. Since the rise in the price of food in 2007, the competition between the cost of food and biofuel has become a challenge [98]. This situation persists presently, though it is an anomaly. As a result of cases where the biomass used can also serve as food, the use of feedstock that is not edible should be avoided. The impediments to biofuel production in Nigeria are multifaceted and include the high cost of production, weak government policies, limited public awareness, land tenure complexities, and inadequate technological advancements.

The cost of processing biofuels currently surpasses that of fossil fuels, rendering the venture unattractive to potential investors [99,100]. Access to new technology remains challenging, but the government and the private sector can play pivotal roles by offering subsidies and interventions.

Weak government policies and a lack of public awareness are additional barriers to widespread biofuel adoption in Nigeria. Establishing standardized policies to promote biofuels would be a positive stride, creating a collaborative platform for industries, non-governmental agencies, private investors, research institutes, and academia [101]. Poorly developed biomass utilization policies hamper progress toward its development. Challenges like shortages of policy formulation and manpower, lack of synergy among policy-making organizations, inconsistency in government vision and programs, absence of enabling legislation, insufficient data on energy potentials, and financial constraints have, over the years, stunted progress [14]. Poor institutional framework, inadequate policy implementation [102], lack of coordination, high initial capital costs, weak technology dissemination, insufficient skilled manpower, poor baseline information, and the need for strengthened infrastructure support for increased renewable energy utilization [13].

The prevailing communal control over land in Nigeria, dictated by the land tenure system, introduces barriers for investors, with tribal and inter-ethnic conflicts over land disputes hindering the effective utilization of fallow land in rural communities. Nomadic herdsmen invading arable farmlands further exacerbate the situation, posing a significant threat to farming in various rural areas and resulting in the loss of human lives. Evaluation of biomass conversion facilities should consider treated acres, demonstrated capacity, and multi-stakeholder commitment. To maximize economic benefits, biomass facilities should share economic activity benefits with local communities, encouraging high-return community-based approaches. Co-locating value-added enterprises with biomass facilities enhances economic value and reduces local resource demand [94].

Poor technological advancement is also challenging despite satisfying results from the preliminary tests on biomass sources like sugarcane, cassava, coconut, oil palm, and soya. The agricultural system in the country presents a serious impediment. Notably, the Jatropha Growers, Processors, and Exporters Association of Nigeria emphasized the country's need for 2.4 million liters of biodiesel daily to meet the Paris Agreement on climate change [103]. This presents a substantial opportunity for the government and investors to explore. Technology selection should prioritize efficiency, waste capture and reuse, economic self-sustainability, and local investment to build capacity and assets. Careful consideration is needed to avoid outdated and inefficient biomass technology systems.

Logistical expenses associated with collecting feedstock can potentially diminish biomass's technological feasibility. This is primarily because the project's economic viability hinges on the availability of biomass feedstock in substantial quantities within reasonable proximity [104]. Moreover, other high-value, non-energy applications may present competition for bioenergy production.

Investors typically favor shorter payback periods of 2-4 years, a preference that aligns with power plants featuring lower capital costs despite higher fuel expenses. Given the comparatively elevated capital costs of large bioenergy heat and power plants in contrast to gas or coal plants, the attractiveness of bioenergy project investments is contingent on the assurance of long-term policy support and considerations of feedstock prices [105]. The absence of such assurances may deter investment in bioenergy projects. Sustainability is increasingly critical in bioenergy projects, encompassing environmental and social considerations. Environmental issues include concerns about GHG emissions, land degradation, water resource availability, and biodiversity. Social issues encompass land ownership, employment opportunities, and social equity. Initiatives in biofuel sustainability, led by the country, private entities, and stakeholder groups, are imperative. This entails establishing sustainability criteria and indicators covering GHG emissions, food security, biodiversity, and impacts on soil and water. Certification schemes and technical guidance should also be implemented to assess and monitor the impacts of bioenergy [106]. Although renewable energy adoption is not yet deeply rooted in the country, the government is poised to launch awareness programs, develop policies and incentives, and create a regulatory environment conducive to the thriving of biofuels in Nigeria [107]. Diversifying energy resources by increasing the share of renewables, accompanied by a reduction in nuclear and fossil fuels in the energy mix, will strengthen electricity security [108].

Promoting biomass energy production in Nigeria

Prospects of Biofuel in Nigeria

The power supply in Nigeria is less than 50% of the installed 13,000 MW capacity generated [107,109]. It was estimated that Nigeria would operate 60 million electric generators, which depend on fossil fuels valued at USD 0.25 billion [109,110]. The challenges outlined earlier make the cost of power generation from fossil fuels high; hence, biofuel might be a viable alternative. It also attracts less political and ethnic attention than fossil fuels [111]. Indicators suggest that biofuel will play a major role in the Nigerian renewable energy sector in the not-so-distant future. The country is endowed with unexploited land, which has attracted substantial investment in sugarcane and cassava plantations (see Appendix Table 7). The production of Cassava as a cash crop is well developed in Nigeria. It has an established processing technique for food products and cattle feed. It has exceptional capacity, adapts easily to climate change, tolerates drought conditions and low soil fertility, and is prone to few pests [112]. Government incentives to grow cassava for interested farmers have overturned about 15 tons of average national cassava per hectare of land [113]. In the last decade, Nigeria has produced over 577.99 MT (Appendix Table 7). This is sufficient for bioethanol production to kick off in the country. Also, studies have shown the development of new methods for cassava-to-bioethanol conversion [114]. Its high starch content makes it a good candidate for high-yield biomass for bioethanol production. The required expertise for the enzyme-aided fermentation process can be obtained locally.

Over 4,00,000 hectares of land that can boost the high yield of sugarcane production are available in rural Nigeria [115,116]. Nigeria, a major consumer of sugar, has a high capacity to cultivate sugarcane, coupled with the incentives coming from the government to encourage the industry [117]. Nigeria has the largest sugarcane refinery in Africa. Also, the bagasse generated after the sugarcane juice is removed is a huge resource for biofuel production. Investing in bioethanol is an attractive venture in energy production. The Nigerian government has also given tax waivers to investors in the sugarcane industry since production has been low in recent years [118].

Nigeria has several plant resources that can be employed as biomass for biofuel. Several unexploited and underutilized plant seeds in Nigeria have been identified and characterized [119]. Oil has been isolated from some of these seeds for biodiesel production [120,121], while cellulose has been isolated and characterized from some [122]. Most of these are classified as waste and underutilized. Examples are soybean and *Jatropha curcas* (jatropha) oils. The potential for these seed oils as biodiesel feedstock is huge in Nigeria. Jatropha oil, unlike soybean, is nonedible; hence, it stands as an advantage as biomass for biodiesel production. Solving Nigeria's waste handling and disposal challenge by finding applications for domestic and industrial waste will go down as a major economic, social, and environmental achievement. Wastes generated can be converted to biomass for biofuel production. The amount of organic waste generated in Nigeria, as reported by Suberu et al. [123] in 2013, is stupendous. Also, about 25 million tons of municipal waste are generated annually in Nigeria, according to Sokan-Adeaga et al. [124]. Similarly, several tons of waste are generated from animal waste in Nigeria. These organic wastes can be employed as biomass for biofuel production.

Barriers impeding the use of biomass for biofuel production and utilization include apathy toward agriculture and farming due to rural-urban migration, poor access to funding for agricultural practices, nomadic herdsmen, the land tenure system, high production costs, poor equipment and technology, food insecurity, a lack of public awareness, weak governmental policies, and competition between food and biomass for biofuel. Bioethanol and biodiesel were identified as the most sustainable biofuel renewable energy sources that can be effectively produced and sustained. Cassava, sugarcane, plant seed, and biomass wastes are feasible sources highlighted as biomass for producing bioethanol and biodiesel in Nigeria.

Existing Policies and Development Needs

There is a consensus in Nigeria that renewable energy can play a significant role in the overall energy development of the nation [94,125]. This was amplified by the Renewable Energy Master Plan (REMP) of the country, developed by the ECN in conjunction with the United Nations Development Programme in November 2005. Generally, the overall objective of the REMP is to articulate the national vision, targets, and a road map for addressing key development challenges facing the country through the accelerated development and exploitation of renewable energy. However, it is worth noting that the capital-intensive nature of biomass technology can deter investment. Further, financing the construction of a biomass plant could be complicated due to the many conversion technologies that are required on a pilot scale [58,126]. In this regard, policies and ways forward are necessary as a starting point. The five major indicators considered in policy developments are as follows:

Economic: This indicator comprises the assessment of the energy system regarding its efficiency, electricity cost, and investment cost. The system's efficiency is to be considered the integral parameter that reflects the system's performance as a thermodynamic system. The electricity cost should represent the total energy cost and thus measure the system's quality. On the other hand, the investment cost should comprise material costs, design costs, and the cost of constructing the system [126].

Political: This refers to the political will and determination of the government of the day in formulating and implementing policies and programs that will lead to the project conception, implementation, and development of biomass-based power production [126].

Environmental: This is the governing parameter in evaluating a given energy system because, among the GHGs, the CO_2 concentration in the flue gases of the power plant is the most important characteristic for the environmental assessment of the energy system [127]. This is because evaluating the concentration of the mixture of gases in a given biomass energy system is of primary interest for the quality assessment of the biomass energy system.

Technological: While the parameters for research and development (R&D) in renewable technology are not delineated, a comprehensive technological indicator should encompass a key component, development capital, gauged by the level of R&D investment directed toward biomass-based power plant development. Also, there is a need for an integrated assessment modeling community and policymakers to develop public R&D strategies [128].

Social: This requires that the social aspect be considered when evaluating power plants, which explains why the indicator is currently becoming very urgent. It considers the following sub-indicators: i) new job opportunity, which comprises the number of jobs to be opened per unit MW; ii) area required and health effect on the surrounding population, which are based on the NO_X concentration in the surrounding power plant [126].

Way forward

In Nigeria, biofuels have been identified as sustainable forms of renewable energy with possible feedstocks such as sugarcane, cassava, plant seed, and waste materials. It has also been noted that the feedstocks are predominantly available and accessible with the possibility of maximizing them to drive socio-economic growth [97]. Valorization of waste materials and non-edible, underutilized seed oil will help minimize the controversies associated with food materials as feedstock for biofuel production in Nigeria and beyond. Nigeria should, therefore, embark on developing its technology to run biofuel production from the currently developed cassava and sugarcane industry. In this regard, it is pertinent to create more awareness of the contributions of biofuel to the energy mix and, at the same time, provide a suitable business environment for local and international investors [97]. Therefore, the following are identified for consideration on the way forward toward a more sustainable growth of bioenergy from biomass in Nigeria:

Strengthening the policy strategies for biomass utilization: The National Energy Policy (NEP) and NEMP should be reviewed to be more. This would involve conducting a thorough evaluation of the available biomass resources within the country; identifying and understanding existing legislative, regulatory, and institutional structures related to biomass utilization; determining suitable technologies for biomass utilization; ensuring compatibility with local conditions; actively engaging and mobilizing relevant stakeholders to foster collaboration and shared responsibility; implementing initiatives for the development of expertise and skills necessary for effective biomass utilization; evaluating the existing capacities, both institutional and technical, required for successful biomass utilization; conducting awareness programs to educate and inform stakeholders about the benefits and processes of biomass utilization; establishing clear and achievable national targets for biomass utilization, accompanied by realistic timeframes; fostering collaboration at regional and international levels to leverage expertise, resources, and best practices; and ensuring alignment and harmonization of biomass utilization policies with other sectorial policies and global processes [129,130].

Assessment of the availability of biomass resources in Nigeria: This involves assessing the biomass resource base, which involves the natural resource management structure, planted forests, forest residues, agro-energy crops, agricultural residues, any other biodegradable wastes, and municipal solid and liquid wastes in the country and their potential. It will include the assessment of current trends in the consumption and penetration of conversion technologies for biomass resources in the country [130]. See Appendix Table 7 for the production yield of some selected biomass feedstocks.

Identification of existing legislative, regulatory, and institutional frameworks: This program component aims to help scale up the sustainable use of biomass as a key component of energy strategies. When developing the biomass policy, it is necessary to consider any existing laws or policy decisions that the country may have made in order to avoid conflict and duplication. It is noteworthy that current regulations aim to lessen reliance on fossil fuels and support rural population growth and livelihoods without compromising food security. As part of the policy design strategies, other regulations that should be taken into consideration include specific biofuel blending, particularly those that pertain to the production, use, and promotion of biomass [131].

Identification and development of appropriate technologies: In order to achieve the goals of the biomass development policy, it is necessary to develop both the technical and human capacities as well as the available resources. Therefore, the conversion technologies should be identified for the most efficient utilization of biomass resources. Among the technologies may include improved wood stoves, gasification (biomass combustion for heat and power), biodigesters, and pyrolysis of wastes, among others [132,133].

Stakeholders' involvement and mobilization: This helps in designing a biomass policy that will reflect and address the nation's priorities; thus, there is a need to follow a multi-stakeholder approach to help identify and address the risks, including different interests and concerns, to achieve the benefits anticipated. The way it will be implemented-that is, the individuals involved and the procedure to be followed-determines the stakeholder's effectiveness. A few of the major players would be i) central government agencies (MDAs) dealing with energy; ii) state and local government representatives; iii) labor and trade organizations; iv) the private sector (producers, distributors, and users of biomass); v) providers of bio-energy facilities; vi) producers of bio-energy technologies; and vii) financial institutions (banks and finance institutions), keeping in mind bilateral and multilateral organizations.

Capacity development: These make sure the necessary knowledge is available because, in most situations, the degree of training and skills obtained dictates the future performance standards. Because they concentrate on people, institutions, and systems and demonstrate a long-term commitment, this activity is directed toward public, private, and non-governmental organizations. The United Nations Economic Commission for Africa has recommended a number of activities, some of which are as follows: i) assisting businesses in sourcing, integrating, installing, operating, maintaining, and servicing bioenergy systems; ii) educating policymakers about policies and programs for small landholders to accelerate the adoption of bioenergy; and iii) educating senior management and loan officers in the financial and banking sectors about the benefits and risks of financing biomass-based projects through pilot projects and programs that minimize initial investment risks [131]. This process ensures that the right people, who possess the required skills, are in place to drive the entire process.

Assessment and identification of institutional and technical capacities: Although many agencies of government have been working on various areas of biomass development, it is only the ECN that is entrusted with the responsibility to produce the policy on energy and all its ramifications; however, it is expected to involve other stakeholders who have the technical capacities [130]. However, to design a good policy, it is important for the country to also look beyond its borders to benefit from lessons learned from other countries within and outside its region, which would greatly benefit the country.

Sensitization and awareness creation of stakeholders: Although the utilization of traditional biomass by the rural and urban poor settlements has contributed a higher percentage of the total primary energy in the country, the potential for modern biomass energy is unknown to a greater percentage of the population. This is because of the poor awareness and sensitization of the country's modern technologies, including foreign markets. Due to the non-recognition of resources like agro-processing residues and urban waste, they are burned in open fields as a way to avoid disposal costs. In this regard, some of the tools that can be used to attract the attention and raise the awareness and eventual interest of the actors (producers, users, investors, financial and political actors) in agro-processing residuals and urban waste as sources of energy may include the national consultation process, workshops and discussions, dissemination of relevant publications, and media campaigns [130].

Setting of national targets with timeframes: Targets for biomass development based on needs, possibilities, and available implementation capacities and incentives will need to be set. The targets must be spread into short, medium, and long terms in line with the national priorities and visions [130].

Involvement of regional and international cooperation: Since biomass production, trade, and use transcend national borders, policies to be set may become ineffective when they are not broadly supported at regional levels. In this regard, biomass energy sector modernization and rationalization cannot be successfully implemented in Nigeria alone without considering the neighboring countries' best practices. In this regard, it is important to note that policy coherence and long-term effects are best realized in regional contexts [130].

Harmonization with other sectoral policies and global processes: Biomass policy should be integral to an overall national energy policy and thus should not be standalone. This implies that it should be an integral part of the agro-industrial development and transport sector strategies, which are part of the national development strategy (macroeconomic and sectoral). In this regard, it is important and necessary to be abreast of the provisions of other sectoral policies relating to energy and biomass, in particular, when designing biomass policies [130].

R&D: Strengthening R&D in Nigeria is important to developing cutting-edge solutions that will deploy valorized biomass. Many underutilized biomass wastes are yet to be identified and characterized for potential biofuel feedstocks, technology development, equipment development, testing facilities, and safety.

Mobilizing investments and credit facilities for adoption of technologies: It is critical to attract financial resources and facilitate their deployment toward biomass projects. The government should enact policies and regulations to create an enabling business environment for biomass energy investment. This will increase investors confidence. It could be in the form of subsidies, tax breaks, and feed-in tariffs for bioenergy projects. Financing mechanisms tailored to biomass energy projects, such as venture capital, project finance, and PPP, should be developed. To provide credit facilities and funding for biomass valuation for energy initiatives, development finance institutions, commercial banks, and international donors such as the World Bank, African Development Bank, Green Climate Fund, and Global Environment Facility should be contacted. To further drive the advancement of rural electrification in Nigeria, we must establish pilot bioenergy plants in each LGA. These will serve as demonstration and training centers, showcasing the potential of bioenergy to power mini-off-grid electricity systems for rural communities. It will further demonstrate the viability of bioenergy, build local capacity, and create a scalable model for broader implementation. Funding can be secured through PPP arrangements, leveraging the strengths and resources of both the public and private sectors.

It can be concluded that there is a need for a comprehensively integrated policy together with a vigorous implementation strategy to facilitate the rapid diffusion of renewable energy in the country's energy mix. The existing flow of information on renewable energy technologies is inadequate, despite the wide establishment of demonstration projects on various energy forms to exhibit the performance and efficiency with which services are delivered. Such projects are likely to sensitize the public and assist in creating markets for renewable energy. Further, there is a need for capacity building at institutional and personnel levels to help identify and acquire the technical, organizational, and managerial skills required for the increased development of renewable energy. In this regard, activities relating to entrepreneurship and managerial skills development training programs and technical courses in renewable energy technologies can be established. These will be used to identify and nurture energy service companies to provide services to rural areas. Lastly, the current R&D centers and technology development institutions must be adequately strengthened to support the shift toward increased renewable energy utilization [134].

Conclusions

The transformation of Nigeria's energy landscape from fossil fuels to biofuels hinges on two critical factors: i) identifying technological gaps across all economic sectors; and ii) prioritizing sustainability in energy generation and utilization policies. Determining the technology required for biomass conversion requires deciding on a primary energy source. To match technological innovation with capacity-building programs, a thorough analysis of the pathways by which biomass decomposes is necessary. The chosen policy and management approach must consider environmental concerns, energy decentralization, and resource availability for project success. Selecting an optimal location involves evaluating feedstock quantity and type, solar intensity, refining facility proximity, and technological transfer, with a preference for areas displaying co-processing potential. The land tenure system, high production costs, ineffective government policies, and competition between the production of food and feedstock for biofuels are some of the obstacles preventing the development of biofuels. To address these issues, more research must be done on sustainable bioenergy alternatives like bioethanol and biodiesel, which are made from cassava, sugarcane, and other easily accessible resources.

With the demand for clean energy rising worldwide, diversifying into biofuels is essential. By paying attention to waste management, socioeconomic growth can be facilitated by the abundance of biomass resources. Developing indigenous technology for biofuel generation from established industries like cassava and sugarcane is essential. Government-led awareness campaigns and a conducive business environment for investors, supported by cost recovery policies, are imperative. Infrastructure improvements, such as north-south rail lines, can facilitate biomass transportation for processing. The initial technology can be sourced globally, with local capacity gradually established. A phased introduction of biofuels into the energy mix ensures a sustainable transition. Nigeria urgently needs alternative energy sources, particularly in the northern region, to address the energy gap and reduce costs associated with energy transportation. Energy decentralization between the north and south is essential, with renewable energy offering a viable solution. Government commitment to renewable energy sustainability, policy realignment, and legislative support are crucial. Transporting biomass can be made easier with solar-biomass pyrolysis technology and newly planned rail lines. The gradual and sustainable blending of biofuels into the national energy mix is the key to a successful transition.

Recommendations

Provide a legal framework, ensure feedstock availability, and implement the necessary technology to produce fuel from biomass sustainably.

To identify technology gaps and develop policies that prioritize sustainability in the generation and use of energy, encourage collaboration across sectors.

Focus on solar-pyrolysis technology due to its versatility in processing biomolecules and producing various energy carriers.

Take into account resource availability, energy decentralization, and environmental concerns when developing policy and management strategies.

Evaluate feedstock quantity, solar intensity, refining facility proximity, and technological transfer when investing in biomass conversion technology.

In each of Nigeria's 774 LGAs, set up small-scale off-grid power systems and pilot biomass plants as training and demonstration facilities for expanding biomass electricity for rural populations.

Appendices

Year	Cashew nuts, in shell			Cassava, fresh			Cocoa beans			Coconuts, in shell			Cow peas, dry			Maize (corn)			Oil palm fru
	Area harvested (Mha)	Yield (0.1 g/ha)	Production (Mt)	Area harvested (Mha)	Yield (0.1 g/ha)	Production (Mt)	Area harvested (Mha)	Yield (0.1 g/ha)	Production (Mt)	Area harvested (Mha)	Yield (0.1 g/ha)	Production (Mt)	Area harvested (Mha)	Yield (0.1 g/ha)	Production (Mt)	Area harvested (Mha)	Yield (0.1 g/ha)	Production (Mt)	Area harvested (Mha)
2013	0.17	11.42	0.19	6.74	70.32	47.41	1.24	2.96	0.37	0.04	68.22	0.27	3.59	12.89	4.63	5.76	14.62	8.42	3
2014	0.13	7.83	0.1	7.1	76.55	54.32	1.14	2.88	0.33	0.04	68.76	0.27	3.7	5.78	2.14	6.35	17	10.79	3.11
2015	0.13	7.39	0.1	7.9	72.66	57.41	1.06	2.86	0.3	0.03	70.3	0.21	3.64	6.34	2.31	5.55	17.19	9.54	3.23
2016	0.13	7.42	0.1	6.67	90.76	60.53	1.05	2.84	0.3	0.03	71.9	0.23	4.81	7.79	3.75	5.9	17.84	10.53	3.31
2017	0.14	7.14	0.1	6.76	90.74	61.35	0.89	2.8	0.25	0.03	73.49	0.23	5.01	7.74	3.87	6.39	16.64	10.63	3.55
2018	0.14	7.14	0.1	6.95	94.04	65.35	0.95	2.84	0.27	0.03	75.09	0.23	4.55	8.25	3.75	6.54	16.72	10.93	3.74
2019	0.14	7.25	0.1	9.78	58.27	56.97	0.88	2.83	0.25	0.03	76.8	0.23	4.55	8.35	3.8	6.8	18.51	12.6	3.77
2020	0.17	5.49	0.09	9.61	57.8	55.57	1.19	3.01	0.36	0.03	77.49	0.23	4.97	8.31	4.13	6.05	20.51	12.4	3.89
2021	0.19	4.33	0.08	9.98	58.36	58.24	1	2.79	0.28	0.03	78.55	0.23	5.04	8.36	4.21	6.21	20.54	12.74	4.86
2022	0.15	5.12	0.07	10.03	60.66	60.84	1.02	2.74	0.28	0.03	79.61	0.23	4.78	8.65	4.13	5.8	22.33	12.95	4.91
Average			0.103			57.799			0.299			0.236			3.672			11.153	
Total	1.49	70.53	1.03	81.52	730.16	577.99	10.42	28.55	2.99	0.32	740.21	2.36	44.64	82.46	36.72	61.35	181.9	111.53	37.37

TABLE 7: Crop Production and Harvested Areas of Some Energy Crops in Nigeria

Additional Information

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