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Biomass Resources and Energy Access in Nigeria: A Scoping Review

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Abstract:
Nigeria, commonly known as the "giant of Africa," has a large population and abundant energy resources, yet is facing epileptic power supply challenges. This thesis explores the potential of biomass resources in addressing the country's limited electricity supply and energy access challenges, focusing on agricultural residues, municipal solid waste, livestock waste, and forest residues. The study adopts a scoping review method using the 2018 PRISMA-ScR extension as a guideline to assess the current potential of biomass resource utilization. It examines the potential, major trends driving the field. Findings reveal that Nigeria's biomass resources could significantly contribute to electricity generation. Major cities identified could potentially generate between 0.4 – 15.36 billion GWh of energy annually, which can generate a substantial amount of electricity. If properly managed, total city waste could generate approximately 20,378 metric tonnes daily. Additionally, based on 2022 data, popular commodity crops in Nigeria can yield an annual substantial estimate of 2,918.50 million metric tonnes of biomass suitable for power generation, which translates to 3.391 million GWh energy potential with livestock waste offering further energy potential of 950.53 thousand metric tonnes, which translates to 263,889 MWh and 0.26 GWh energy potential. However, challenges such as policy gaps, infrastructure limitations, limited funding, market barriers and appropriate technology currently constrain the full exploitation of bioenergy adoption. The review findings provide suggestive evidence for stakeholders and policymakers in diversifying Nigeria's electric power generation through best practices. Despite study findings, there is a need for conducting further research that could exhaustively quantify biomass resources and pave the way for facilitating strategic bioenergy infrastructure development and optimal biomass resource logistics.

Acknowledgement

I would like to express my sincere gratitude to everyone who as contributed to the completion of my master's program, my family and friends, for their unwavering support and encouragement throughout this journey. I am especially grateful to the University of Helsinki for granting me a half tuition fee waiver, which has been instrumental in enabling me to complete my studies. Special thanks to my supervisors, Kari Hyytiäinen, University of Helsinki and Chigozie Nweke-Eze, University of Bonn, for their valuable time, patience and guidance in making this project successful. I equally appreciate the Department of Economics and Management for the technical and social support rendered. Without all these, focusing on and achieving my academic goals would not have been possible. Thank you to all who have been part of this journey; your contributions have been invaluable.

Acronyms

AR: Agriculture Residue

AW: Animal Waste

BRE: Biomass resource assessment and electricity access

BT: Biomass conversion technologies

ECC: Environmental Impact and Climate Change

FAO: United Nations Food and Agricultural Organization

LR: Livestock Residue

MSW: Municipal Solid Waste

NDC: Nationally Determined Contribution

NZE: Net Zero Emissions

OECD: Organization for Economic Cooperation and Development

PCC: Population, Concept and Context

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

PSC: Policy and socio-economic considerations

GEA: Global Energy Assessment

MWh: Megawatt-hour (a unit of energy)

RPRs: Residual-to-Product Ratios

GWh: Gigawatt-hour (a unit of energy)

PJ: Petajoule (a unit of energy)

Tg: Teregram (a unit of mass)

MT: Metric Ton (a unit of mass)

MTOE: Megatonne of Oil Equivalent

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1 Introduction, Background and Aim of Study

1.1 Introduction

Energy Access is fundamental to a nation's advancement. A limited energy supply hinders economic progress, constrains socio-economic activities, and negatively impacts the overall standard of living. There has been significant progress globally in adopting renewable sources in recent decades. However, many countries in Sub-Sahara Africa are still at an introductory level in terms of bioenergy renewable penetration (Warner & Jones, 2017). Developing countries like Kenya and India, have looked to renewable energy solutions as a successful approach to addressing the increasing energy needs of their people. There is no universally accepted definition of modern energy access. The International Energy Agency (IEA) defines it as reliable and affordable access to clean cooking facilities and enough electricity to meet basic household needs, with the expectation that this supply will grow to match regional averages over time. This definition serves as a benchmark for measuring progress towards Sustainable Development Goal (SDG) 7[1] and for guiding future analyses. However, it primarily focuses on households and does not account for electricity access for businesses and public buildings, such as schools and hospitals, which are essential for economic and social development (IEA, 2022). To improve energy access, developing countries need to fully utilize renewable energy alternatives. In Nigeria, leveraging abundant biomass resources could significantly increase electricity supply and enhance economic performance in rural areas. For this study, energy access is therefore considered electricity availability, that is, the availability of reliable electricity.

1.2 Background and Rationale

Nigeria, Africa's most populous nation and leading petroleum producer faces a paradox where abundant energy resources coexist with widespread energy scarcity (Jekayinfa et al., 2020a). Despite having significant reserves of oil, natural gas, coal (which releases large amounts of greenhouse gases and is not enough to generate electricity) and potential renewable energy sources, the country struggles with ensuring access to energy and electricity, which is crucial for its socioeconomic progress (Oyedepo, 2012).

[1] SDG 7: Ensure access to affordable, reliable, sustainable and modern energy for all

Despite the abundance of renewable energy resources in Nigeria, most have yet to be utilized (Ojolo et al., 2012).

Figure 1 shows the total energy production in Nigeria from various sources for the year 2022, while *Figure 2* shows the share of electricity production from renewables - solar, wind and hydro and the (Ember, 2024; IEA, 2024). Fossil fuels account for 75% of Nigeria's total energy production, with the remaining 25% coming from renewables. Bioenergy, solar, wind, and hydropower electricity reached 61 GWh, 101 GWh, 3 GWh, and 9204 GWh, respectively. While these figures show a notable increase compared to the previous year, electricity from bioenergy and wind production remains relatively low.

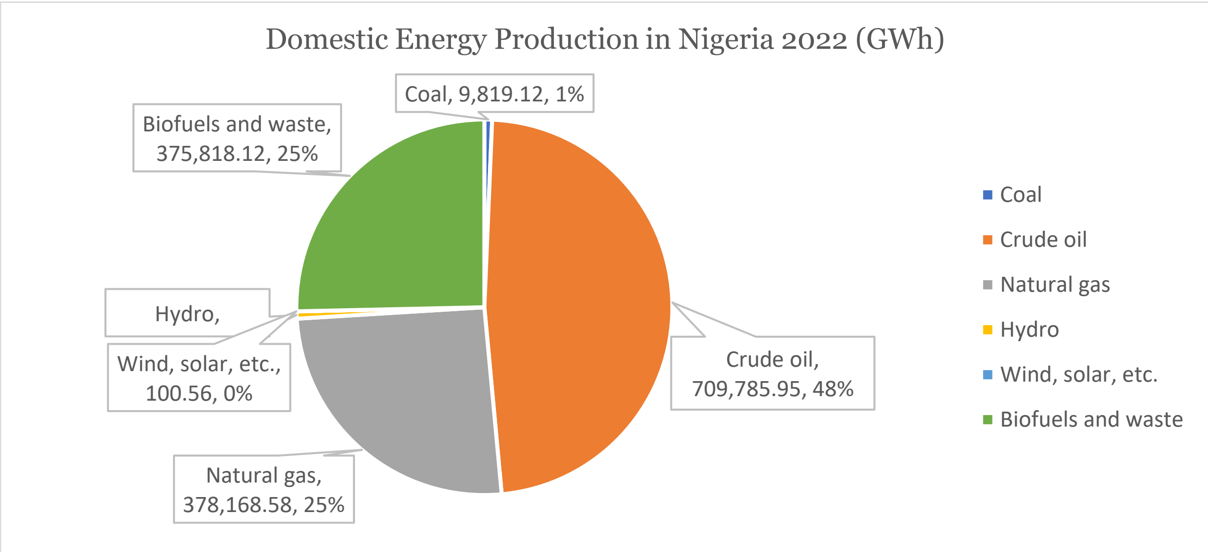

Figure 1. *Current energy production (GWh) from renewables and non-renewables. Source: IEA, 2022*

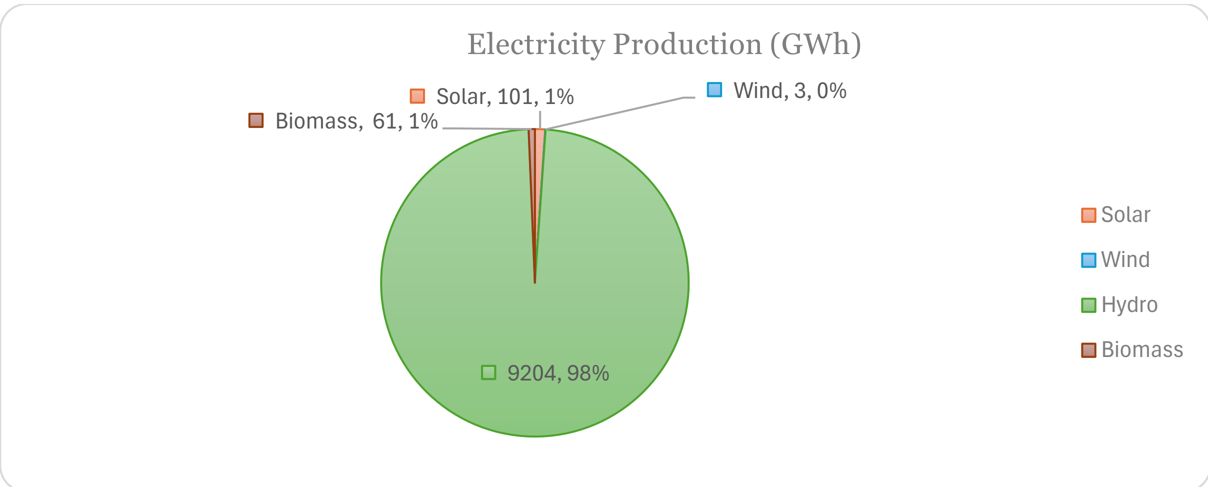

Figure 2. *Current electricity production (GWh) from RE source in Nigeria. Source: IEA, 2022; IRENA, 2023; Statista and Ember, 2022 1306870.*

Recent studies show that biomass energy potential is huge, to the tune of 2.33 EJ (647,222 GWh), with agricultural residues, animal wastes, and forest residues being the major contributors (Jekayinfa et al., 2020b; Ugwu et al., 2022). This implies that about 99.9% of biomass energy potential is still untapped. The contribution of bioenergy to electricity production in the country has consistently ranged between 20 and 61 GWh. It is anticipated that the energy potential will continue to increase and could potentially reach 29.8 EJ (8277778 GWh) by 2050 (IRENA, 2023).

Over the years, Nigeria has seen changes in electricity demand due to population growth, urbanisation, and technological advancements. Since 2000, Nigeria's electricity demand has increased by 122.72% (Ember, 2024; IEA, 2022). The trend in *Figure 3* shows that domestic electricity production is consistently higher than electricity supply with continuously rising electricity demand. This is because part of the production is exported to neighbouring countries – Niger Republic, Benin Republic and Togo, based on an existing multilateral agreement between Nigeria and the countries for the supply of electricity (Daily, 2017; Vanguard, 2020). Electricity demand experienced a significant reduction between 2018 and 2020. This decline is partly attributable to the total collapse of the electricity sector recorded in 2017. During this period, Nigeria was ranked the second worst nation in terms of electricity supply reliability, with power availability dropping to 3,851 MW due to insufficient gas supply, inadequate distribution and transmission infrastructure, and low water reserves. Some studies highlight that drivers of electricity consumption include population, per capita income, and grid failures/electricity shortages (Onisanwa & Adaji, 2020). The sharp decline in electricity demand between 2017 and 2018 can be closely linked to these factors. Specifically, during this time, the country saw a negative growth in per capita income, from -1% to -4%, which likely contributed to reduced electricity consumption. Additionally, a significant portion of the population continues to lack access to electricity, and frequent falls of the national grid exacerbated the situation. This period of negative economic growth and persistent infrastructure challenges resulted in a notable drop in electricity demand.

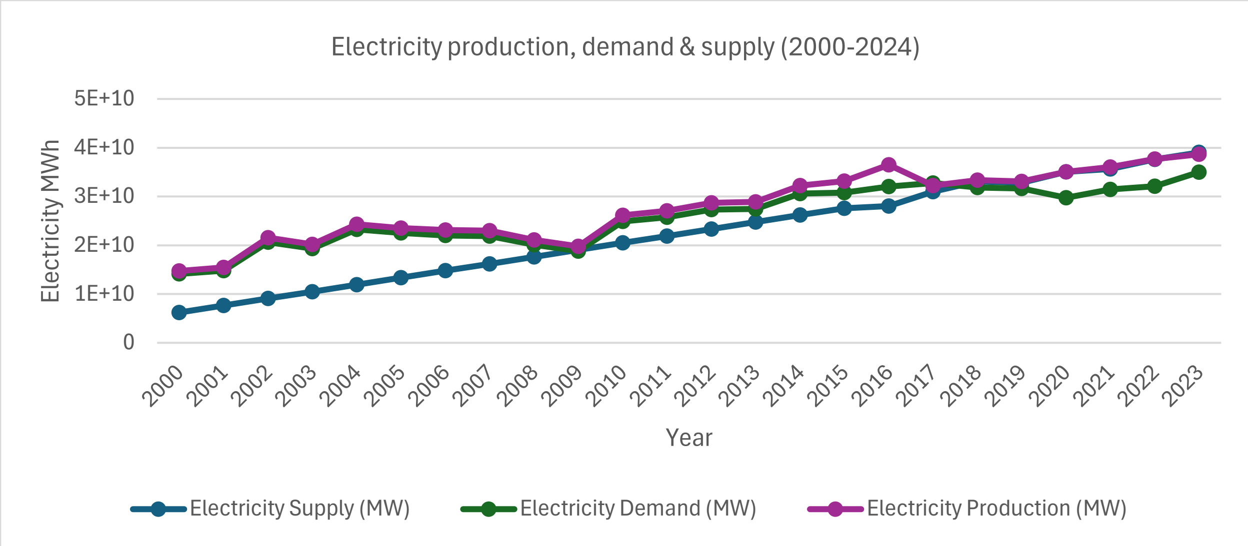

Figure 1. *Chart of Electricity Trend Based on Statista 1294934 ; ember-climate.org 1306955 & National Bureau of Statistics (NBS) 2024.*
Nb: Domestic production is consistently higher than domestic supply because some of the production is exported to several neighbouring countries based on multilateral agreements between the countries and Nigeria. (Daily, 2017; Vanguard, 2020).

Further reports from the National Bureau of Statistics (NBS) show that in 2022, Nigeria's electricity demand exceeded 32,000 GWh, marking an increase of 1,730 GWh compared to the previous year. This represents an upward trend from 2020. Between 2000 and 2010, the demand remained steady, but it has been increasing annually from then until 2017. However, in 2020, just over half of Nigeria's population still lacked access to electricity. On the other hand, electricity supply amounted to 8,890 GWh, which was lower than approximately 9,490 GWh supplied in the same period in 2020 (Ember, 2024). This reflects a slight increase from the previous quarter's 5,611 GWh but a year-on-year decline of 1.74% of 5,956 GWh in Q1 2022 (National Bureau of Statistics, 2023).

As a result of rapid population growth and persistent decrease in electricity supply, many people use costly and polluting generators as a backup (Ezealigo et al., 2021). Between 2021, around 23,000 GWh of electricity were produced from this fossil fuel and in 2022, nearly half of the electricity demand was met by diesel and petrol generators, resulting in significant pollution and health concerns (Stears and Sterling, 2022). It is evident that the electricity supply shortage in Nigeria is quite substantial, with a deficit of approximately 194,148 GWh, which is about 97.1% of the estimated demand of 200,000 GWh per quarter (National Bureau of Statistics, 2023). This shortage has extensive economic repercussions, such as impeding industrial expansion, diminishing productivity, and raising operational expenses. Residential consumers also face frequent power outages and strain on the existing grid infrastructure. The factors contributing to this shortfall include issues with power generation capacity and transmission and distribution bottlenecks. Financial constraints, regulatory and policy issues, operational problems, limited transmission grid capacity, technical and non-technical losses, financial constraints, and inadequate tariffs also add to the challenges (Ezealigo et al., 2021).

To bridge the electricity supply-demand gap and reduce the country's CO2 emissions, there is a need to expand the energy mix by harnessing the abundant biomass resources and bioenergy to improve energy and electricity access nationwide. This would lead to technological progress towards a green and carbon-neutral economy for the country. Bioenergy stands out as the most important renewable energy option, available today and in the near- and long-term future. Statistics shows that 77.8% of Nigeria's land mass is available for biomass energy production (Ugwu et al., 2022), but it is very much less utilized for energy generation. Therefore, it must prioritize the use of renewable energy, including bioenergy, to successfully achieve its nationally determined target (Anyaoha & Zhang, 2021)

Electricity generated from materials of biological origin (biomass) is called bioenergy power or, put simply, biopower. Biomass is defined as the mass of live or dead renewable organic matter derived from plants and animals (Ben-Iwo et al., 2016a; FAO, 2009). It is considered a clean renewable energy source for several reasons – because its initial energy comes from the sun, i.e., the ability to store chemical energy from the sun, which is generated by plants during photosynthesis, renewability potential, carbon neutrality and waste utilization, among its many other benefit. Biomass can be used in many ways viz electricity generation, heating and cooling and fuel. It can be transformed into liquid and gaseous fuels through different methods such as thermochemical, biochemical, and mechanical processes (Perea-Moreno et al., 2019). Figure 4 shows the different varieties of biomass sources (Raina Shubhamand Singh, 2022). The energy generated from the various sources translates to biofuel, biogas, bioethanol and biodiesel, which is used to create electricity, heat and transport fuel (Carneiro & Ferreira, 2012a), showing the diverse usage of bioenergy potential in biomass.

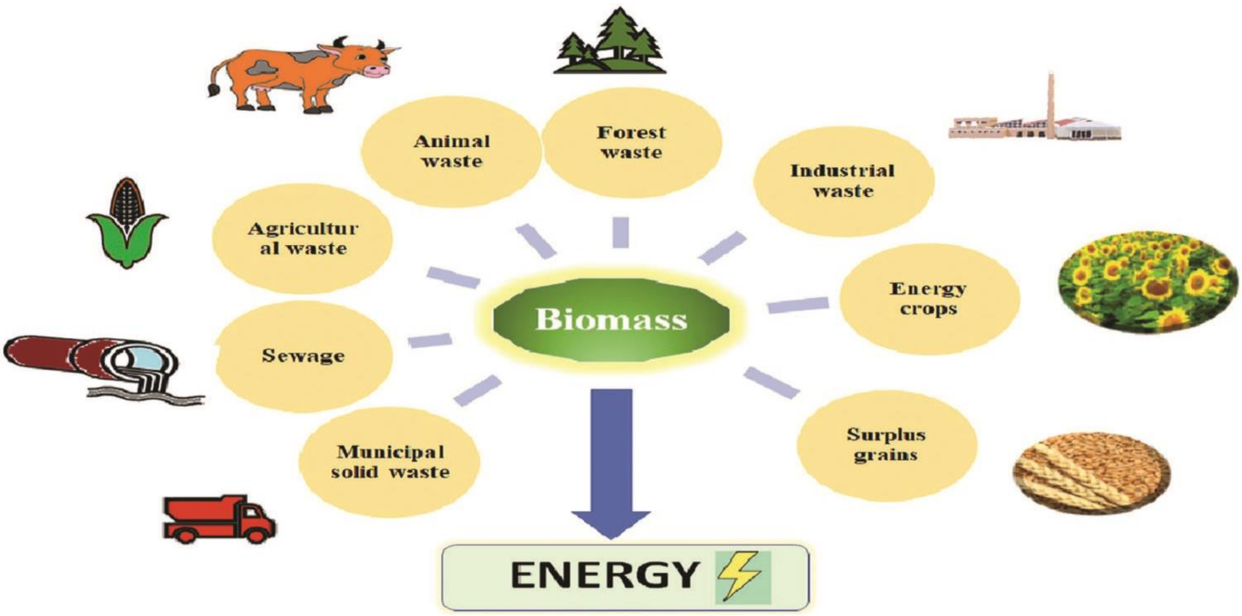

Figure 2. *Classification of different sources of biomass* (Raina Shubhamand Singh, 2022). Reprinted with Springer's approval (Order number: 501916065)

1.3 Current state of bioenergy production in Nigeria

Since the inception of the Nigerian Biofuel Policy and Incentive (NBPI) in 2007, which was aimed at creating a favourable investment climate and ushering the country into the bioenergy sector, the expected progress has not been made. The Nigeria National Petroleum Corporation (NNPC) was tasked with leading the policy implementation. Despite initial plans and investments, progress in the bioenergy sector has been slow. Over $3.86 billion was invested in the construction of 19 ethanol biorefineries, 10,000 units of mini-refineries, and feedstock plantations to produce over 2.66 billion litres of fuel-grade ethanol annually. Additionally, 20 biofuel projects were introduced, of which four are still in the conception stage, eight in the planning stage, seven are under construction and only one is currently in operation (Ohimain, 2010, 2013), the actualisation of biofuels has not come to fruition.

In 2011, the Nigeria Export and Import Bank (NEXIM) provided loans to some companies to commence commercial production of the biofuel projects (Ben-Iwo et al., 2016a). Prior to the biofuel policy, biogas research was initiated in the 80's, and pilot-scaled research has continued since then, leading to the establishment of several biogas plants with capacity 10-20m^3 (Akinbomi et al., 2014). Some Nigerian universities also embarked biogas projects through the construction of biogas digesters (Umar et al.,

2021) and introduction of low technology biogas project by in internation NGOs (Babalola & Oyedepo, 2019). Until mid-2024, bioenergy's contribution to electricity production in the country consistently remained between 10 and 20 GWh.

However, recent updates now show an adjusted increase to 61 GWh (Ember-climate, 2024). This is attributed to the limited progress made so far, with bioethanol, biodiesel and biogas being the major biofuels proposed for transportation and indoor combustion (Ben-Iwo et al., 2016a). Among these, biogas appears more feasible at the industry level compared to biodiesel which is still under investigation. Despite the vast potential for waste-to-energy conversion, Nigeria continues to rely heavily on hydropower for electricity, missing opportunities to harness the significant amount of waste that could provide energy for both urban and rural communities.

On a global scale, biomass energy has grown rapidly in recent years (Cao et al., 2015). Modern bioenergy is the leading renewable energy source globally, making up 55% of renewable energy and over 6% of global energy supply (IEA, 2023). The Net Zero Emissions by 2050 (NZE) Scenario predicts a significant growth in bioenergy use to replace fossil fuels by 2040. Many countries are fully harnessing the potential of their biomass resource for electricity generation. Finland is at the forefront of embracing bioenergy, with a substantial portion of its renewable energy mix coming from bioenergy sources (Ranta et al., 2021). A key reason for this is that Finland's strong forest industry, which not only contributes to the economy but produces significant by-products such as wood chips and sawdust suitable for bioenergy production and efficiently utilized for both heat and electricity generation (Cao et al., 2015), further reinforcing Finland's leadership in renewable energy. Current statistics show that Asia leads in biomass electricity generation with nearly 276,000 GWh, followed by Europe with around 238,000 GWh. While America produced approximately 164,000 GWh, Oceania contributed about 4,000 GWh, and Africa generated roughly 2,000 GWh (IEA, 2022).

In 2020, global electricity generation from biomass reached 685,000 GWh as seen in *Figure 5*. Of this total, 69% was produced from solid biomass sources, 17% from municipal and industrial waste, and 13% from biogas (World Bioenergy Association, 2023).

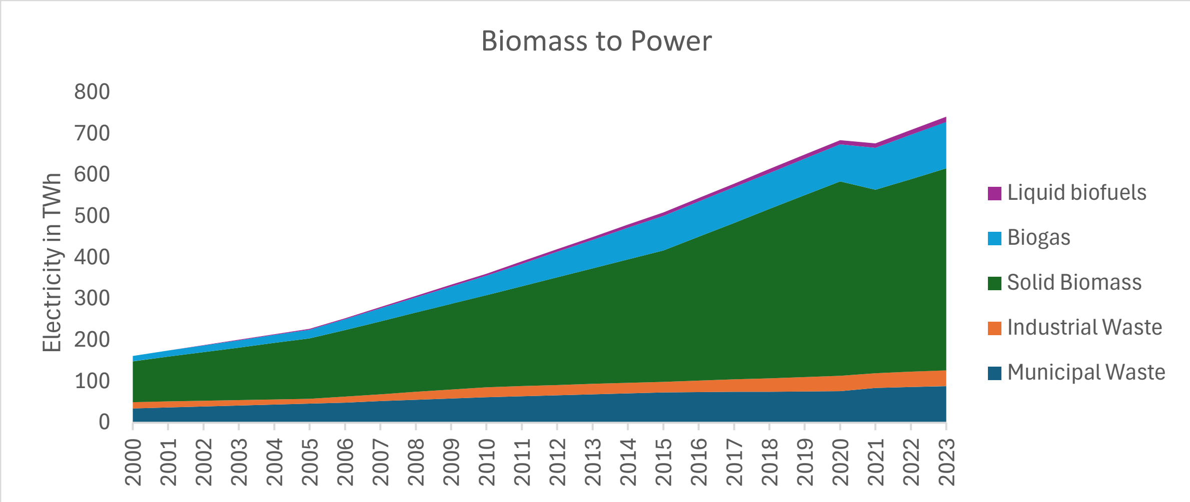

Figure 5. *Global Biomass Electricity generation. Source(s): IEA, World Bioenergy Association 2000-2020.*

Statistics indicate that 77.8% of Nigeria's land mass is available for biomass energy production (Ugwu et al., 2022). Based on the 2023 report from the Food and Agriculture Organization (FAO), Nigeria's total land area is estimated to be 92.3 million hectares, with approximately 70.8 million hectares dedicated to agricultural purposes. Several studies also reveal that Nigeria can boast about 11 million hectares of forest and woodland reserves, approximately 245 million livestock animals, and around 28.2 million hectares of arable land (Jekayinfa et al., 2020a; Ogueri, 2015; Ugwu et al., 2022) , with density of solid waste ranging from 250 kg/m3 to 370 kg/m3, higher than solid waste densities found in developed countries (Chibueze Ogwueleka, 2009; Harir et al., 2015). Additionally, about 227, 500 tons of animal wastes produced per day (Vincent-Akpu, 2012). With these figures, the nation can produce about 1.2 million tonnes of biomass resource daily (Carneiro & Ferreira, 2012). and about 144 million tonnes yearly (Shaaban & Petinrin, 2014).

In contrast to most developed countries like Finland, Sweden and Denmark, where economic success is often linked to the use of biomass resources for electricity and heat-enhancing their energy security and reducing greenhouse gas emissions (Carneiro & Ferreira, 2012b; Lian et al., 2022), Nigeria's biomass is predominantly used in rural areas. *Figure 6* illustrates the trend in electricity generation from bioenergy in Nigeria from 2000 to 2022. While electricity from bioenergy production remained relatively stable between 10-30 GWh during the early 2000s, there has been a noticeable increase since 2018, with production reaching approximately 61 GWh in 2022 (Ember; IRENA, 2024). This upward trend indicates some progress in bioenergy utilization, though significant potential remains untapped.

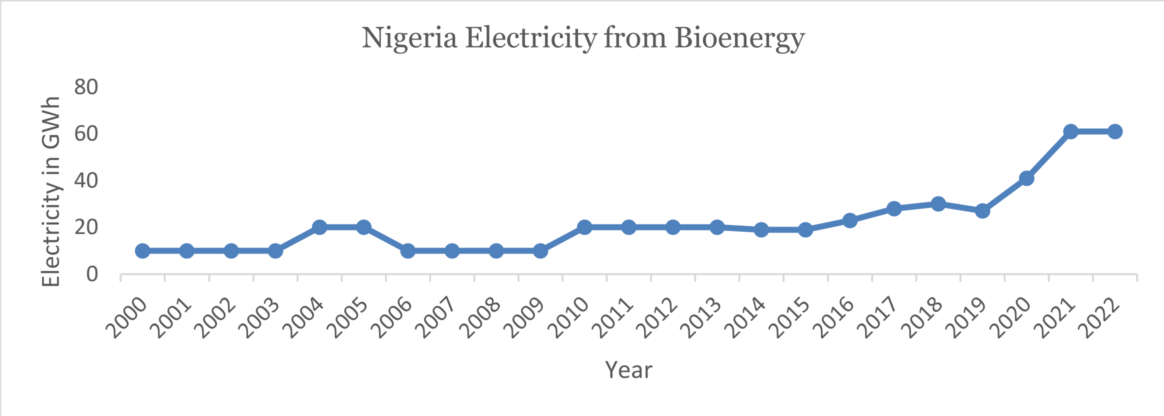

Figure 6. *Electricity Production Bioenergy 2000-2023. Source: IRENA 1306870; ember-climate.org 1306870*

Although there have been some impacts on increasing access to available and sustainable electricity through different projects implemented by international development cooperation agencies, these interventions majorly focus on solar and wind resources.

To achieve long-term economic and environmental sustainability, Nigeria needs to diversify its energy mix and assign a larger role to bioenergy. Biomass by-products, which include urban and industrial wastes, are a significant problem in Africa due to poor management, posing serious urban and environmental public health issues (Ogwo et al., 2012). However, recovering energy and other resources from these wastes can transform the situation, turning an environmental problem into a valuable asset for socioeconomic development and poverty alleviation (Hasan et al., 2021) and solving the issue of epileptic electricity in the country.

1.4 Objectives of Study

Given this context, the objective of the study is to assess the potential of biomass for bioenergy in addressing energy and electricity challenges in Nigeria and propose suitable solutions. The biomass resource will be focused on non-edible sources categorized under second-generation biofuels, thereby making them a more sustainable option. It adopts a scoping review methodology to answer the following questions.

1. What is the current potential for bioenergy generation from biomass resources in Nigeria, and how has the utilization of biomass resources for electricity evolved over time?

2. What are the major research themes and trends in biomass and bioenergy in generating electricity in Nigeria?

3. To what extent are biomass-based power technologies are feasible for electricity generation in small-scale settings in Nigeria, and what factors are essential for assessing their use considering economic and environmental impact?

The research questions are addressed comprehensively throughout the thesis. Chapter 2 discusses the materials and method for the scoping review, followed by Chapter 3, which discusses the results and output from the review. Chapter 4 dwells on discussion, summary of evidence, limitations, identification and introduction of future study areas, and conclusion.

2 Materials and Methods

This section introduces the conceptual framework for this study, which is grounded in two theories: natural resource governance and energy transition to combat climate change. It is then followed by the methods for the scoping review work.

2.1 Natural Resource Governance (NRG)

Natural resource has a crucial role to play in renewable energy development (Hackett & Dissanayake, 2011) and effective governance is essential in this sector (Nchofoung & Ojong, 2023). Limited progress in renewable energy development within a country is often linked to its governance structure, which influences regulatory and business policies and shapes the direction of investment (Li et al., 2022; Liu et al., 2021). Natural resource governance provides a framework for managing natural resources in a way that promotes sustainability, fairness and equitable distribution of benefit (Springer et al., 2021). For Nigeria, which has abundant biomass resources, efficient resource management can support the transition to a clean energy future and provide a foundation for bioenergy projects that prioritize local benefit, align with sustainability goals, and reduce the country's dependency on fossil fuels.

2.2 Energy transition theory

Carbon emissions are the leading cause of global climate change and a serious threat to sustainable development (Wu et al., 2018). Energy transition theory is a critical framework for understanding the shift from high-carbon to low-carbon energy systems, a process essential for mitigating climate change and fostering sustainable development (Riahi et al., 2007, 2012). This theory provides a lens through which societies can understand the necessary technological, economic, and policy changes to achieve a cleaner energy future (Messner & Schrattenholzer, 2000; Riahi et al., 2007).

2.3 Governing energy transition resources

Transitioning to sustainable energy resources requires a framework that balances economic growth with environmental stewardship. As economic activities increase, awareness of environmental impact grows, and government can implement strategies to combat climate change. Governance here means setting policies that enable bioenergy projects to proceed sustainably, ensuring equitable access to energy, supporting job creation, and mitigating any negative environmental impacts. A framework that combines natural resource governance with pathways for energy transitions supports a responsible, inclusive, and effective transition to bioenergy in Nigeria. The schematic diagram in *Figure 7* illustrates how these theories are interlinked, showing natural resource governance as the foundation, global energy assessment (GEA) pathways as the operational layer, and policy alignment, which is key in governing and achieving sustainability in the energy transition process.

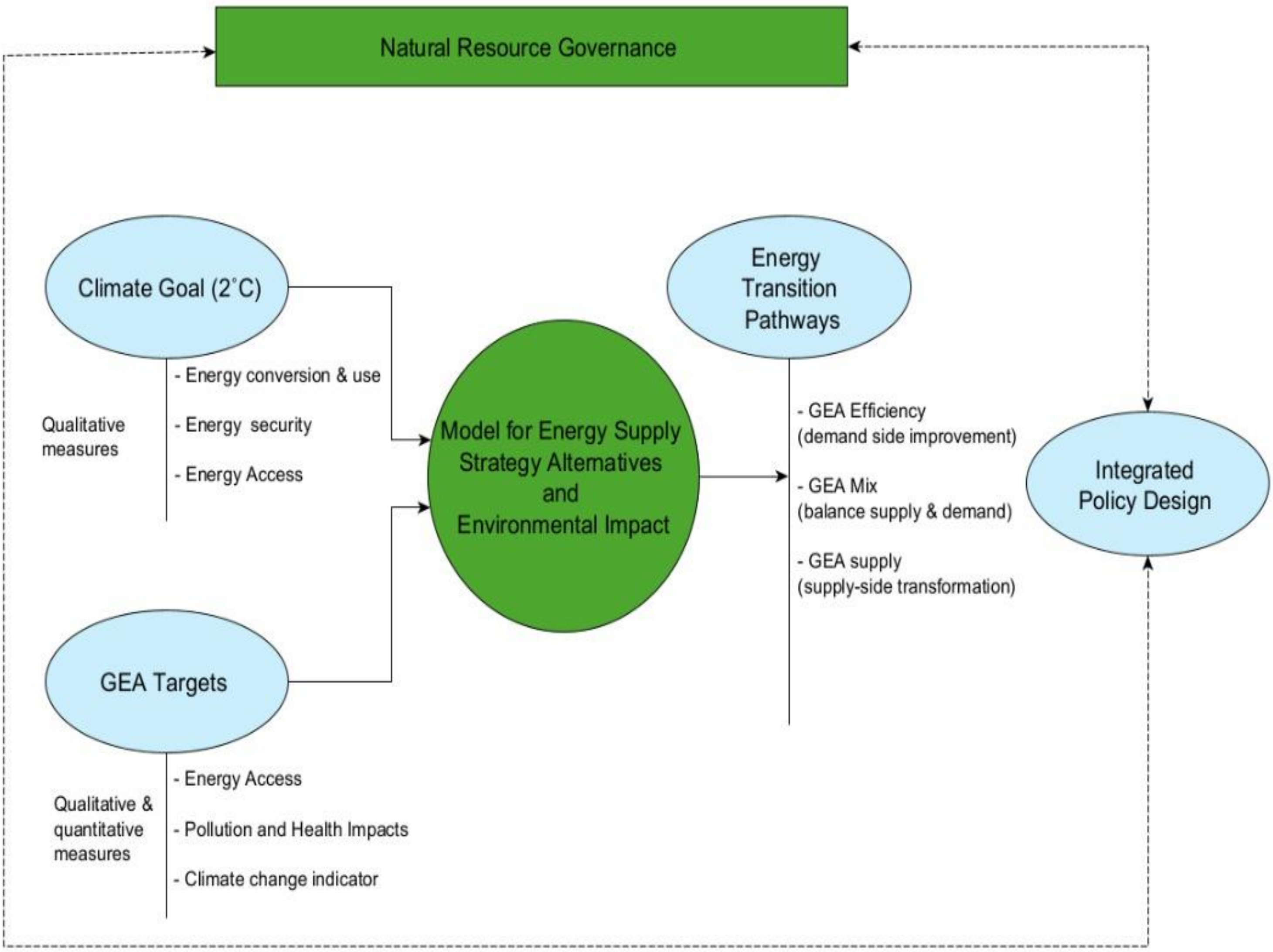

Figure 7. *Author's diagram developed from the global energy assessment scenario development process (Messner & Schrattenholzer, 2000; Riahi et al., 2007, 2012)*

2.4 Methods and Data

This study utilizes a scoping review and follows the methodological recommendations of (Tricco et al., 2018) based on earlier works by Arksey & O'Malley (2005), Levac et al. (2010), Peters et al. (2020). They define a scoping review or scoping study as:
"*a form of knowledge synthesis that addresses an exploratory research question aimed at mapping key concepts, types of evidence, and gaps in research related to a defined area or field by systematically searching, selecting, and synthesising existing knowledge*".

The study also adopted the PRISMA-ScR checklist guideline (Tricco et al., 2018) with some modifications to suit the writing style. Scoping reviews serve multiple purposes: They assess the extent, range, and characteristics of evidence on a topic, evaluate the need for a systematic review, summarise diverse findings across methods or disciplines, and identify gaps in the literature to inform future research planning. The checklist consists of nine activities, which have been condensed into five stages – identifying relevant literature through various search sources and setting the search terms, defining eligibility and selection criteria, implementing screening procedures, extracting and synthesizing data from selected literature with the research questions in mind, and finally charting the data.

This method was chosen for several reasons: broader unit of analysis, i.e. convenience for the research questions, the nature of the research topic and study area (biomass to power has not been gaining much attention in Nigeria), data unavailability, data inconsistency, and the flexibility to incorporate both quantitative and qualitative approaches into scoping studies. While primary data collection would have been ideal, this study is conducted remotely and relies on information and data obtained online and from literature.

2.5 Literature Search Methodology

A preliminary electronic search was conducted using search engines such as Google Scholar, Scopus, Research Gate and Academia, with relevant search terms related to biomass and bioenergy. Although not formally reported, this initial search was to better understand the existing literature and its quality and assess the feasibility of completing the thesis within the required timeframe. For reporting purposes and a more structured approach, a second electronic search was conducted using Google

Scholar and Scopus database in June 2024 using the search string ("Biomass sources" OR "bioenergy") AND ("energy access" OR "electricity access") AND Nigeria. The two-search database was used because it searches full text. Secondly, as a web search engine, it indexes scholarly literature from various online sources, including peer-reviewed journals, academic books, and conference papers. This method provides a comprehensive way to find literature, particularly peer-reviewed literature, across different databases. The literature search aligned with review questions and the research topic, following the population, concept and context (PCC) framework. The study selection period spans from 2007 to 2024, with 2007 chosen as the starting point due to the release of Nigeria's biofuel policy and incentives to promote a robust bioenergy sector. This also signals that the study is grounded in real-world developments and policy initiatives, providing context, historical perspective, and feasibility considerations.

The study language considered is English. Except for my supervisors, no reviewers or verifiers were involved in the search, as this was my master's thesis. The search protocol is presented in Appendix 1.

2.6 Defining Eligibility Criteria

To be eligible and qualify for inclusion, studies had to explore specific aspects of biomass to power generation in Nigeria. The following criteria were applied.

a. Inclusion of studies related to or conducted in Nigeria from 2007 till date.
b. Exclusion of studies in languages other than English because the official language of Nigeria and most academic writings are written in the English language
c. Inclusion of studies that explore specific aspects of biomass to power generation in Nigeria, particularly municipal solid waste, agricultural residues, forest residue and livestock waste.
d. Inclusion of studies that discuss electricity generation from both biomass and other renewable sources (like solar, hydro and wind)
e. Inclusion of quantitative or qualitative or both studies
f. Inclusion of Interdisciplinary studies that provide a comprehensive view
g. Exclusion of duplicate studies or publications

2.7 Method of Selection of Sources of Evidence

The study used a systematic approach to select comprehensive and relevant sources of evidence. Specific search terms and keywords were used to narrow down the final selection of publications reviewed for this study. Inclusion and exclusion criteria were adopted to ensure that only high-quality evidence is considered. This method aimed to gather diverse sources for robust research findings. Figure 8 below shows a summary of the protocol.

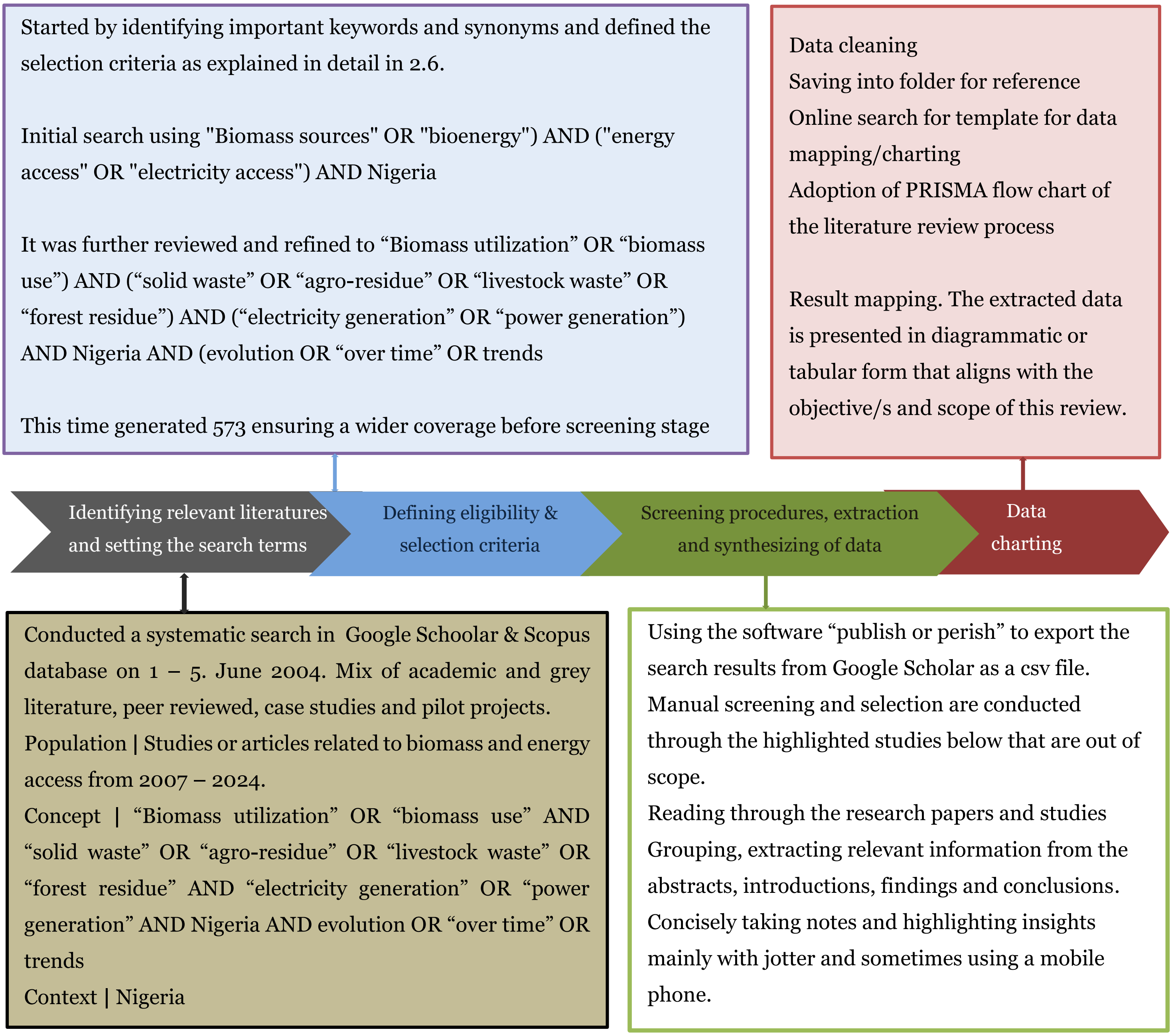

Figure 8. Summary of search protocol and methods adapted from (Chigbu & Nweke-Eze, 2023)

2.8 Data Selection

Data from the electronic search was screened down to 998 studies after removing duplicates, records deemed ineligible by the automation tool “publish or perish”. Other records that were outside the scope of this study or linked to other studies outside the scope were not considered for these studies. This study was exported to Excel for extraction, grouping, synthesis, manual screening, and removal of duplicate studies. Manual screening was conducted in Excel, and a full-text assessment was performed on 303 studies, excluding 201 studies that were not indexed in the database or were non-relevant. Finally, 84 studies were selected that matched the review criteria for this work between 2007 and 2024. Data was charted in Figure 9.

2.9 Data Analysis and Synthesis

The data extracted from the studies were analysed in a spreadsheet for easy identification and analysis. A schedule containing the names of authors, publication year, title, type of study, biomass thematic topic/areas, abstract, summary, key findings, limitations, and future research suggestions. The data extraction process relied on the assumption that the reported data was accurate and reliable, that the studies were comparable, and that the extracted data was relevant to the research questions and objectives. It was simplified by categorizing various biomass sources and technologies into broader groups and concentrating on important findings related to the research questions.

The charted data were analysed using a combination of qualitative and quantitative methods. The qualitative analysis included identifying and synthesizing the key themes and patterns across the studies, while the quantitative process involved summarizing and comparing numerical data, such as estimated biomass potential and technological performance metrics. The findings were then synthesized to provide a comprehensive overview of the current knowledge on biomass energy in Nigeria, addressing the research questions and objectives of the scoping review.

2.10 Charting of Sources of Evidence

The flowchart in *Figure 9* illustrates a step-by-step literature selection per the PRISMA guideline. Included studies and their thematic areas are further discussed in the next sub-headings.

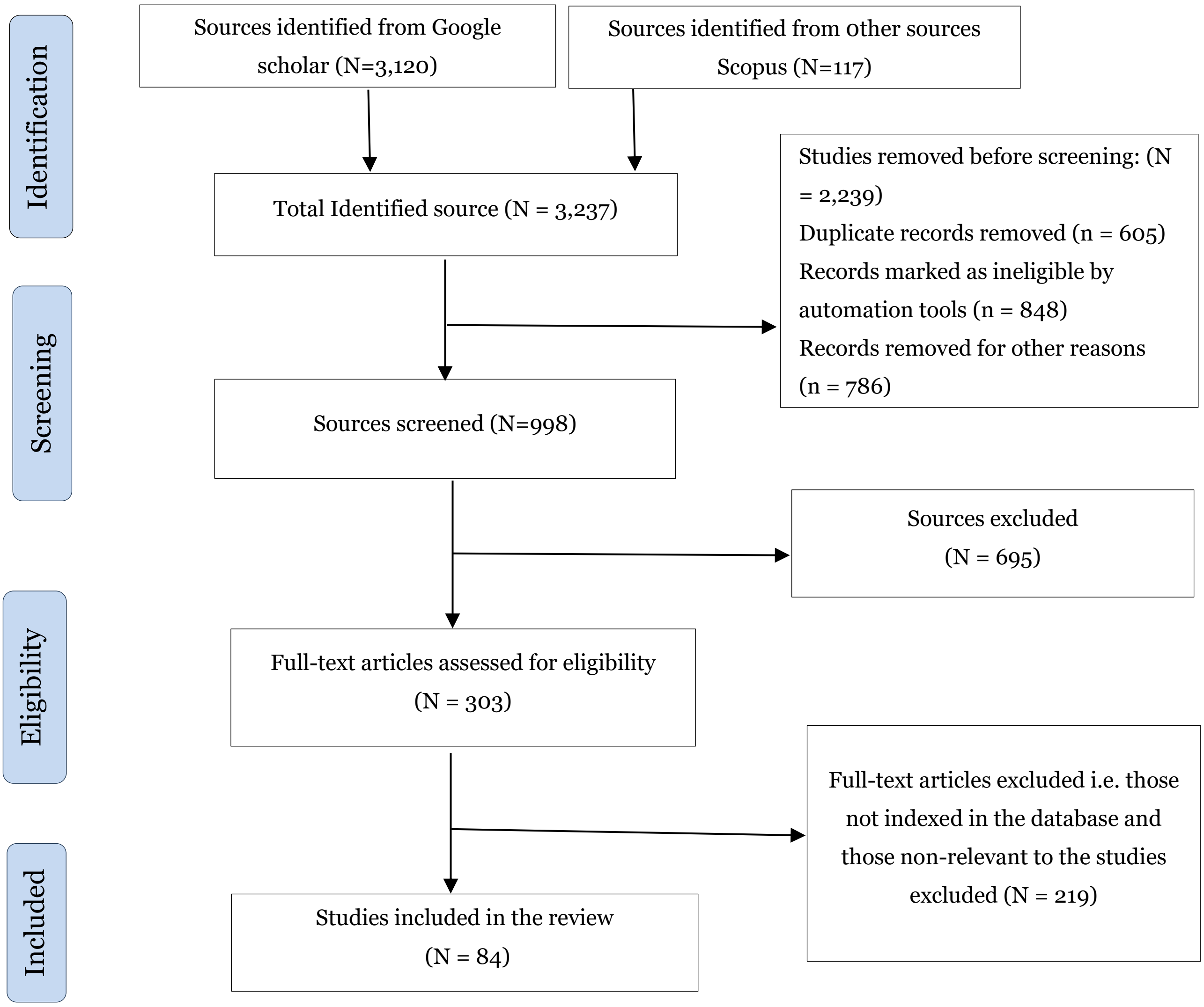

Figure 9. PRISMA flow chart for individual article selection

The selected literature reveals various insights into the country's bioenergy landscape, particularly regarding the potential of biomass as a renewable energy source. While significant biomass resources exist, their utilization for power generation is still developing. Key themes from the literature include the assessment of current biomass potential flowing from municipal solid waste, forest residue, livestock and agricultural residue evolving technologies for energy conversion, and the socioeconomic impact of integrating biomass into the national grid.

2.11 Study range and general characteristics of the reviewed literature

Of the identified studies spanning from 2007 to 2024, about 80% were published after 2014, indicating a growing interest and focus on biomass energy research in Nigeria during this period. Studies selected for this review were categorized into four main themes based on the research focus. 60% of studies relate to biomass resource assessment, focusing on quantifying and characterizing the available biomass resources for energy and electricity usage while utilizing various methodologies such as reports from FAO, previous studies, field surveys, remote sensing, and GIS to estimate the potential energy and electricity yield and from agricultural residues, municipal solid waste, and forest residues. This assessment is essential in understanding the renewable energy potential of biomass sources in Nigeria and determining their suitability for generating electricity and energy at large. 15% of the studies discuss various biomass conversion technologies for energy production, including combustion, gasification, anaerobic digestion, and pyrolysis and evaluated the technical performance, efficiency, and scalability of these technologies for generating electricity, producing heat, and synthesizing biofuels. 10% of the studies examined the environmental impact of biomass energy production to evaluate the overall sustainability of biomass energy systems, while 15% explored policy, regulatory frameworks, and socioeconomic factors influencing biomass energy in Nigeria.

3 Result

This section presents the results of the selected sources of evidence, the results of individual sources (Appendix II), and a summary of the sources of evidence as they relate to the research questions.

3.1 Appraisal and results of individual sources of evidence

This study addresses the three central research questions by critically appraising the various sources of evidence identified, aiming to provide a deeper understanding of Nigeria's biomass energy landscape.

3.1.1 Table of studies related to the review question and objectives

Table 1 below gives an overview of studies that are closely related to the objectives of the review. Each study included in the table has been chosen for its relevance in addressing the main research questions, such as the current bioenergy generation capacity in Nigeria, the development of biomass utilization for electricity, and the feasibility of biomass-based power technologies in small-scale settings. By highlighting these key studies, the table provides a structured view of the existing research, thematic trends, and technological advancements in bioenergy. This literature synthesis will help to shape discussions and propose solutions for addressing Nigeria's energy challenges using sustainable biomass resources.

Table 1: Publications addressing the research questions

Aspects of the Research Questions*	Authors and Years	Focal Subjects
Current bioenergy capacity for energy/ electricity generation in Nigeria [2]	Sokan-Adeaga & Ana (2015), Simonyan & Fasina (2013)	Availability, potential and prospects of biomass resources for bioenergy generation and electricity supply.
	Jekayinfa & Scholz (2009), Jekayinfa et al. (2020)	Quantity and cost of crop residues – maize, millet, sorghum, cassava, groundnut, plantain and cowpeas utilized for energy generation; potential resource for biomass energy
	Afolabi et al. (2021)	Country-level assessment of agri-food waste for bioenergy generation.
	Adeleke et al. (2023)	Biomass for bioenergy application

[2] ****tackles No. 1 and 2 aspects of the research objectives and questions**

Aspects of the Research Questions*	Authors and Years	Focal Subjects
	Ogwo et al. (2012)	Comprehensive examination of biomass energy as a potential alternative and renewable energy source
	Diji (2013)	Exploration of biomass power as a renewable energy source for electricity generation
	Ezealigo et al. (2021)	Identification and evaluation of the various biomass resources
	Olanrewaju et al. (2019)	Energy generation from agro-residues, forest residues, MSW, animal and human wastes
	Ojolo et al. (2012)	Estimates of biomass energy resources based on demographic data, agricultural production rates and energy content
	Mohammed et al. (2014)	Bioenergy potential for distributed power generation
	Ukoba et al. (2024)	Multicriteria GIS-based assessment of biomass energy potentials
	Adubaa and Shimada (2023)	Viability of sustainable biomass electricity generation
	Obidike et al. (2020)	Biogas from waste
	Akinshilo et al. (2019)	Energy potential from MSW for developing metropolis
	Chowdhury et al. (2022), Audu et al. (2020), Ogbu et al. (2022).	Multi-criteria assessment approach to recycling slaughterhouse waste and future sustainable energy
	Mohammed et al. (2020)	Agricultural biomass for sustainable electricity generation
Biomass resource power technological approaches [3]	Sobamowo et al. (2018)	Techno-economic analysis through gasification technology
	Ugwu et al. (2022)	Conversion pathways for biomass
	Maina et al. (2023), Chukwuma et al. (2021).	Waste to energy conversion technologies, sustainability and economically viable solutions for energy challenges
	Mohammed et al. (2012)	Technological approaches for biomass conversion
	Diemuodeke et al. (2023)	Optimal sites for agro and forest residue conversion plant
	Ejiofor et al. (2020)	Rice husk gasification technology
	Okey et al. (2019), Danjuma et al. (2008)	Biomass briquette and rural development, market development and R&D
	Diyoke et al. (2014)	wood-fired biomass gasification
	Nilanjana Banerjee (2023)	Novel technological advancements in bioenergy conversion
	Sobamowo & Ojolo (2018), Diyoke et al. (2014), Akhator et al. (2019)	Gasification technology, sustainable energy production, economic development
	Ejiofor et al. (2020)	Rice husk and gasification technology
	Nomanbhay et al. (2017)	Electricity power from oil palm using pyrolysis and liquefaction production method
	Balogun et al. (2018), Akinrinola et al. (2014), Okekunle et al. (2016).	Agro residuals for power generation using pyrolysis and liquefaction
	Anka Garba & Zangina (2015)	Rice husk fired energy using incineration and indirect combustion

[3] **tackles No. 3 aspects of the research question and objectives**

Aspects of the Research Questions*	Authors and Years	Focal Subjects
	Obi et al. (2019)	Briquetting, MSW, Syngas for electricity
	Nubi et al. (2022),	Landfill gas to energy production from Jatropha curcas and MSW
	Jensen et al. (2020), (Ngumah et al., 2013)	Anaerobic production of electricity, Biogas, biofuel, Agro residue, livestock and organic waste

*the focal point of entry was directly on the research questions

Source: Compiled by the author using various literature reviews, September 2024.

Based on the full list of publications (n=84), which explains the growing need for biomass to power in Nigeria, *table 1* shows how some selected studies directly address aspects of the research questions. The studies cover different geographical areas and topics. Instead of focusing on research gaps specific to each study, the above table emphasizes literature that either directly or indirectly relates to the research questions. In the process of discussing and analysing these issues—which were the primary methods used to interpret findings within the broader context of biomass energy—additional relevant literature has been included and cited. This provides supporting evidence and allows readers to understand the broader and specific scenarios related to the subject matter. This approach, therefore, ensures a comprehensive interpretation of the studies within the framework of this research.

3.1.2 Key publications on thematic drivers of biomass to energy production

This section identifies the publications selected for review based on the authors' contributions and the specific research gaps or key topics they address. Identifying the studies aims to provide a comprehensive understanding of the research questions. The table itself shows the major research themes and trends in biomass and bioenergy for electricity generation, highlighting the critical research areas and emerging trends in the field. See *Table 2*, which tackles the second research question.

Table 2: Trends and Thematic Drivers of Biomass to Energy Production in Nigeria

Code	Theme [4]	Subject/main Terms	Authors
	Biomass resource assessment	Technical potential for biomass resource, bioenergy production from various biomass sources	Ezealigo, et al. (2021), K. Simonyan, O. Fasina (2013), Ojolo et al. (2012),

[4] **Tackles No.2 aspects of research question and objectives**

Code	Theme [4]	Subject/main Terms	Authors
	and electricity access		Olanrewaju et al. (2013), Adeleke et al. (2023), Longhurst et al.(2016)
		Energetically usable crop residues	Jekayinfa et al. (2020), Sambo (2009)
		Biomass to power and electricity production	C.J (2023)
BRE		Biomass and biofuel prospects	Sokan-Adeaga et al. (2015)
		Characterization of selected biomass for bioenergy production	Yahya, Asmau et al. (2023)
		GIS approach for assessing the biomass energy potential and identification of appropriate biomass conversion technologies	Ukoba et al. (2023), Ukoba et al. (2024)
		Potential of bioenergy resources for distributed power generation development	Mohammed et al. (2014)
		Distributed power generation for rural Nigeria	Giwa et al. (2017)
	MSW/Biomass waste	Waste to energy(wte), energy recovery, valorization, recycling, economic potential	Okafor et al. (2022)
		Socioeconomic factors, bio-waste, energy recovery potential, energy content, biogas recovery	Chukwuma et al.(2021b), Akpahou et al. (2024)
		Biogas, electricity, municipal solid waste	Mokhtar et al. (2012)
		Conversion feasibility of MSW to electricity, renewable energy, power generation	maina et al. (2015), maina et al. (2023), Olujobi et al. (2021)
MSW		waste to power generation adopting the incineration technology, w aste forecast, energy recovery	Akinshilo et al. (2019), Aderoju et al. (2017)
		waste resource utilization, viability of present and projected municipal solid waste streams	Lawal et al. (2023)
		waste characterization, waste management, electricity supply, waste to energy, life-cycle assessment, life-cycle costing, social life-cycle assessment	Amber et al. (2012), Nubi et al. (2022)
	Agro-residues	Energetically usable crop residues	Jekayinfa et al. (2020), Ojolo et al. (2012), longhurst et al. (2016)
		evaluation of oil palm frond biomass, feedstock for bioenergy	Ezeh et al. (2023)
		Utilization of casava waste, biomass yield, bio-methane yield, bio-ethanol production	Ekop et al. (2019), Ozoegwu et al. (2017)
AR		Crop production and bioelectricity generation	Aawafo et al. (2024), Iye and bilsborrow (2013), Anyanwu et al. (2013)
		rice straw and husks potential for electrification, maize and cotton stalks, casava and other residues, RPR for different crop residues	Garba et al. (2015), Aduba and Shimada
		Corn cob residue for electricity, gasification	(2023), Sokan-Adeaga et al. (2015), Akpahou et al. (2024), Akinbami and momodu (2012)
		bioethanol, biofuel for transportation, bio-ethanol production from lignocellulosic biomass	Suberu et al. (2012), Suberu et al. (2020), Adeleke et al. (2023)

Code	Theme [4]	Subject/main Terms	Authors
	Animal waste/livestock feed	cow dung, anaerobic digestion, biogas generation	Odekanle et al. (2020)
		Anaerobic digestion, Slaughterhouse, Slaughterhouse waste, biogas production, biogas from slaughterhouse	Kabeyi and Olanrew aju (2022)
LS		poultry excreta, sheep, goat, pig and cattle excreta, renewable energy, anaerobic digestion and biogas	Ngumah et al. (2013)
		total wastes generated, abattoir waste, biomethane, electricity, and mitigated methane emission	Audu et al. (2020)
	Forest residue	wood waste-pow er generating system	Akinbami and momodu (2012)
		biomass carbon stock, forest vegetative zone	Olorunfemi et al. (2019)
		bamboo, biomass, extractives, lignin content, gross heat value, fuel value Index	Sadiku et al. (2016)
FR		Wood resources, waste, sawdust, waste utilization, renewable energy, mini-grid, power technologies,	Oluoti et al. (2014), Owoyemi et.al (2016)
		Forest waste, biomass, GIS, net-zero, optimal sites	Ukoba et al. (2023)
		Forest waste, biofuel, sawdust, wood chips, bark, waste management, wood, biomass, bioenergy, climate change, global warming	Ogbu et al. (2022)
	Biomass conversion technologies	conversion technology, advanced energy systems, energy analysis, bioelectricity and gasification, pyrolysis, physiochemical, anaerobic digestion, transesterification	E.I Ohimain (2012); Ugwu et al. (2022); Ben-Iwo et al. (2016)
		Techno-economic analysis, biomass, gasification, feedstock generation, rural electrification	Sobamowo and Ojolo (2018)
BT		Biomass, decentralised, economic viability, gasification, levelized cost of electricity, biomass gasifier, biomass power system, annualized replacement cost.	Diyoke et al. (2014), Diyoke et al. (2021)
		Biomass, briquetting, densification, appropriate technology, rural development	Obi et al. (2014), Danjuma and Tukur (2008)
	Environmental Impact and climate change	Bioenergy, emission, renewable energy	Suberu et al. (2020)
		Waste, oil palm, biomass, fuel, climate change, integrated algal/oil palm refinery, crude oil palm sustainability, energy crop	Abogunrin-Olafisoye et al. (2024), Brimmo et al. (2013)
ECC		Carbon emission, biomass, renewable energy practise via biological wastes to electricity, electricity, environment, waste, dogmatic legal analysis	Olujobi et al. (2022)
		waste management, disposal, collection and recycling, waste characterization, life cycle assessment of electricity from wastes	Ogwueleka (2009), Nnaji (2015), Nubi et al. (2022)
		Biomass consumption, health and environment	Sa'ad and Bugaje (2016)

Code	Theme [4]	Subject/main Terms	Authors
	Policy and socio-economic considerations	Renewable energy, energy policy, energy crop, agro-residues, MSW, techno-economic feasibility.	Giwa et al. (2017)
PSC		Energy governance, energy policy, energy market, energy poverty, public policy, distributed generations	Monyei et al. (2018), Edomah et al. (2017)
		Socio-political and technological factors, investment policy and legislative issues, biofuel policy, biomass conversion, incentives and financing, research and development, private investments, economic viability	Mohammed et al. (2017)
		Clean energy alternatives	Ohimain (2015a and 2015b)
		Socio-political, technological and legislative issues, biofuel policy, policy conflicts and inconsistencies	Nasidi et al. (2010)
		Biomass, gender, energy, rural households, bioenergy recovery	Orifah et al. (2018)

Source: Compiled by author using various literature review, September 2024

The quest for bioenergy in Nigeria is undeniably a legitimate ambition. This is because the global focus on bioenergy production has gained significant traction, and the potential benefit could be immense if the necessary conditions are met. As a member of the global community, Nigeria must explore alternative means of improving its already struggling economy. It is, therefore, important to identify the publications based on the authors' identities and the key topics or research gaps that were the review's focus.

3.2 Current potential for biomass resource utilization

Nigeria has significant biomass resource potential for electricity and energy generation, estimated at approximately 2.33 EJ (Jekayinfa et al., 2020; Ugwu et al., 2022). This translates to 647,222 GWh of energy generation. Key contributors include agricultural residues, which generate about 1.09 EJ (302,777 GWh), primarily from crops like cassava, maize, and rice. Other sources include animal wastes 0.65 EJ (180,555 GWh), municipal solid waste 0.11 EJ (30555 GWh), and forest residues 0.05 EJ (13,888 GWh). So far, studies suggest that the country could generate between 2.0 and 5.5 EJ annually from biomass resources, which translates to 555,556 GWh and 1.5 million GWh annually, respectively. While Ojolo et al. (2012) estimated that a biomass energy reserve reaching 5.5 EJ with a potential to increase to 29.8EJ 8,277,778 GWh by 2050, Olanrewaju et al. (2019) estimated a potential of approximately 62 Mtoe translating to 72,106 GWh energy potential. On the other hand, Agba et al. (2010) estimate that Nigeria's bioenergy could reach 1.2 PJ, equivalent to 333 GWh energy potential. Similarly, Simonyan & Fasina O (2013) concluded that there are significant opportunities for harnessing various types of biomasses in Nigeria, with an estimated 557,891 GWh, which is equivalent to 47.97 MTOE of biomass residues and wastes available for exploitation each year. However, (Olanrewaju et al., 2019) in their study, provided a higher estimate, reporting a potential energy yield of 49 Mtoe from biomass residues, which exceeds Simonyan et al.'s estimate by 1.03 Mtoe which is 11,978.9 GWh potential difference. Mshelia Balthi (2021) highlighted that Nigeria can produce up to 1.2 million metric tons of biomass daily. This is about 1162.2 GWh of energy production/per day. Despite this vast potential for biomass-based bioenergy production, large-scale bioenergy implementation remains limited, and the country's current output remains relatively low due to competing use of resources and insufficient policy enforcement to promote bioenergy development in the country. Ezealigo et al. (2021) explored the potential of biomass for Nigeria's energy sector, especially for electricity and biofuel production, with non-food sources like agricultural residues offering a more sustainable option.

The current utilization of biomass resources for electricity generation in Nigeria is limited, primarily due to overdependence on fossil fuels and an inadequate energy mix. However, the country has abundant biomass resources that, if properly harnessed, could significantly enhance electric power generation and reduce greenhouse gas emissions. *Table 3* further provides a comprehensive outcome of data for each source of evidence that effectively captures the current capacity for biomass resource utilization.

Table 3: Individual sources of evidence on current biomass resource utilization for electricity production

Author	**Article Type**	**Study Method**	**#Studies reviewed** [5]	**Key findings**
Ezealigo et al. (2021)	Conference paper	Computational and Analytical approach	23	. Higher energy potential from biogas than cellulosic ethanol compared to similar residue.

[5] total references were used as proxy for # of studies reviewed in each paper

Author	Article Type	Study Method	#Studies reviewed [5]	Key findings
Simonyan & Fasina (2013)	Reviewed article	Quantitative estimation	69	. Potential for 2.01 EJ (47.97 MTOE) of energy production from 168.49 million tonnes annually for electricity
Sokan-Adeaga & Ana (2015)	Journal	Desk review	109	. 78% contribution of biomass as primary energy supply . Worthwhile future for biofuel production
Olanrewaju et al, (2019)	Journal	Quantitative estimation. Fieldwork data collection	24	. Current biomass capacity of over 200 billion kg/yr. . Potential to generate about 62 Mtoe (2.6 billion GJ) of energy, which is around 51% of the country's total energy consumption in 2015
Jekayinfa et al. (2020)	Review article	Desk review	338	. Overall, about 2.33 EJ could be generated from the available biomass resource in Nigeria
Okafor et al. (2022)	Journal	Systematic review	90	. About 20.5 mt are generated in the year 2020, while about 34.5 mt is estimated to be generated for the year 2040. . Yielding about 812.7 million m3 and 1.3 billion m3 of methane gas for 2020 and 2040, respectively and translated to 16,256 GJ (year 2020) and 54,128 GJ (year 2040) of energy.
Ojolo et al. (2012)	Journal	Quantitative estimation from secondary data sources	29	. Nigeria's energy potential is expected to increase from 3.2 EJ in 2010 to 29.8 EJ by 2050, matching projected energy demand until 2025, but including fuelwood provides a more accurate forecast beyond that.
Mohammed et al. (2014)	Review article	Review methodology	50	. Estimated energy potential from different biomass sources amounted to 451.2 PJ which can be harnessed for decentralised distributed power.
Ukoba et al. (2023)	Journal	Theoretical assessment using a spatial analysis data collection	146	. Total estimated energy potential from crop and forest residue is 4162.92 PJ/year with southern region having a higher crop residue potential and northern region, a higher forest residue potential . Various biomass conversion technologies, such as anaerobic digestion, fermentation, pyrolysis, and gasification, can be utilized for electricity generation in Nigeria.

Author	Article Type	Study Method	#Studies reviewed [5]	Key findings
Onwumelu Davidson Chukwudi (2023)	Review article	Comprehensive literature review	48	. Total biomass energy potential captured in the studies is estimated to be 2,582.26 PJ/year (61.67 Mtoe). This includes 2,033.85 PJ/year from crop residues, 28.88 PJ/year from perennial crop residues, 106.39 PJ/year from animal wastes, 28.83 PJ/year from human wastes, and 21.36 PJ/year from municipal solid wastes.
Mshelia Richard Balthi (2021)	Article	Desk research	68	. The northeast region was found viable for generating electricity from solid waste and biomass resources, with up to 1,249 MW and 4,752 MW, respectively.
Ejiofor et al. (2020)	Journal article	Quantitative approach	23	Research showed that Adani's local community could generate 3,636 tons, which has the potential to generate 1.52 MW of electricity. The designed gasification system can generate up to 13,132.8 MWh of electricity annually with an annual energy demand of 3,236 MWh which is more than enough to sustain the community.

Source: Compiled by the author using various literature reviews, September 2024

The following sub-sections discuss the potential, composition and energy value of the different components of Nigerian biomass.

3.2.1 Agricultural residue (AR)

Agricultural residues (AR) are richly available as biomass resources in Nigeria. Unlike cultivated crops, which compete for land and water resources essential for food production, agricultural residues do not interfere with food supply chains, making them a sustainable alternative for energy generation.

Biomass-derived fuels and other energy sources are classified into various generations – first, second, third and fourth generations based on the feedstock used in their production (Adeleke et al., 2023). First-generation biofuel, primarily derived from cereal, oil and sugar crops, using an established technology to generate bio-alcohols (bioethanols, propanol and butanol), biodiesel, biogas and even syngas. Second-generation biofuels are usually generated from sustainable feedstock produced from cellulosic materials directly from the crop residues and waste itself with limited impact on GHG emission and invisible impact on biodiversity and land use. Unlike first-generation biofuel, second-generation (non-edible cellulosic crop) are biochemically produced petroleum-gasoline substitutes (Awoyale & Lokhat, 2019), making them a better alternative to first-generation biofuels which have raised concerns about food security vs fuel dilemma and emphasizing the need for sustainable production of crucial crops to address these issues. Microalgae feedstock and biofuel obtained from biotechnological tools, i.e. genetically engineered plants and microbes, are considered examples of third and fourth-generation feedstock – based on photo-biological solar fuels and electro fuels, which are often time considered a case of advanced biofuel, but still not proven that its high efficiency can be maintained after scaling up technology to larger production plant (Ajoku, 2012). Iye & Bilsborrow (2013) estimated a total agricultural residue availability at 55.9 Tg annually, i.e. 55.9 million tonnes, with an energy potential of 657.01 PJ (182502 GWh), highlighting the abundance of field residues in northern regions. Comparatively, Jekayinfa & Scholz (2009) projected a future increase in agro-residue availability from 58 million tonnes in 2004 to 80 million tonnes by 2010, suggesting a growing trend in biomass potential.

Focusing on specific residues, Anyanwu et al. (2013) emphasized on the substantial energy potential of rice husk and straw, generating 2555 GWh and 2416 GWh of energy, respectively, while identifying other promising residues like oil palm biomass and cocoa pod husk. Ozoegwu et al. (2017) expand on this by discussing the significant waste generation from cassava processing, driven by its 4.3% annual production increase, showcasing cassava's bioenergy potential. Similarly, Akpahou et al. (2024) find that in Benin state, cassava, maize, and cotton residues contribute over 98% of the state's energy potential, with maize identified as a leading bioenergy feedstock. Other studies have drawn the potential for corn cob, rice husk, millet, maize, bagasse, sorghum and other prominent residues for electricity generation as well as private sector's growing involvement in rice milling, with many mills using rice husk for self-sufficient electricity generation
while also benefiting surrounding communities. Individual sources of evidence for the selected number of studies that reviewed energy potential for agricultural residues are captured in *Appendix 2 Table 4 Agriculture residue.*

Table 5 provides an overview of the energy potential of major AR, of which cassava is the most studied crop residue, generating a higher total energy potential from 2007 to 2022, as shown in *Fig. 10.* AR residue in *Table 5* is categorized into their various commodity groups, such as cereals, roots and tubers, fruits and vegetables, oil crops and pulses, and sugar crops with their corresponding RPRs at agricultural production stage. The total energy potential generated from these crops in 2020 could amount to about 2918.50 million metric tons available for power generation. This translates to 3.39 million GWh energy potential. Oil crops and pulses stand out with the highest energy potential 1769 MT (206 GWh), driven primarily by groundnut straw, followed by cereals with a total energy potential of 862 MT (100 GWh). Furthermore, roots and tubers demonstrate a moderate energy potential of 266 MT (309 GWh) while fruits & veg. and sugar crops contribute with 13 and 8 million MT energy potential translating to 15108 GWh and 9297 GWh of energy potential, respectively.

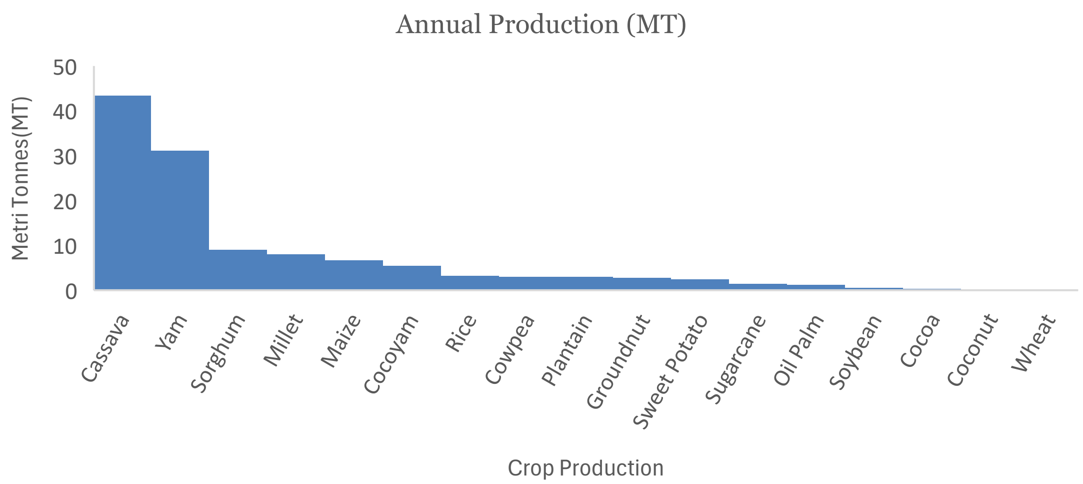

Figure 10. *Annual production of largest studied crop resides and their total energy production from 2007-2022* *[FAOSTAT]*

Table 5. *Energy potential of major agricultural residues in Nigeria based on 2020 crop production*

Commodity groups	Crops	Residue/waste	2022 Crop production (MT)[1]	Residue-to-product (RPR)[2]	Total residue generated (MT)	Energy Content (MJ/kg)[3]	Energy Potential
Cereals	Maize	Stalk	12.949	1.59 [A]	20,588,910	15.48 [B]	318.716
	Millet	Stalk	1.941	3.0 [B]	5,823,000	15.51 [B]	90.315
	Rice	Straw/husk	8.502	1.66 [A]	14,113,320	15.56 [B]	219.603
	Sorghum	Stalk	6.806	1.99 [A]	13,543,940	17.00 [B]	230.247
	Wheat	Stalk	0.11	1.50 [D]	165,000	17.51 [D]	2.889
Roots & Tubers	Cassava	Peels	60.836	0.25 [ABC]	15,209,000	10.61 [AD]	161.367
	Cocoyam	Stalk	3.3	0.5 [A]	1,650,000	14.24 [A]	23.496
	Sweet Potatoes	Straw	4.011	0.5 [A]	2,005,517	14.24 [A]	28.559
	Yam	Peels	61.171	0.06 [CE]	3,670,260	14.24 [A]	52.265
Fruits & Veg.	Coconut	Shell	0.226	0.25 [AC]	56,382	18.09 [C]	1.020
	Plantain	Trunks/leaves	3.090	0.25 [CE]	772,500	16.13 [C]	12.460
Oil crops & Pulses	Cocoa	Pod	0.280	0.93 [A]	260,400	15.12 [A]	3.937
	Cowpea	Shells	4.134	1.75 [AC]	7,233,988	19.44 [AF]	140.629
	Groundnut	Straw	42.840	2.30 [CF]	98,532,000	15.66 [A]	1543.011
	Oil palm	Bunch	12.609	0.25 [AC]	3,152,235	15.51 [A]	48.891
	Soybeans	Straw	1.060	2.50 [A]	2,650,000	12.38 [BF]	32.807
Sugar crops	Sugarcane	Bagasse	1.526	0.3 [B]	457,677	18.10 [F]	8.284
							2918.497

Source: Compiled by author using various literature review, September 2024

[1] Crop Production (MT) from the FAOSTAT. MT value in million tonnes

[2] RPRs at agricultural production stage were collated from: A (Ezealigo, et al., 2021); B (Mohammed et al., 2014); C (Jekayinfa & Scholz, 2009); D (Iye & Bilsborrow, 2013); E (Ojolo et al., 2012); F (Simonyan K.J & Fasina O, 2013).

[3] MJ/kg based on higher heating values reported for tubers including yam, potatoes, cassava

3.2.2 Municipal Solid Waste

MSW are waste collected and treated by or for municipalities (Akpahou et al., 2024). Major sources of waste in Nigeria are collected from households, commercial centres, institutions and industries. According to (Beatrice Abila & Jussi Kantola, 2013), approximately 25 million tonnes of waste annually. Average energy potential in some Nigeria cities is Lagos-10,000 MWh (Akinshilo et al., 2019) ; Ibadan - 3600 MWh (Ubanwa et al., 2021); Ilorin - 3244 MWh (Ibikunle et al., 2019); Aguata - 545 MWh (Chukwuma et al., 2021); and Enugu - 1571 MWh (Nwoko et al., 2020).

Recovering energy from municipal solid waste is essential for promoting sustainable cities and communities. MSW is made up of two components – organic (biodegradable and non-biodegradable) and inorganic (recyclable), depending on how the energy is converted, either through thermochemical or biochemical (Ogunjuyigbe et al., 2017). While the thermochemical options include incineration, pyrolysis, and gasification technology, the biochemical conversion of waste to energy is largely accomplished through anaerobic digestion techniques, which have become very common over the years (Mohammed et al., 2017). With a rapidly growing population, average waste generation in Nigeria could amount 0.53 kg/c/d (Kaza et al., 2018) which is within the range of 0.4 – 0.66 kg/c/d reported in Ogwueleka (2009) and Lawal et al.2024). Urban areas have potential to generate minimum of 15.7MW/day of electrical energy and is projected to increase to 33.4MW/day by the year 2035 (Lawal et al., 2024).

According to the (World Bank, 2023) each Nigerian currently generates about 0.51 kilograms of waste per day, which is projected to reach 107 million tonnes by 2050. This development poses both significant challenges and potential opportunities for the country. Of the different composition of waste, organic waste makes up the largest total waste as shown in *Figure 11* while total waste generation across major Nigeria cities is approximately 20,378 metric tonns. This translates to 23,683 MWh of energy potential.

Appendix 2 Table 4 MSW summarizes the sources of evidence that capture significant energy generation potential from MSW in various regions of Nigeria. Lagos is a key focus area studied, and this could be due to data accessibility from the Lagos Waste Management Authority. Suberu et al. (2012b) estimated that Lagos alone has the potential to generate a minimum of 442 MW of electricity from MSW, addressing the region's persistent power issues. In contrast, Ityona Amber et al. (2012) focused on the calorific value of waste, reporting a 700kw/day of electricity from incinerating 1,500 tons of MSW. This translates to 1743 MWh of energy potential. Both studies have shown that waste-to-energy initiatives are viable initiatives for the country. Other regions, such as Abuja, Ilorin, Ibadan and Jalingo, also show considerable potential, with projections of increased waste generation and methane emissions by 2030 and beyond.

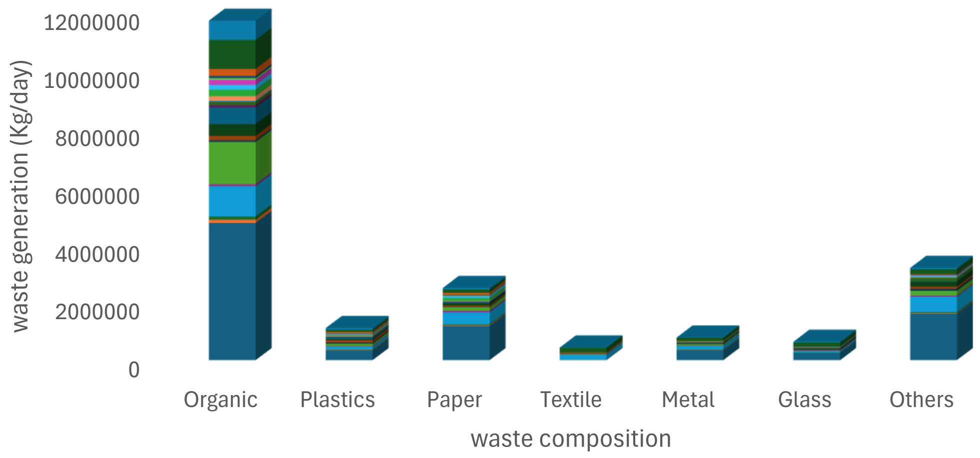

Figure 11. *Waste generation ratio and composition rate for the year 2021. Data from literature.*

Between 2007 and 2021, solid waste recorded a very high organic content ranging from 54-56%, which is within the range reported in Lawal et al. (2024) and Okafor et al. (2022). With the population rising by over 10 million between 2022 and 2024, the proportion of organic waste is expected to increase significantly. In addition, between 2007 and 2014, total energy value from municipal solid waste for a single city increased from 6.14% to 212.74% of the allocated power supply from the national grid.

3.2.3 Livestock waste

Over the years, Nigeria has used livestock husbandry for commercial and subsistence purposes. Yet, livestock waste has been one important biomass resource for energy that has often time been overlooked. Only a few studies have exclusively studied energy potential from livestock waste. This could be due to the limited availability of data and coordination of livestock production and waste/residue across the regions. Popular waste associated with livestock production is animal dung, which is generated from camels, cattle, donkeys, sheep, goats, pigs, and chickens. Out of these species, chicken is the largest over the years. *See Figure 12*.

From the reviewed literature, one of the highlights of energy generated from livestock production is the potential environmental benefit. Adeoti et al. (2014) estimated that Nigeria has a biogas potential of at least 1.62 billion cubic meters annually from livestock manure and suggested that replacing diesel-based electricity generation with biogas could save up to 0.60 million tons of CO2 emissions annually. In addition, most of the studies emphasized the energy efficiency gaps in slaughterhouses that could be bridged with technological upgrades precisely via anaerobic digestion to ensure that energy generated from slaughterhouses is fully harnessed. Odekanle et al. (2020) provided a more specific case study from an abattoir site, showing that conversion efficiencies can generate between 1,040 MWh and 1,664.6 MWh of electricity from biogas, depending on conversion efficiencies.
Different studies have led to different results in different energy potentials. However, the total energy potential from these studies is within the reported similar range. See Appendix 2 *Table 4* LS for sources of evidence for livestock wastes. The total energy potential of 950.53 GJ in Table 6 illustrates the current energy potential from popular animal waste in 2022. This translates to 263,889 MWh and 0.26 GWh energy potential that can be generated from the livestock wastes.

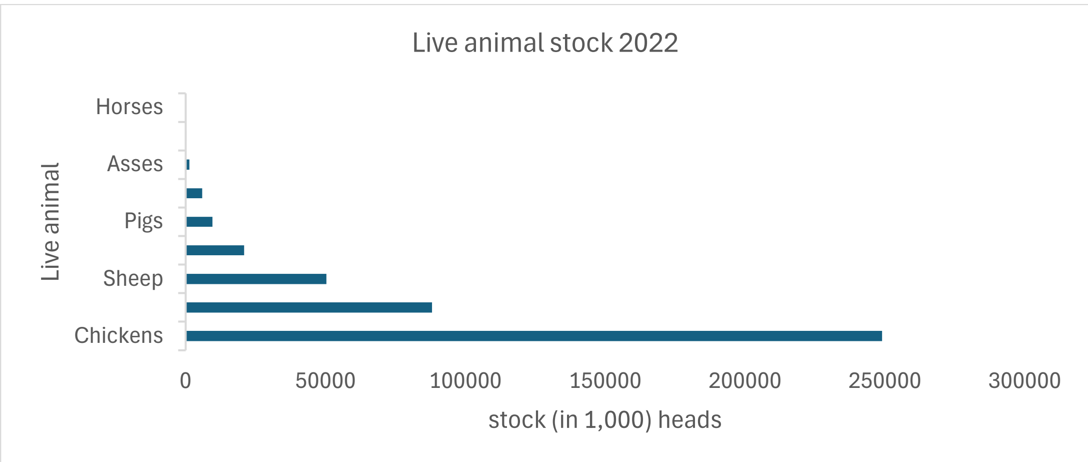

Figure 12. *Stock of live animals by type (in 1000 heads). FAO 2022. Source ID: 1297861*

Table 6. *Current energy potentials of livestock population, manure energy, and reference energy values.*

Livestock species	Population[d] ('000)	Dry waste[e] (Kg head^{-1} day^{-1})	Annual waste output (kg)	Energy value[e] (GJt-1)	Total energy potential
Chicken[e]	248,992	0.06	12618000	11.0	138.80
Cattle	20,905	1.80	15048900	18.5	278.40
Goat	88,037	0.40	22889900	14.0	320.46
Sheep	50,284	0.40	11631400	14.0	162.84
Pig	9,510	0.80	4548550	11.0	50.03
Total					950.53

Source: Compiled by the author using various literature reviews, September 2024

[d] FAO statistics 2022, 2021 (assessed 15.09.2024)

[e] Source: (Mohammed et al., 2014b), reported values updated to reflect the current potential

3.2.4 Forest residue

Nigeria's forests cover vast areas, providing not only ecological benefit but also a treasure trove of energy sources. Forest wood biomass and its byproducts have been a significant source of primary energy majorly used in the country (Mohammed et al., 2014a). Forest area is land under natural or planted stands of trees of at least 5 meters in situ, whether productive or not, and excludes tree stands in agricultural production systems (for example, in fruit plantations and agroforestry systems) and trees in urban parks and gardens (FAO, 2022). There are about 1,129 forest reserves in Nigeria (FAO Statistics, 2022).

Attention has been paid to the untapped power of bamboo biomass, with *Bambusa vulgaris* emerging as a valuable energy resource comparable to fast-growing plantation species, with an average producing 241.7 Mg/ha of biomass in 2005 (Sadiku, 2016). This not only opens door for sustainable energy but also provides an alternative to the depletion of traditional wood resources. Meanwhile, the sawmill industry, a significant player in forest residues, has been highlighted by Akinbami & Momodu (2012), who estimates that 100 sawmills produce 12,220 m³ of sawdust annually which is enough to power an 8 MW plant and displace over 73,000 tonnes of CO2 emissions per year. This is further expatiated by Oluoti et al. (2014), whose findings suggest Nigeria's lumber industry could generate 1.3 TWh of electricity from 1.8 million tonnes of wood waste. This translates to 1300 GWh of energy potential, demonstrating the feasibility of turning what is often discarded into a valuable energy source. On the other hand, Jekayinfa et al. (2020a) provided a sweeping estimate of the total energy potential of forest residues, placing it at 0.48 EJ (133,333 GWh) when including wood fuel and charcoal. These staggering figures reflect the untapped promise of Nigeria's forests as a key driver of renewable energy.

The selected literature of *Appendix 2 Table 4 FR* shows that forest residue as a potential bioenergy source has both its environmental and energy generation benefit, as well as a significant untapped potential of forest resources. *Table 7* shows forestry products and production quantity for 2020, 2021 and 2022. From the table, we can see no change in the production quantity due to the unavailability of data. Also, there are no statistics for the use of forest residues in Nigeria. Nevertheless, estimates show that the current energy potential from forest residue is about 411.54 PJ/yr translated to 114,317 GWh. (Ukoba et al.,2023) The reported obtainable forest residues and their energy potential are updated for the year 2024, as shown in *Table 8*.

Table 7. *Forestry products and production quantity in Nigeria 2020, 2021, and 2022 FAO Statistic*

Products	Production		Year		
	M^3	Tons	2022	2021	2020
Wood fuel, coniferous	√		0	0	0
Wood fuel, non-coniferous	√		67607483	67239649	66883195
Sawlogs and veneer logs, non-coniferous	√		7600000	7600000	7600000
Pulpwood, round and split, non-coniferous	√		22000	22000	22000
Other industrial roundwood, non-coniferous	√	√	2400000	2400000	2400000
Wood charcoal	√		4907916	4828689	4750741
Sawnwood, coniferous	√		2000	2000	2000
Sawnwood, non-coniferous all	√		2000000	2000000	2000000
Veneer sheets	√		1500	1500	1500
Plywood	√		56000	56000	56000
Particle board	√		40000	40000	40000
Mechanical and semi-chemical wood pulp		√	9000	9000	9000
Chemical wood pulp		√	14000	14000	14000
Chemical wood pulp, sulphate, unbleached		√	14000	14000	14000
Recovered paper		√	20000	20000	20000
Newsprint		√	0	0	0
Printing and writing papers		√	1000	1000	1000
Other paper and paperboard		√	18000	18000	18000

Source: Compiled by the author using FAO dataset, September 2024

Table 8. *Estimated Forest Residues and Their Energy Potentials in Nigeria for the Year 2022. Updated*

Forest Resource	Density (kg/m³)	Volume (m³)	Mass (tonnes)	Forest Residue ('000 tonnes)	LHV (kJ/kg)	E Theoritical (PJ/year)	AF (-)	E technical (PJ/yr)	E economical (PJ/yr)
Wood fuel, non-coniferous	521	67607483	35223498.6	24960.7481	19500	486.7346	0.6	292.0408	80.7785
Sawlogs and veneer logs, non-coniferous	675	7600000	5130000	3693.6000	19500	72.0252	0.6	43.2151	11.9533
Pulpwood, round and split, non-coniferous (production)	550	22000	12100	8.7120	19500	0.1699	0.6	0.1019	0.0282
Other industrial roundwood, non-coniferous (production)	449	2400000	1077600	775.8720	19500	15.1295	0.6	9.0777	2.5109
Wood charcoal	951	4907916	4667428.116	3364.0409	28000	94.1931	0.6	56.5159	15.6323
Sawnwood, coniferous	415	2000	830	0.5976	19500	0.0117	0.6	0.0070	0.0019
Sawnwood, non-coniferous	560	2000000	1120000	806.4000	19500	15.7248	0.6	9.4349	2.6097
Veneer sheets	451	1500	676.5	0.4871	19500	0.0095	0.6	0.0057	0.0016
Plywood	595	56000	33320	23.9904	19500	0.4678	0.6	0.2807	0.0776
Particle board	661	40000	26440	19.0368	19500	0.3712	0.6	0.2227	0.0616
Mechanical and semi-chemical wood pulp	-	-	9000	6.4800	19500	0.1264	0.6	0.0758	0.0210
Chemical wood pulp	-	-	14000	10.0800	19500	0.1966	0.6	0.1179	0.0326
Chemical wood pulp, sulphate, unbleached	-	-	14000	10.0800	19500	0.1966	0.6	0.1179	0.0326
Recovered paper	-	-	20000	14.4000	19500	0.2808	0.6	0.1685	0.0466
Printing and writing papers	-	-	1000	0.7200	19500	0.0140	0.6	0.0084	0.0023
Other paper and paperboard	-	-	18000	12.9600	19500	0.2527	0.6	0.1516	0.0419

Source: Compiled by author, adapted from(Ukoba et al., 2023) , September 2024.

3.3 Bioenergy Production Technologies (Pathways for Nigeria)

Biomass technologies in Nigeria are at different stages of development, with most of them still in the research and development phase, and only a few progressing to pilot or commercial implementation (Ben-Iwo et al., 2016a). This shows the need to expand the use of the most efficient technologies currently available and to speed up the development and deployment of new technology options that can further enhance biomass utilization for energy production. The conversion of biomass to energy involves transforming it into different fuels through two main techniques - thermochemical and biochemical conversion processes (Banerjee, 2023; Diji, 2013; Simonyan & Fasina, 2013). These techniques offer significant potential for small-scale electricity generation and depend on different factors such as the type of feedstock, the moisture content, end use and the financial feasibility of the biomass conversion process (Ben-Iwo et al., 2016; Ukoba et al., 2023).

Thermochemical processes include direct combustion, pyrolysis, gasification, and liquefaction, which are particularly useful for converting solid biomass into heat, fuel gases, and liquid bio-oil (Demirbas, 2009). These processes are considered efficient and adaptable, particularly gasification and pyrolysis with thermal efficiencies ranging between 30% and 60%, which can convert a wide variety of biomass types into energy, making them viable for electricity production in small communities (Ben-Iwo et al., 2016a). Although gasification plants are not very common in Nigeria, their end product is syngas, which can be directly used to fuel engines or turbines for electricity generation. Furthermore, they have a lower environmental footprint compared to traditional fossil-fuel-based energy systems, as they significantly reduce carbon emissions. On the other hand, the biochemical conversion process includes anaerobic digestion, transesterification, and fermentation, which are essential for producing biogas, biodiesel, and bioethanol. These processes are highly relevant for rural agricultural communities, where livestock waste, agro-residues, and forest residues are readily available feedstocks. Evidence shows that Anaerobic digestion is widely applicable in small-scale settings (Sobamowo & Ojolo, 2018) and gasification, most especially is probable for an intended scale of 5 -50kW$_e$ (Loeser & Redfern, 2008) thus, it not only provides a source of renewable electricity but also produces digesters, which can be used as organic fertilizer, adding an economic benefit to smallholder farmers (Traub et al., 2021). The energy conversion efficiency of anaerobic digestion is generally lower than that of thermochemical processes, but it remains a valuable option for communities with substantial organic waste (Ogunjuyigbe et al., 2017).

In terms of economic viability, the feasibility of implementing these technologies at small scales depends on several factors, including the availability of feedstock, the cost of technology, and local energy demand. Small-scale biomass plants can benefit from community-driven models, reducing the upfront capital costs by leveraging local labor and materials (Diyoke et al., 2014). This is true for rural electrification programs, where decentralized energy system can drastically reduce the associated costs of expanding the national grid (Mohammed et al., 2014b). Furthermore, generating electricity from biomass is best utilized through distributed generation systems which are more efficient for small-scale application. However, large-scale commercial bioenergy projects are quite uncommon because biomass typically has a low bulk density and energy content, making it less suitable for large-scale applications (Suberu et al., 2012a).

Among the various biomass production methods shown in *Figure 13*, incineration and direct combustion stand out as the most widely studied approach, as reflected in the findings of several authors in *Table 9*. This is attributed to its simplicity and cost-effectiveness, especially for developing countries like Nigeria (Okafor, Nzekwe, Ajaero, et al., 2022).

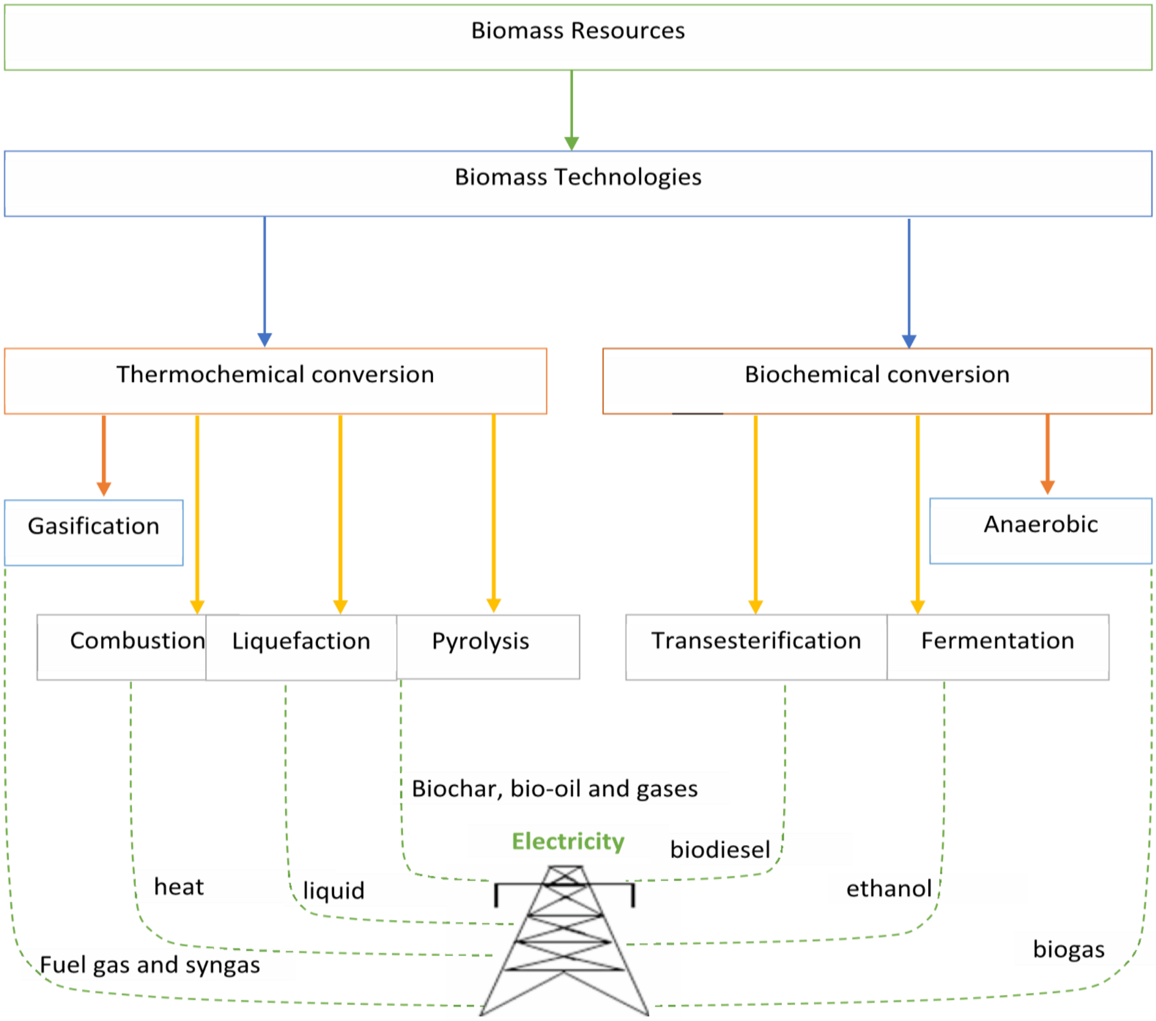

***Figure 13**. Biomass conversion technology. Reprinted with approval. Ordering number: 5892920266393*

Table 9: *Bioenergy production method worked on by authors and suggested for Nigeria*

Conversion Process	Method	Biomass	Focus	Authors
	Incineration & Direct combustion	MSW	Electricity and transport fuel	(Olanrewaju et al., 2019)
		MSW	Power production	(Akinshilo et al., 2019)
		MSW	Electric and energy	(Ibikunle et al., 2019, 2021)
		MSW	Electrical power generation	(Aderoju et al., 2019)
		MSW	Electricity generation	(Ogunjuyigbe et al., 2017)
		Oil palm residue	Bioenergy production	(Anyaoha & Zhang, 2021)
		Rice husk	Fired energy	(Anka Garba & Zangina, 2015)
Thermo chemical		Corn residues - stalk, cob, and straw	Energy recovery	(Mohammed et al., 2020)
	Pyrolysis & liquefacation	Oil palm	Electricity power with clean gas engine	(Nomanbhay et al., 2017)
		Musa spp. (banana and plantain) residues	Bioenergy	(Ayokunle O. Balogun et al., 2018)
		Energy crops and wood - Terminalia superba, Gmelina arborea, Lophira alata, Nauclea diderrichii and palm kernel expellers (PKE)	Power generation	(Akinrinola et al., 2014)
		Jatropha curcas fruit shells and seed coat	Biofuel and electrical power	(Odetoye et al., 2018)
		Cassava peels	Biofuel production	(Okekunle et al., 2016)
	Gasification	Fuel wood, saw dust, Agro-waste & MSW	Decentralized electricity generation	(Diyoke et al., 2014)
		Energy crops, palm kernel expellers and wood	Power generation	(Akinrinola et al., 2014)
		Rice husks	Off-grid electricity generation for rural communities	(Ejiofor et al., 2020)
		Wood chunks and shavings	Syngas for electricity generation	(Akhator et al., 2019)
	Briquetting	MSW	Power generation	(Obi et al., 2019)
	LFG to Energy	Jatropha curcas (Non-edible)	Bio-oil production	(Odetoye et al., 2018)
		MSW	Waste to energy	(Nubi et al., 2022)
		MSW	Biogas and electricity production	(Ayodele et al., 2018)
		MSW	Gas for energy production	(Yusuf et al., 2019)
	Anaerobic	MSW	Biogas and electricity production	(Ayodele et al., 2018)
		MSW, AR, LS	Biogas	(Okonkwo et al., 2018)
		Organic waste	Biogas	(Ngumah et al., 2013)
		Carica papaya petioles	Biofuel	(Jensen et al., 2020)
Biochemical		Manihot spp (cassava), Saccharin spp (sugarcane), corn cobs, Oryza sativa (rice husks or hulls, mango peels and sorghum bicolor	Bioethanol from lignocellulose	(Awoyale & Lokhat, 2019)

Conversion Process	Method	Biomass	Focus	Authors
		Sugarcane and sorghum	Bioethanol production	(Nasidi et al., 2010)
		Animal manure and MSW	Biogas methane	(Suberu et al., 2012b)
	Fermentation	Cassava wastes	Bioethanol, Biomethane	(Ekop IE et al., 2019)
	Biochemical/ biorefining	MSW and agro residues	Biofuels, biomaterial, and biochemical production	(Igbokwe et al., 2022)
		Agro-wastes	Biofuel for transportation	(Ben-Iwo et al., 2016b)
	Hybrid systems	Jatropha feedstock	Biodiesel, bioelectricity	(Sadiq Aliyu et al., 2017)
		Gas turbine and general biomass	Power Systems	(Diyoke et al., 2021)
	INC/LFGTE and ICE/AD	MSW	Bioenergy and advanced waste management	(Ayodele et al., 2017)

*INC – incineration *LFGTE – Landfill gas-to-energy *AD – Anaerobic. Source: Compiled by the author using various literature reviews, September 2024

Incineration and direct combustion stand out as the most studied approach in terms of biomass conversion technologies, with direct combustion being the most common biomass conversion procedure in Nigeria, as most households combust agricultural residues for heating and cooking. Traditional cooking procedure employs the use of firewood, which has low efficiency and causes threats to health (Umar et al., 2021). This is then followed by gasification and anaerobic digestion application. Economic feasibility of some of the conversion technologies like incineration gasification, anaerobic and fermentation for stand-alone generation plants was identified to be supported by lower operational and maintenance costs (Diyoke et al., 2014; Ukoba et al., 2023) and are further associated with technologies like microturbines, which are favoured for their flexibility and reduced maintenance needs compared to conventional internal combustion engines (Loeser & Redfern, 2008), thereby introducing a hybrid system (Diyoke et al., 2021) that can be cost-effective. Factors that determine the viability of small-scale technology conversion include the following – conversion level (Sobamowo & Ojolo, 2018), plant cost (Ben-Iwo et al., 2016a), conversion time and simplicity (Aderoju et al., 2019; Ejiofor et al., 2020) and applicability to scale-up (Diyoke et al., 2021; Nasidi et al., 2010; Ogunjuyigbe et al., 2017).

3.4 Prospect, Environment and socio-economic Impact on biomass Electricity

The prospects of biomass for electricity generation lie in its energy potential. The fact that biomass resources can be obtained from multiple sources makes it a unique source for bioenergy production. So far, there has been quite a little progress in adopting biomass resources for electricity production, as shown in the emerging bioenergy projects investments. Even though this progress is slow and many of them are still in the planning stage as shown in *Table 10* (Ohimain, 2010). The land is available; some studies have highlighted plant location (Chukwuma et al., 2021), and some have identified appropriate conversion technologies that can be fully adopted to produce electricity in some region efficiently (Ukoba et al., 2023).

The environmental impact of biomass electricity is its potential to significantly reduce greenhouse gas emissions and combat climate change, thereby making it a cleaner and more sustainable alternative to fossil fuels (Anyaoha & Zhang, 2021). Nigeria generates a huge amount of waste, which needs to be better managed and contributes to GHGs. One key environmental benefit is transforming waste into electricity. In 2014 alone, 353,717 tonnes of waste was generated and projected to increase to 2,223,497 tonnes by 2035 (Lawal et al., 2024). This translates to 411,097 MWh of energy potential.

Table 10. *Emerging bioenergy projects in Nigeria*

Project	Cost '$	Location	Owners	Feed stock	Feedstock QTY 'M	Project summary, production/yr	Land take (ha)	Project Phase
Automotive biofuel project	306M	Agasha Guma, Benue state	NNPC/private sector	Sugarcane	1.8M	75 million litres, 116,810 metric tonnes (sugar), 59 MW (electricity)	20,000 (16,000 will be cultivated)	Planning
Automotive biofuel project	306M	Bukaru, Benue state	NNPC/private sector	Sugarcane	1.8M	75 million litres, 116,810 metric tonnes (sugar), 59 MW (electricity)	20,000 (16,000 will be cultivated)	Planning
Automotive biofuel project	306M	Kupto, Gombe state	NNPC/private sector	Sugarcane	1.8M	75 million litres, 116,810 metric tonnes (sugar), 59 MW (electricity)	20,000 (16,000 will be cultivated)	Planning
Automotive biofuel project (Kwali Sugarcane ethanol project)	80 - 100M	Abuja, F.C.T	NNPC/private sector	Sugarcane	1.8M	120 million litres, 10–15 MW (electricity)	26,374 estimated	Planning
Automotive biofuel project	125M	Ebenebe, Anambra state	NNPC/private sector	Cassava	3 - 4M	40–60 million litres	15,000	Planning
Automotive biofuel project	125M	Okeluse, Ondo state	NNPC/private sector	Cassava	3 - 4M	40–60 million litres	15,000	Planning
Ethanol refinery and sorghum farm	70M	Arigidi, Akoko, Ondo	Global biofuel ltd	Sweet sorghum	1.05M, Est.	84 million litres bio-refineriesþfarm estimated	30,000 acquired	EPIC
Ethanol refinery and Sorghum farm	92M	Illemso, Ekiti state	Global biofuel ltd	Sweet Sorghum	385,000 Est.	30.8 million litres bio-refineriesþfarm estimated	100,000 acquired	EPIC
Ethanig (via Starcrest Nigeria Energy)	300M Est.	Katsina Ala/River Basin of Benue	Private	Sugarcane	3.25M Est.	100 million litres, sugar, and electricity	50,000	Planning
Ethanig (via Starcrest Nigeria Energy)	300M Est.	Kebbi state	Private	Sugarcane	3.25M Est.	100 million litres, sugar, and electricity	50,000	Conception
Savannah sugar company	167M	Numan, Adamawa	Dangote Industries Ltd	Sugarcane	1M	Expansion to produce 100M litres,1B tonnes sugar, 100,000 metric tonnes fertilizer and 300 MW electricity	36,000 (Lau, Taraba State)	Planning
Kwara Casplex Ltd.	90M Est.	Kwara state	Private/govern ment	Cassava	300,000 Est.	38.86 million litres	15,000	EPIC
Oke-Ayedun Cassava ethanol project	18M	Oke-Ayedun, Ekiti State	Ekiti state govt./ Private	Cassava	238,500	38.1 million litres bio-refinery + farm	15,000	EPIC
CrowNet Green Energy ethanol plant	122M	Iyemero, Ekiti	Ekiti state govt./ Private	Cassava	150,000	65 million litres, (100 t of starch and 50 t CO_2/ day)	12,500	Operational
Cassava ethanol plant	115M	Taraba state	Taraba state	Cassava	300,000	72M litres, 360,000t of cassava flour,1.87M tonnes CO_2 and 57 MGy of liquid fertilizer, 1600 MW electricity	30,000	EPIC
Niger State Govt. ethanol plant	90M Est.	Niger state	Niger state	Cassava	150,000	27 million litres, bio-refinery + farm estimated	15,000	EPIC
Cassava bioethanol plant	138M	Niger Delta Region	NA	Cassava	0.32M Est.	58 million litres, bio-refinery + farm estimated	20,000	Conception
Bioethanol from sugarcane/molasses	85M	Niger Delta Region	NA	Sugarcane	0.857M Est.	68 million litres	67,692 Estimated	Conception
Cassava industrialization project	16.4M	Ogun state	Private + Govt.	Cassava	75,000 Est.	3 million litres	5,000	Conception
National Cassakero cooking fuel programme	1B	36 states + Abuja	Private	Cassava		1.44 billion litres	500,000	EPIC

Source: (Ohimain, 2010)

Methane emissions from solid waste, around 491,000 tons in 2015, are expected to rise to 670,000 tons by 2030. This translates to 570,651 MWh of electricity and a projected value of 778,688 MWh by 2030. Yusuf et al. (2019) translated this to be 3.48 × 109 kWh of electricity in 2015, and around 4.74 × 109 kWh by 2030. Estimates have also shown that hybrid systems of incineration and anaerobic digestion could reduce global warming potential (GWP) of the country's waste management sector by 75.3 – 84.8% (Ayodele et al., 2017) . Biogas from livestock and animal waste can reduce the reliance on traditional fuels and lower methane emissions (Adeoti et al., 2014) which are more potent greenhouse gas than CO_2. In addition, livestock wastes not only reduce environmental pollution but provides farmers with renewable energy and organic fertiliser, improving soil health and productivity (Audu et al., 2020a) – all of which support sustainable agricultural practices.

In terms of socio-economic impact, biomass is the only RE that has a high labour employment rate. It impacts on factors like employment, wages (Ben-Iwo et al., 2016b) health and gender inclusion (Orifah et al., 2018). Usually, biofuel development takes place in rural areas, this not only improves rural livelihoods but also enhance access to energy services like electricity and clean water, reducing workload for women and children and improve health by lowering indoor air pollution.

4 Discussion

In this chapter, we summarize our results and key findings, addressing the research questions and highlighting the implications of these findings for policy and future research.

4.1 Current potential for bioenergy generation

From the results, we found that Biomass resources have multiple sources of which agricultural residues present substantial energy potential, with an estimated total annual energy potential ranging from 3.39 million GWh annual of which field residues are the most abundant compared to processing residues. Key agricultural residues highlighted in these studies includes rice husk, cassava peels, corn cobs, and oil palm biomass. Each of these residues has specific energy yields, with rice husk and straw, and cassava being popular for their potential in electricity generation (Anyanwu et al., 2013; Iye & Bilsborrow, 2013; Ozoegwu et al., 2017). Rice husk alone could generate approximately 0.41 million MWh/year, while rice straw could produce about 2.55 million MWh/year, totaling nearly 2.96 million MWh/year. Further findings show that the Northern regions have the highest availability of agricultural residues, with over 85% of field residues located there. This regional concentration is critical for targeting bioenergy initiatives (Jekayinfa & Scholz, 2009). This is followed by municipal solid waste generated from major cities, with a net generating potential exceeding 10,000 MW. Major cities identified in the studies were Lagos, Ibadan, Ilorin, Aguata city of Anambra states and Enugu city. With Lagos generating between 442 – 10,000MWh electricity potential on average. Ibadan and others with generating potential 3,600 MWh, 3,244 MWh, 545 MWh and 1571 MWh. This translates to 15360 MWh (15.36) billion GWh total energy potential for these cities annually. Waste from these cities alone could power the individual states if proper waste management is implemented across all states without having to dwell so much electricity from hydropower. This emphasizes the viability of waste to energy production, which could be more economically favourable compared to fossil-fuel-based energy sources. Trends in waste-to-energy studies emphasized biogas from MSW and indicated a rising trend in waste generation in the coming years. Waste generation in Ibadan was expected to rise from 477,001 tons in 2017 to 966,897 tons by 2036 (Ayodele et al., 2018). This would be about 112,374 MWh by 2036. Results also showed that livestock, although not contributing so much compared to other resources due to limited data on livestock wastes, have potential for biogas. It is found that Nigeria has a minimum biogas potential of 1.62 billion m^3 per year from livestock manure suggestion was made on replacing diesel fuel-based electricity generation with biogas-derived methane, which could save 0.60 million tons of CO2 emissions per year (Adeoti et al., 2014). Forest resource on the other hand is quite diverse and the reported obtainable forest residues and their energy potential haven't changed so much from the year 2020 to 2022. However, current estimates show an updated current energy potential from forest residue amounting to 411.54 PJ/yr, translated to 114,317 GWh which is like the value 4.12PJ/yr reported by (Ukoba et al., 2023).

The study findings so far have indicated that agricultural residues, municipal solid waste, livestock waste, and forest residues collectively present a substantial opportunity for Nigeria to expand its energy mix by adopting bioenergy. For potential to be maximized, there is need for a more accurate, region-specific data to fully quantify these resources.

4.2 Major Research Themes and Trends

Key themes in the selected studies focus on biomass resource assessment and electricity access, with most authors addressing one or two specific biomass - MSW or AR or LS or FR in individual studies. Few authors who addressed all, did not go in depth in terms of energy potential. These studies often combine their findings with discussions on appropriate technologies for energy conversion while examining the socioeconomic benefit of integrating biomass into Nigeria's national grid. The trends suggest that while there is a growing interest in biomass energy, a disproportionate number of studies have concentrated on MSW compared to other biomass sources. This trend is particularly evident in the articles, where many studies on MSW primarily focus on general waste management practices rather than going in-depth into their energy potentials. This gap indicates a pressing need for more targeted research that addresses energy potential for electricity generation.

Another emerging theme is the socio-economic impact of biomass energy integration into the national grid. Several studies highlight the potential for biomass energy to create jobs, stimulate local economies, and improve energy access in rural areas (Ben-

Iwo et al., 2016a). However, there is need for more empirical research that quantifies this benefit.

4.3 Feasibility of biomass-based power technologies

Result suggests different pathways for bioenergy production, noting that the country has however embarked on its journey to bioenergy production, even though most of the current project is still on planning stage. It highlighted that most biomass technologies are at different stages of development while some are still in research and development. Among the many conversions process, gasification, incineration and direct combustion from thermochemical process is widely used from MSW biomass, owing to its cost-effectiveness and applicability. This is followed by pyrolysis & liquefaction which uses majorly agro residues for power generation. Studies from biochemical conversion process reveals more of anaerobic digestion in producing biogas from MSW and agro residues followed by gasification technology employing majorly agro residues. Generating bioethanol and biomethane through fermentation of cassava wastes is also a popular practice in small scale settings (Ekop IE et al., 2019). Very few studies highlighted hybrid systems using Jatropha feedstock for power system generation (Sadiq et al., 2017), gas turbine from general biomass (Diyoke et al., 2021) as well as advanced technology for waste to energy using a combination of incineration and landfill gas to energy (Ayodele et al., 2017, 2018) from MSW biomass.

The study also revealed tha the viability of small-scale biomass conversion technologies depends on factors like conversion efficiency, setup cost, conversion time, simplicity, and scalability. Higher conversion efficiency makes the technology more appealing, while lower setup costs improve its economic feasibility. Faster and simpler conversion processes reduce operational challenges and costs, making implementation easier. Scalability is also important, as technologies that can expand to meet growing energy demands are better suited for long-term use.

4.4 Constraints to the contribution of biomass to energy availability

While the prospect and opportunity of biomass for electricity generation lies in its energy potential, assessed in the previous sections, the economic and socio-economic benefit it creates in terms of job creation, available and reliable electricity, etc., several significant challenges hinder its effective contribution to the country's electricity supply. A significant issue across literature is lack of robust infrastructure necessary for biomass collection, processing and distribution (Akinbami & Momodu, 2012; Ben-Iwo et al., 2016a). This infrastructure gap not only increases the operational costs for biomass electricity production but also limits access, especially in the rural areas where biomass resources are plentiful. Financial barriers (Lawal et al., 2024) such as insufficient financial support coupled and the high cost for technological equipment (Abila, 2012; Aderoju et al., 2019; Sokan-Adeaga & Ana, 2015) further complicates the situation. Even when funding is available, complex bureaucratic procedures often delay projects if not inhibits the project (Ogunjuyigbe et al., 2017; Yusuf et al., 2019); outdated technology (Diyoke et al., 2014; Igbokwe et al., 2022; Sobamowo & Ojolo, 2018); weak policy and regulation issues (Aliyu et al., 2017a; Babalola & Olayinka Oyedepo, 2019; Giwa et al., 2017; Ohimain, 2013) which ends up creating a fragmented regulatory environment that is not conducive to large-scale investment; economic and market challenge (Ayodele et al., 2018; Igbokwe et al., 2022; Zang et al., 2020) environmental and social acceptance factors (Chukwuma et al., 2021; Mohammed et al., 2020; Okafor et al., 2022; Ukoba et al., 2023) highlighting the resistance from communities that are wary of potential environmental impacts, such as deforestation and land degradation. This community resistance can delay projects and reduce the available biomass resources, adding complexity to the deployment of biomass for electricity production.

4.5 Biomass-to-energy production: Lessons from other countries

The discussion of this section leads to policy recommendations. Bioenergy Projects across the globe have been significantly advancing, with China, Brazil and the US leading in Asia and North and South America, respectively. In 2023, China held the highest bioenergy capacity globally, closely followed by Brazil, US, India and Germany. (IRENA, 2024a). Countries in the EU are very much utilizing bioenergy, with Germany, Finland, Sweden, Italy and the Netherlands gaining popularity in biomass to-energy production; the progress made in EU is due to its adoption of the EU Green Deal and the Fit-for-55 package, which aims to make the European climate neutral by 2050 and increase renewable energy share target to 40% (IEA, 2021a). *Table 11* shows countries and their utility-scale bioenergy power stations.

While China, with a cumulative bioenergy capacity of 2,955 MW, leveraging AR, MSW as primary feedstock has advanced bioenergy policies like feed-in tariffs that guarantee financial stability for bioenergy projects (IEA, 2021c) its, policy-driven environment incentivizes investments in biomass-based electricity and biogas, fostering a favourable market for advanced bioenergy infrastructure. India, majorly adopting AR as primary feedstock with an installed bioenergy capacity of 247 MW, follows a more decentralized model, integrating bioenergy with coal-fired power plants to achieve greater fuel efficiency through co-firing (IEA, 2021f). Brazil and the United States showcase two different but complementary approaches to bioenergy development in the Americas. While Brazil leads with the highest installed bioenergy capacity in the America continent, reaching 12,688 MW (IEA, 2021b), driven by its established policy frameworks, fertile land and favourable climatic for sugarcane cultivation providing a steady and cost-effective feedstock for its bioenergy production, the United States, with a cumulative bioenergy capacity of 2,306 MW (IEA, 2021g), takes a different approach focused on diverse feedstocks and efficiency driven innovation.

Bioenergy ventures began in Africa in the 80's but started gaining grounds in the mid to late 2000s (Gatete & Dabat, 2017)Despite its promising resource, Nigeria faces a considerable challenge in bioenergy development, with only one identified operational bioenergy plant stressing a critical gap in its bioenergy infrastructure. Meanwhile, Kenya is leading in bioenergy potential with fully operational infrastructure, making it a practical model for bioenergy deployment that prioritizes health, environmental sustainability, and rural development.

Table 11. *Bioenergy development across countries*

Country	[1]Policy / Initiative	[1]Objectives	[2]Cumulative installed bioenergy capacity (MW)	[2]Status	[2]Fuel type & Major Feedstock	[1]Research focus related to bioenergy	*Challenges
Nigeria	National Biofuel Policy and Incentives (2007)	10% ethanol blend. 100% local biofuel production by 2020. Agricultural integration to biofuel	No expected capacity. Instead a land requirement of 873,566 ha(based on emerging biofuel companies need)	Announced & pre-construction	Transgenic varieties of 1st G feedstock-cassava, sorghum, sugarcane, Jatropha curcas and non-edible crops.	Bioenergy conversion technologies, waste-to-energy R&D, bioenergy data	I, II, III, IV, V, VI, VII, X, XI, VII, XII
Kenya	Bioenergy Strategy 2020-2027 National Climate Change Action Plan (NCCAP) 2018-2022	0.8% cooking biogas by 2030 0.07% biogas electricity generation of the RE mix. 10% bioethanol gasoline blend for transport sector. 1-25% biodiesel blend to traditional diesel.	34 MW cumulative installed biopower capacity (BC)	All in operation	1st G feedstocks, wood and other biomass (solid), animal wastes.	biogas technology, improved biomass cookstoves & alternative biomass feedstocks e.g. Prosopis juliflora	I, II, III, V, X
Brazil	RENOVABIO (policy for biofuels); PROINFA 2004 (incentive program for alternative sources of electric energy); Reserve energy auctions (LER 2008); National electric systems operator (ONS) regulations.	27% blend of ethanol in gasoline and 11% biodiesel in diesel. Biomass for power generation. Competition of biomass derived energy sources and growth in bioelectricity;	12,688 MW cumulative BC with 27 utility-scale power station units above 30MW capacity.	All in operation	Agro wastes (solids), wood, paper mills waste	Biofuel & demonstration plants e.g. PAISS program for cellulosic ethanol and drop-in biofuels.	IV, V, VII, VIII, IX
India	Biomass utilisation for power generation through co-firing in coal-based power Plants (2017). The National Policy on Biofuels (NPB) 2018	5-10% blend of biomass pellets for coal based thermal power plants. 20% blend of ethanol in petrol and 5% biodiesel in diesel by 2030	247 MW cumulative BC with 11 utility-scale power station units above 30MW capacity.	All in operation	Mostly agro-wates (solids)	Advanced conversion technologies,	I, III, V, VI, VII, VIII, X,
China	Fixed feed-in tarrif (2010); Guiding Opinions on Promoting the Development of Biomass-based Heating (2017)	0.75 yuan per kilowatt hour (including tax) benchmark feed-in tariff. Price policy for bio-power, biogas and biofuels.	2,955 MW cumulative BC with 542 utility-scale power station units above 30 MW capacity	All in operation	Agro-wastes (solids), paper mill wastes, municipal & industrial waste, wastewater & sewage, wood & other biomass (solid)	Flexible processing methods for cost reduction, new approaches of cellulosic ethanol technology.	III, V, VII, VIII, X, XI, IX
Finland	Finnish Bioeconomy strategy 2014 National Energy and Climate Strategy 2030.	Increase bioeconomy output up to EUR 100 billion by 2025 30% increase in share of biofuels used in road traffic by 2029	471 MW cumulative BC with 11 utility-scale power station units above 30 MW capacity	All in operation	Wood & other biomass (syngas), paper mill wastes, municipal & industrial wastes, agro-waste.	Waste-to-energy for transport fuel, biogas production. sustainable liquids fuels, green hydrogen from electrolysers.	IV, V, XIII, XIV

Country	[1]Policy / Initiative	[1]Objectives	[2]Cumulative installed bioenergy capacity (MW)	[2]Status	[2]Fuel type & Major Feedstock	[1]Research focus related to bioenergy	*Challenges
United States	Renewable fuel standards (RFS). Energy Independence and Security Act of 2007 (EISA). Biodiesel Mixture Excise Tax Credit 2005, amended 2008	50% biomass-based diesel, 50% advanced biofuel & cellulosic biofuel 60%. 9% increase in biofuel volume until 2022 & 20% gasoline cost reduction from 2007 until 2017. $1.00 per-gallon income tax credit on biodiesel, renewable diesel, or agri-biodiesel	2,306 MW cumulative BC with 24 utility-scale power station units above 30MW capacity	All in operation	Wood & other biomass (solids), paper mill wastes, municipal and industrial waste	Scale-up for energy efficiency	II, III, IV, VII
Germany	Renewable Energy Sources Act (EEG) 2000,2017&2021 Biomass-electricity-sustainability ordinance (BioSt-NachV) 2009 Biomass Ordinance 2001 Climate Action Plan 2050	Expansion for 8.4 GW (8,400 MW) biomass by 2030. liquid biomass to receive feed in tariffs for bioenergy under Germany's Renewable Energy Law	655 MW cumulative BC with 8 utility-scale power station units above 30MW capacity	All in operation	Municipal & Industrial wastes, paper mill wastes, wood & other biomass (solids)	Agro-biomass & aquatic sources, biogenic wastes, Green hydrogen, carbon dioxide removal (CDR	II, III, IV, V, VI

Table 4: Bioenergy development across countries
Source: Compiled by author using various data sources, September 2024.

*I (access to financial support), II (outdated or high-cost technology), III (policy), IV (food security), V (environment and climate change), VI (lack of incentive), VII (infrastructure logistics), VIII (complex regulatory framework), IX (market competition), X (public awareness), XI (data accuracy), XIII (integration with other technologies), XIV (efficiency).

[1] (Anyaoku O.A, 2007), (Ohimain, 2010); (Kenya Bioenergy Strategy, 2020) (Kenya National Climate Change Action Plan, 2018); (IEA, 2021b), (IEA, 2021f), (Das, 2020), (IEA, 2021c), (IEA, 2021d), (IEA, 2021g), (IEA, 2021e), (Arasto et al., 2021; *Bioeconomy-Products-2035-Whitepaper-VTT-Luke_1*, 2021).

[2] Global bioenergy power tracker methodology; global energy power tracker, installers of bioenergy powerplants Information updated to 2022. Accessed October 20, 2024. Copyright © Global Energy Monitor. Nb: Cumulative installed bioenergy capacity (MW) includes multiple facilities existing at a particular location, each facility representing 30 and above MW units and entire collection of units at a given location representing 'power station'

5 Policy Recommendation and Limitations

Biomass is among the few renewable energy sources that are unaffected by weather, seasonal changes, or time of day and can be stored for use on-demand use. This scoping review reveals that poor policy implementation is a key factor hindering the potential of biomass energy resources and the full adoption of bioenergy in Nigeria. Several actions are necessary to expand biomass-based electricity availability: strengthening the regulatory framework for bioenergy utilization, as the current biofuel policy is insufficient to drive progress. The country needs to fully integrate biomass into the national energy strategies, given its promising biomass resources, including waste-to-energy technologies; and introducing effective bioenergy policies, as other countries have done, to boost biomass's role in power generation. Renewable energy subsidies, tax rebates, and feed-in tariffs have greatly increased the share renewables in the OECD energy mix, and Nigeria should similarly incentivize biomass investments to attract local entrepreneurs, create jobs, and foster innovation in biomass conversion. the country should therefor incentivize biomass energy investment to attract local entrepreneurs, create jobs and encourage innovation in biomass conversion technologies. Public awareness campaigns are also essential, helping citizens understand the benefit of biomass energy while encouraging responsible waste management, as practiced in Finland and Germany.

Limitations to these studies includes data gaps, as it was challenging to find up-to-date data on Nigeria's bioenergy development and biomass resources. They were more studies on MSW, AR than LR and FR, with many focusing on general waste management, without specifically addressing biomass types, quantities, and energy potentials. This gap hindered precise estimations of biomass energy especially for livestock and forest residues, which requires more accurate, regionalized data. In addition, the reliance on available literature restricted the study to secondary data and did not include primary data collection, which would have provided richer, location-specific insights. The study did not address all technological aspects of biomass conversion, such as emerging technologies with potential to improve biomass energy efficiency, which were outside the scope of this work. However, as biomass energy technology is growing and evolving in advanced countries, technology constraints at the time of this study may not represent future capabilities or applications in Nigeria

6 Conclusion

There is an untapped potential for biomass resources to address pressing issues and contribute to a sustainable energy transition in Nigeria. Given that the country is rich in biomass, one of the oldest forms of energy, there is still ample opportunity to harness this energy source and invest rapidly in bioenergy for rural electrification, carbon reduction and sustainable economic growth. Based on the scoping review approach, the study shows that major cities could generate between 440 MWh and 15,360 MWh of energy annually, generating a substantial amount of electricity. This translates to between 0.4 - 15.36 billion GWh of energy potential for electricity annually. The study also finds that the total energy potential generated from different common local commodity crops in the country amounted to about 2918.50 million metric tons available for power generation annually; this translates to 3.391 million GWh of energy potential, minimum to be realized annually. Meanwhile, only a few major livestock wastes were accounted for due to data limitation, generating 3.46 kg of waste per day and 950.53 thousand metric tons available for energy potential, translating to 263,889 MWh and 0.26 GWh of energy potential. With diverse biomass resources from agroforest residues and solid and livestock wastes, the country can increase its energy mix.

The recent removal of fossil fuel subsidies in May 2023 has caused a sharp rise in fuel costs for electricity generation, yet the necessary shift to biomass as an alternative energy source has not been fully realized. This delay in diversification means that energy costs remain high, limiting access to affordable electricity and continuing dependence on costly, non-renewable energy sources. Nigeria can accelerate its bioenergy sector but first it needs to address the identified constraints. However, overcoming data gaps, increasing funding for research, and developing region-specific targeted policies will be critical to achieving these goals.

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Appendices

Appendix 1: Study selection

7/1/24, 11:18 AM "Biomass" OR "Bioenergy" OR "Biofuel Nigeria" OR... - Google Scholar

Biomass resources and **bioenergy** potentials in Nigeria
KJ Simonyan, O Fasina - African journal of agricultural ..., 2013 - academicjournals.org
… This paper reviewed the **biomass** resources available in Nigeria and the potential of … status of **biomass** resources and their **bioenergy** potential and the possibility of utilizing **biomass** to …
Save Cite Cited by 186 Related articles All 8 versions

Bioenergy–a sustainable and reliable energy source
IEA **Bioenergy** - International Energy Agency **Bioenergy**, Paris ..., 2009 - publications.tno.nl
… Many **bioenergy** routes can be used to convert a range of raw **biomass** feedstocks into a final energy product. Technologies for producing heat and power from **biomass** are already well-…
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4 0 3 0

Bioenergy
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J Cook, J Beyea - **Biomass** and **bioenergy**, 2000 - Elsevier
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M Ozturk, N Saba, V Altay, R Iqbal, KR Hakeem… - … and Sustainable Energy …, 2017 - Elsevier

… Both countries have good potential to use **biomass** resources, but political backing … **biomass** potentials of Turkey and Malaysia, while providing an insight into data on different **biomass** …

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… considerable studies about **biomass** and **bioenergy** potential, … existing researches about **biomass** and **bioenergy** potential … progress of **biomass** and **bioenergy** potential estimation, from …

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YM Bar-On, R Phillips, R Milo - Proceedings of the National …, 2018 - National Acad Sciences

… We show that terrestrial **biomass** is about two orders of magnitude higher than marine **biomass** … We find that the **biomass** of plants dominates the **biomass** of the biosphere and is mostly …

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Appendix 2: Sources of selected studies

Table 5: List of studies chosen for detailed analysis

Agricultural residue (AR)

Author	Article type	Study method	#Studies reviewed	Key findings
Iye & Bilsborrow, (2013)	Journal article	Quantitative Assessment	44	. Total annual agricultural residue available in Nigeria was estimated to be 55.9 Tg, with a potential energy value of 657.01 PJ of which field residues were the most abundant, accounting for 38.4 Tg/yr compared to 17.4 Tg of processing residues. . Northern zones having the highest availability of residues, with over 85% of the field residues located there.
(Jekayinfa & Scholz, 2009)	Journal article	Quantitative	33	. Around 58 million tonnes of selected agro-residues with energy potential of about 20.8 MT of oil equivalents were potentially available in 2004. . Projected availability in 2010 is estimated to be around 80 MT.
(Anyanwu et al., 2013)	Journal article	Quantitative review	85	. Nigeria could generate substantial amount of 660,000 tons of rice husk and 870,000 tons of rice straw annually, which could produce 9.2 PJ and 8.7 PJ of energy, respectively. . Other larger productions are oil palm biomass, cocoa pod husk and animal manure that can be utilized for energy generation
(Ozoegwu et al., 2017)	Article	Mixed method of qualitative & quantitative	88	. Cassava production in Nigeria has been increasing at a rate of about 4.3% per annum since 1997, leading to vast waste generation from cassava processing that constitutes a major agricultural residue of high bioenergy content.
(Anka Garba & Zangina, 2015)	Article	Quantitative	22	. Estimated annual production of rice straw and rice husk in Nigeria is 4.34 million tons and 0.70 million tons, respectively. . electric power generation potential from rice straw and rice husk is 2.55 million MWh/year and 0.41 million MWh/year, respectively, totaling 2.96 million MWh/year. . potential GHG emissions savings from using rice straw and rice husk for electricity generation is estimated to be 5.8 million tons CO2-equivalent per year.
(Akpahou et al., 2024)	Article	Quantitative with primary data	62	. Benin state has a total energy potential of 142.63 PJ/year in 2021, with agricultural residues contributing over 98% of this potential. . Maize, cotton, and cassava were identified as the top three contributors. . bioenergy potential available for electricity generation is 85.6 PJ, with maize, cotton, and cassava residues being the most promising feedstocks.
(Suberu et al., 2012a)	Journal article	Quantitative analysis with secondary data	31	. Potential power generation from corn cob residues in Nigeria could reach nearly 3,000 MW in 2010, assuming 70% of the residues are available for power generation. . Results also show a fluctuating potential over the years, influenced by factors like climate, farm inputs, and cultivated area.

Author	Article type	Study method	#Studies reviewed	Key findings
(Ekop IE et al., 2019)	Journal article	Quantitative analysis with secondary data	48	. One kilogram of cassava peels can yield 118 grams of biomethane and 226 grams of bioethanol. . One litre of cassava wastewater can yield 16 grams of bioethanol and 9 grams of biomethane. .One litre of bagasse can yield 20 grams of bioethanol and 10 grams of biomethane.
(Aduba & Shimada, 2023)	Journal paper	Mixed method approach with primary data through field survey	20	. Most rice mills in Nigeria are privately owned, with many starting operations in the last 8 years. . Approx. 68 rice mills and/or clusters can generate 2-12 MW of electricity from rice husk, meeting their own energy needs and providing electricity to nearby households. . Utilizing rice husk for electricity generation can save over 89,000 kg of CO2 emissions daily by reducing open burning and improper disposal.
(Awoyale & Lokhat, 2019)	Review article	Quantitative approach, primary data based on estimates	67	. Nigeria has significant potential to produce bioethanol from agricultural residues, with an estimated annual production capacity of 7.556 × 10^9 L. . Cassava peels, sugarcane bagasse, corn cobs, mango peels, sorghum straw, and rice husks were identified as the major lignocellulosic feedstocks available in the country.
(Ejiofor et al., 2020)	Journal article	Quantitative approach	23	annual availability of rice husk in Adani local community is 3,636 tons, which has the potential to generate 1.52 MW of electricity.

Municipal solid waste (MSW)

Author	Literature type	Study method	#Studies reviewed	Key findings
(Suberu et al., 2012b)	Journal	Mixed method with secondary and primary data collected via survey.	25	. Lagos metropolis has an estimated power generation potential of around 442 MW from MSW, which is significant enough to help address the persistent power supply issues in the region.
(Ityona Amber et al., 2012)	Journal	Quantitative through spot sampling. Sampling protocol includes 5 samples of 10kg msw from dumpsites	25	. Potential for 44-0.66 kg/capita/day of MSW with a 200-400 kg/m³ density. . Average calorific value of the MSW was 17.23 MJ/kg, with a high water content of 20-49%. . With an incineration plant capacity of 1500 tons of msw per day, 700 kW of electricity per day could be generated
(Chukwuma et al., 2021)	Journal Article	Quantitative assessment using GIS	22	. Annual cumulative bio-waste generation of three LGAs is estimated to be about 9,133,220 kg, 3,992,735 kg, and 6,909,450 kg, respectively.

Author	Literature type	Study method	#Studies reviewed	Key findings
(Akinshilo et al., 2019)	Journal Article	Quantitative approach with secondary data	36	. 1 ton of MSW in Lagos can generate 0.6683 kg of carbon, producing 1.333 kg of methane through a chemical reaction. . Energy recovery potential from the dry waste is estimated to be over 1300 GWh/day, with a net generation potential of over 10,000 MW power. . Processing cost of MSW for energy generation is found to be economically viable compared to the cost of fossil fuel-based energy.
(Okafor, Nzekwe, Nduji, et al., 2022)	Journal article	Quantitative approach with secondary desktop data	74	. Average MSW generation rate in the 22 cities is 0.56 kg/person/day . Estimated total MSW generated in these cities in 2021 is 20,378 tons per day or 7.4 million tons/yr. . composition of the MSW is: organics (56%), plastics (9%), paper (13%), glass and metal (3% each), textiles (2%), and others (14%).
(Lawal et al., 2024)	Journal article	Quantitative approach, using primary data from field surveys and secondary data	61	. MSW has a high organic content of 54.1% and projected to increase from 353,717 tonnes in 2014 to 2,223,497 tonnes by 2035. . Estimated methane gas generation was 9.85 Gg/year in 2014, which could potentially produce 15.7 MW/day of electricity and is projected to increase to 33.4 MW/day by 2035.
(Namo, 2015)	Journal article	Mixed method approach - quantitative source via primary sources e.g. field experiment and measurement), qualitative via direct observation	13	. around 18,144 tons of waste per year is comes out from Jalingo metropolis, out of which 15,930.43 tons are available for energy. . The bio-chemical and thermo-chemical conversion processes can potentially generate 62,596.80 kW and 151,016.14 kW of net power, respectively.
(Yusuf et al., 2019)	Research article	Mixed method approach	77	. Yearly waste generation increased from 6,471 Gg in 1959 to 26,600 Gg in 2015 and is projected to reach 36,250 Gg by 2030. . Methane emissions from this waste were 491 Gg in 2015 and are expected to reach 669 Gg by 2030.
(Ayodele et al., 2018)	Journal article	Quantitative life cycle assessment (LCA) approach	57	. Waste generation potential of Ibadan city could increase from 477,001 tons in 2017 to 966,897 tons in 2036 . Electricity generation potential ranged from 321.73 to 652.15 GWh for AD and 63.25 to 436.18 GWh for landfill gas recovery.
(Ibikunle et al., 2021)	Journal article	Quantitative assessment	23	. 203,831 tonnes of municipal solid waste was produced during the study period in one metropolis at the rate of 1.12 kg per capita per day.

Author	Literature type	Study method	#Studies reviewed	Key findings
				. 280 tonnes/day of municipal solid waste with low heating value of 19 MJ kg -1 , would generate 1478 MWh of heat energy and 18 MW of electrical energy potentials discretely, and grid of 13 kW.

Livestock waste (LS)

Author	Article type	Study method	#Studies reviewed	Key findings
(Adeoti et al., 2014)	Journal article	Quantitative approach using secondary data	70	. Nigeria has a minimum biogas potential of 1.62 billion m^3 per year from livestock manure. . Replacing diesel fuel-based electricity generation with biogas-derived methane could save 0.60 million tons of CO2 emissions/yr.
(Odekanle et al., 2020)	Journal article	Quantitative study with primary data from abattoir site	56	. 1040 MWh and 1664.6 MWh of electricity can be generated from biogas at low-end and high-end conversion efficiencies, respectively.
(Audu et al., 2020b)	Journal article	Mix method approach. primary and secondary data from slaughterhouse	75	. No abattoirs had automated systems for meat and waste processing . Slaughterhouse can generate 709 kW of electricity with anaerobic digestion.
(Ngumah et al., 2013)	Journal article	Quantitative approach using established coefficients to estimate the amount of biogas that can be derived from each livestock.	20	. Studies found that bout 15.74 billion m^3 of biogas from livestock waste (cattle excreta, sheep and goat excreta, pig excreta, poultry excreta, and abattoir waste) per annum is generated. This includes 6.52 billion m^3 from cattle excreta, 2.3 billion m^3 from sheep and goat excreta, 0.92 billion m^3 from pig excreta, 2.5 billion m^3 from poultry excreta, and 4.42 billion m^3 from abattoir waste.
(Simonyan K.J & Fasina O, 2013)	Journal article	Mixed method approach	69	.Total estimated of dry matter from animal dung in for the year was 15.762 million tons per year, with a potential biogas yield of 4.19 billion m^3/year translated into 29.25 GJ.

Forest Residue (FR)

Author	Article type	Study method	#Studies reviewed	Key finding
(Sadiku, 2016)	Peered Reviewed article	Quantitative approach via samples and laboratory analyses	72	. Study explored bamboo species (Bambusa vulgaris), the most dominant bamboo biomass in Nigeria, as a suitable alternative to wood resource which has never been explored. . Average biomass production of bamboo was reported to be 241.7 Mg/ha, which is comparable to a fast-growing plantation species and can serve as an important source of energy.
(Akinbami & Momodu, 2012)	Journal article	mixed method approach with primary data via field survey,	16	. 100 sawmills were identified generating about 12,220 m3 (66,000 tonnes) of sawdust per year with potential to

Author	Article type	Study method	#Studies reviewed	Key finding
		questionnaire and participatory approach		power an 8 MW generating plant with an annual output of 79,089 MWh. . Utilizing the sawdust and rice husk for power generation can avoid over 73,000 tonnes of CO2 emissions per year.
(Oluoti et al., 2014)	White article	white paper with a mix of secondary sources, such as research papers, policy documents, and industry news	53	. About 1.3 TWh of electricity can be generated from the 1.8 million tonnes per year of wood waste produced by the lumber industry in Nigeria. . The technical and economic analysis shows that internal combustion and stirling engines are the most economically feasible options for small-scale power generation, while gas and steam turbines are more suitable for medium/large-scale biomass power plants.
(Ukoba, Diemuodeke, Briggs, Imran, Ojapah, et al., 2023)	Journal	mixed-method approach, utilizing both quantitative and qualitative data.	60	. About 4.12 PJ/yr of energy could be derived from forest residues to support bioenergy development.
(Ogbu et al., 2022)	Research paper	Qualitative approach	30	. More than 93% of all wood processing industries in nigeria are sawmills. . Forest wastes such as logging residues, sawdust and wood waste have significant potential for bioenergy. . About 1.8 million tonnes of the total estimated 7 million tons per year of sawdust and other forest wastes in Nigeria can generate 1.3 TWh of electricity.
(Owoyemi et al., 2016)	Review article	Quantitative via secondary data from literatures,	24	. 1.8m tons of sawdust and 5.2 million tons of wood waste annually. In 2010, 1 million m^3 of wood waste was generated and 500 m^3 was generated from plywood. . 104,000 m3 of wood waste is generated daily nationwide. Wood waste in Lagos and Abeokuta is estimated at 294,979.9 tons/year and 2,288 m3, respectively.
(Jekayinfa et al., 2020a)	Review article	mixed-methods approach, using both quantitative and qualitative data including previous research report.	338	. Estimated energy potential for forest residue at 0.48 EJ, considering both wood fuel and charcoal . The potentials of wood fuel and charcoal were estimated at 0.38 and 0.05 EJ, respectively and when added to forest residue, increases the energy potential.
(Simonyan K.J & Fasina O, 2013)	Reviewed journal	Mixed method – quantitative and qualitative assessmnent	69	. total forest and wood processing residues in Nigeria in 2010 were estimated to be 1,367,400 m^3 (9.54 MJ) from logging residues (stumps, branches, leaves, defect logs, off-cuts, and sawdust) and 1,139,500 m^3 from sawmilling residues (bark, slabs, edgings, trimming, and sawdust).

Source: Compiled by author using various data sources, September 2024

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