UJEAS

UNIZIK JOURNAL OF ENGINEERING AND APPLIED SCIENCES

UNIZIK Journal of Engineering and Applied Sciences 6(2), June (2026), 3502-3517
Journal homepage: https://journals.unizik.edu.ng/index.php/ujeas
PRINT ISSN: 2992-4383 || ONLINE ISSN: 2992-4391

Biomass in Nigeria: The Present State, Obstacles, and Potential as Alternative Fuel Energy

Abubakar Hamzat[1*], Hassan Mudathir Abdulsalam[2] and Abdulkabir. Raji[2]
[1]Department of Metalwork Technology Education, School of Technology Education, Federal College of Education (Technical), Gombe, Nigeria
[2]Department of Mechanical Engineering, Faculty of Engineering, Modibbo Adama University, Yola, Nigeria
[*]Corresponding Author's E-mail:abubakarhamzat5@gmail.com

Abstract
This study presents a structured review of biomass energy in Nigeria, focusing on its current status, technological pathways, challenges, and future prospects. A systematic search of peer-reviewed literature, reports, and databases was conducted to synthesize evidence on present State of biomass energy potentials in Nigeria, analyse technologies of biomass conversion, and obstacles and future prospects. Nigeria generates approximately 144 million tonnes of biomass annually, with an estimated technical energy potential of about 2.33 EJ. Despite this abundance, biomass utilization remains largely traditional and inefficient. The review identifies key barriers, including technological limitations, weak policy implementation, financial constraints, and environmental concerns. The findings further reveal that advanced conversion technologies such as pyrolysis, gasification, and anaerobic digestion remain underdeveloped in Nigeria. The paper highlights opportunities for sustainable bioenergy development through improved policy support, investment in modern technologies, and integration into national energy strategies. This review contributes by providing a critical synthesis of existing knowledge and identifying research and policy gaps necessary for advancing biomass energy utilization in Nigeria.

Keywords: Agricultural wastes; Biomass; carbonization; Energy; feedstock; Potentials

1. Introduction

Energy is the driving force behind significant developments in every nation and it is essential for both social and economic advancements. Significant changes have been brought about by these advancements, especially in the way that industrial and domestic energy is used (Oliy and Muleta, 2020). Energy is a cornerstone of socioeconomic development. It drives industrial growth, powers transportation, and facilitates the provision of essential services such as healthcare and education. Access to reliable energy sources is directly linked to economic prosperity and improved quality of life. Energy enables productivity, supports job creation, and stimulates technological innovation. Moreover, it plays a critical role in reducing poverty and enhancing the standard of living by powering homes, schools, and businesses (IEA, 2020). The global energy scenario is characterized by increasing demand and consumption driven by population growth and economic development.

According to the International Energy Agency (IEA) (IEA, 2020), global energy demand is expected to rise by nearly 30% by 2040. This surge is largely attributed to burgeoning economies in Asia and Africa, where urbanization and industrialization are rapidly expanding. Non-renewable energy sources, such as coal, oil, and natural gas, have historically dominated the global energy landscape. These resources are finite and concentrated in specific geographic regions, leading to geopolitical complexities and environmental concerns. The extraction and combustion of fossil fuels are major contributors to greenhouse gas emissions, air pollution, and climate change. Despite these challenges, non-renewable energy remains a significant component of the global energy mix due to its high energy density and established infrastructure (BP, 2021). In contrast, renewable energy sources, including solar, wind, hydro, and biomass, offer a sustainable alternative. These sources are abundant, widely distributed, and have a lower environmental impact compared to fossil fuels. Renewable energy is essential for reducing carbon

footprints and mitigating climate change. The adoption of renewable energy technologies has been accelerating, driven by technological advancements, decreasing costs, and supportive policies. For instance, the cost of solar photovoltaic (PV) modules has dropped by more than 80% over the past decade, making solar power increasingly competitive with traditional energy sources (Koutoudjian et al., 2021).

Balancing the energy mix is crucial for ensuring energy security and sustainability. A diversified energy portfolio reduces dependency on any single source and enhances resilience against market volatility and supply disruptions. Integrating renewable energy into the existing grid requires significant investments in infrastructure, storage solutions, and smart grid technologies to manage variability and ensure reliable supply (IEA, 2020). Nigeria has an assortment of biomass residues, agricultural deposits, human and animal wastes, aquatic biomass, and energy crops which, generally are underutilized (Jekayinfa et al., 2020). Several resources, notably agricultural leftovers, have competing applications, such as livestock feed and soil revitalization. An estimate of the technical energy potential of biomass resources found that around 2.33 EJ might be generated from the available resources in Nigeria. (Jekayinfa et al., 2020).

Despite this potential, biomass utilization in Nigeria is largely inefficient, dominated by traditional combustion practices with low energy efficiency and high environmental impact. While previous studies have explored biomass resources and technologies, there remains a lack of integrated synthesis and critical evaluation. The objectives of this paper aim to review present State of biomass energy potentials in Nigeria, analyse technologies of biomass conversion, and obstacles and future prospects. Several studies have been carried out by different researchers to exploit various types of biomass materials as alternative sources of energy. Among these researchers are, Zubairu and Abba (2014) who found out that carbonizing corn cobs biomass resources into briquette charcoal is an effective means of managing solid wastes and a viable source of alternative energy. Bio-coke, a char made from a mixture of biomass/charcoal and coal, is a viable substitute for traditional fossil fuels that reduce CO_2 emissions (Seo et al., 2020). Similarly, in the study of Oliy and Muleta (2020), briquettes are characterized with energy content (higher heating value) from 27.60 to 29.67 MJ/kg.

The work of Yirijor et al. (2023) involved producing briquettes using a mixture of corncob (CC) and coconut husk (CH). It was determined that the optimal mix ratio, resulting in the highest calorific value, favourable moisture and ash levels, high density, and durability index, is CH: CC 20:80. Additionally, the research showed that with the rise in corncob levels, the density of briquettes increased from 584.20 kg/m^3 to 839.80 kg/m^3. Decrease in moisture levels from 5.05% to 4.88%, reduction in ash levels from 5.60% to 3.17%, and elevation in calorific value from 20.35 MJ/kg to 26.75 MJ/kg were reported. Lubwama et al. (2020) reported that the calorific values of carbonized bio-composite briquettes made from rice husks, coffee husks, and groundnut shells ranged from 16.6 MJ/kg to 22 MJ/kg. The drop strength test results for these composite briquettes were all above 86%, indicating good quality. The densities varied between 430 kg/m^3 and 580 kg/m^3. The study highlighted the benefits of producing bio-char bio-composite briquettes compared to those made from a single type of biomass. According to a Kihombo et al. (2021), Africa's present energy supply is insufficient to satisfy the energy demands of the majority of African countries, affecting their economic development and industrial growth. Kraus and Kraus (2021) stated that electricity is an essential requirement for any country that prioritizes industrial growth. This is because industrial development leads to socioeconomic growth, which many countries demand. Nerini et al. (2016) reported that over 1.3 billion people worldwide lacked adequate energy access. This number dropped below one billion in 2017, according to the Renewables Energy Global Status Report by (Raturi, 2019). In 2017, the population globally without electricity access fell below one billion, with around 61% in sub-Saharan Africa and 35% in Asia. To address this, one of the United Nations' (UN) Sustainable Energy for All (SE4All) key goals is to achieve universal electricity access by 2030 (United, 2015). Consequently, countries like China, Germany, India, Brazil, and the USA have diversified into renewable and sustainable energy sources to meet their energy needs (Brodny et al., 2021).

Nigeria aims to meet its growing energy needs sustainably by exploring alternative methods to reduce its carbon footprint and potentially changing its current electricity generation path. The country has significant potential in renewable energy resources such as biomass, solar, wind, and hydropower. According to Akorede et al. (2017), Nigeria is rich in these renewable resources. To address global energy crises, climate change, and energy poverty, the renewable energy supply must be sustainable, economical, efficient, and environmentally friendly. Nigeria receives high solar radiation levels, ranging from 5500 to 6500 Wh/m^2 nationwide (Akorede et al., 2017). Shaaban and Petinrin (2014) reported that Nigeria produces approximately 144 million tonnes of biomass annually. Furthermore, a recent study by Jekayinfa et al. (2020) indicated that about 77.8% of Nigeria's landmass is available

for biomass energy production. The Nigerian government has launched several programs aimed at promoting renewable energy, such as the Rural Electrification Agency's (REA) off-grid electrification projects, which aim to provide clean and reliable electricity to underserved communities (REA, 2021).

Dioha et al. (2016) reported that Nigeria also has a moderate wind regime with speeds of up to 7.5 m/s in the northern parts. Additionally, solar PV electricity can be generated in all parts of Nigeria (Shaaban and Petinrin, 2014). Dodo et al. (2021) stated that the country has 277 dispersed sites for small hydro power generation surveyed in 12 states with prospects and many rivers that can be dammed for large hydro power generation. Although certain renewable energy technologies (RETs) are not yet optimized, their clean, sustainable, futuristic, ecologically beneficial, and inexhaustible characteristics have contributed to a growth in worldwide interest.

2.0 Methodology

This study adopts a structured literature review approach to ensure transparency and reproducibility. The search for literature was conducted using online databases, from Google Scholar, Reports from international organizations (IEA, World Bank, FAO), Web of Science, and Scopus. The search strategy was done using combinations keywords relevant to the study including biomass energy Nigeria, bioenergy potential Africa, agricultural waste energy Nigeria, and biomass conversion technologies. The selected studies were analysed using a thematic synthesis approach, focusing on present State of biomass energy potentials in Nigeria, analyse technologies of biomass conversion, and obstacles and future prospects.

3.0 Results and Synthesis of Literature

3.1 Present State of Biomass Energy Potentials

Agricultural Crop Wastes as Biomass Feedstock and their Potentials

Biomass is a natural carbon-based resource. It refers to biologically derived material that is complex and renewable, with significant chemical variety (Bonechi et al., 2017). Ugwu et al. (2022) also reported that biomass is an unlimited source of energy, hence it is renewable. When compared to other energy sources such as coal and crude oil, it is more dependable, sustainable, and environmentally friendly. According to Ben-Iwo et al. (2016) biomass, or organic material obtained from plant and animal tissue, is gaining popularity as an environmentally acceptable alternative to fossil fuels.

Tursi (2019) stated that biomass can be categorized according to natural forms associated with ecological or vegetation groups. The five types of biomasses are: woody biomass, herbaceous biomass, aquatic biomass, animal and human waste biomass, and mixed biomass. Biomass mixes contain substrate that blends different kinds, resulting in a mixed form. The quest for sustainable renewable alternative energy resources as a result of depletion of the fossil energy (non-renewable) resources and its adverse effect on the environment which include; pollution, global warming, price instability, and irregular supply, called for research and investments in developing alternative energy resources. Consequently, there is a need for a shift from fossil fuels (non-renewable resources) to agricultural wastes (biomass) as alternative renewable energy resources. Biomass is naturally abundant in rural communities and presents a renewable energy opportunity that could serve as an alternative to fossil fuels (Dairo et al., 2018).

Agriculture has been essential to the continued existence of populations and economies in nations like Nigeria, Ghana, and many other African nations. In developing nations like Nigeria, wastes are constantly produced after agricultural produce has been cultivated. These wastes can include rice husk, groundnut shells, maize cobs, maize stalks, tomato wastes, sorghum stalks, bean shells, sugarcane bagasse, and a variety of other materials (Odimegwu, 2019, Oyegoke et al., 2022). According to the United Nation's Sustainable Development Goals UNDP (2022), which aim to improve environmental sustainability and public health, it is crucial to develop a better strategy for managing agro-waste so that it can be safely disposed of or converted into useful products.

Agriculture waste is any material that is undesirable or useless that comes exclusively from agricultural operations that are directly tied to the production of crops (biomass) (Adejumo and Adebiyi, 2020). Jekayinfa et al. (2020) explained that Nigeria has an abundant supply of agricultural waste because of its extensive land area and substantial agricultural operations which generate agriculture residues from plant fibres. Agricultural production, harvesting, and processing generate residues, such as unwanted plants or weeds, corn cobs, rice husks, rice straw, and sugarcane bagasse. Globally, about 2.2 billion tons of crop residues and 1.7 billion tons of municipal solid waste (MSW) are produced each year (Okafor et al., 2022).

Agricultural wastes are by-products which are generated by various agricultural operations and are naturally occurring carbonaceous resource. Gideon et al. (2023) observed that rural farming operations generate various crop residues, including rice husk, rice straws, maize stalks, maize husks, maize cobs, cassava peels and stalks, groundnut shells and straws, soybean pods, sugarcane bagasse and leaves, cotton stalks, manure, tree trimmings, and grass clippings. Many developing countries, especially in sub-Saharan Africa, possess substantial agricultural land, with agriculture being a crucial part of their economies (Jekayinfa et al., 2020). These regions have abundant biomass resources that can be utilized for heat and electricity generation. However, these biomass resources are often used in environmentally and economically detrimental ways. Despite this, in some developing countries, biomass constitutes over 70% of total energy consumption (Kovalyshyn et al., 2019). Keles et al. (2017) projected that by 2030, 823 million people in Africa will depend on biomass for cooking and heating.

Agricultural wastes are potential resource of fuel that can be used to produce a type of solid biofuel known for its renewable and sustainable energy use. The creation of novel technologies that can offer fuel derived from renewable resources is essential. Biomass is a possible source of energy among many different renewable energy sources. Solid biomass is an effective source of energy since it is renewable, carbon-neutral, versatile, highly reactive, possesses a high specific surface area, and in some cases, has low sulphur and ash concentrations, is readily available locally, and is economical (Malico et al., 2019). Due to its characteristics, biomass, has an excellent future as energy resources feedstock. But currently, the potential of agricultural wastes to generate energy is not being fully utilized. Therefore, increasing the use of agricultural wastes could help address the current energy crisis that millions of people and businesses are currently facing or offer an important alternative source of energy to our nation's industries of production.

Agricultural wastes are organic wastes which are composed of a higher fibre content and a lower concentration of nitrogen (Matemilola et al., 2019). Nowadays, the most common type of renewable energy with the least amount of pollution emissions is this vast renewable resource with great potential. Ichu et al. (2020) stated that switching from fossil-based fuels to biomass-derived energy, Nigeria can lower its productions of carbon dioxide (CO_2) and additional greenhouse gases. Ezealigo et al. (2021), Jekayinfa et al. (2020), Okafor et al. (2022), estimated energy potential of different crop wastes generated in Nigeria for 2018 as shown in table 1.

Table 1: Energy potential of agricultural wastes based on Nigeria's crop production in 2018

Crop	**Residue**	**2018 Crop Production (Mt)**	**Residue-to product (RPR)**	**Calculated residue generated (Mt)**	**Energy content (MJ/kg)**	**Energy potential (TJ)**
Oil palm	Bunch	7.8[a]	0.25[b]	1950,000	15.51[b]	30.24
Maize	Stalk	10.2[a]	1.5[b]	15,300,000	15.48[b]	236.84
Cassava	Peels	59.5[a]	0.35[c]	20,825,000	10.6[a]	220.95
Rice	Straw	6.8[a]	1.66[a]	11,288,000	16.02[a]	180.83
Yam	Peels	47.5[a]	0.06[c]	2850,000	16.43[c]	46.82
Sugarcane	Bagasse	1.42[a]	0.3[b]	426,000	13.38[b]	5.70
Plantain	Trunks/ Leaves	3.09[a]	0.50[c]	1545,000	16.13[c]	24.92
Sorghum	Stalk	6.86[a]	2.62[b]	17,973,200	17.00[b]	305.54
Cocoa	Pod	0.33[a]	0.93[a]	306,900	15.12[a]	4.64
Wheat	Stalk	0.0666[c]	1.5[b]	99,900	19.3[b]	1.93
Millet	Stalk	2.24[a]	3.0[b]	6720,000	15.51[b]	104.22
Groundnut	Straw	2.89[a]	1.25[a]	3612,500	15.66[a]	56.02
Cocoyam	Straw	3.3[a]	0.5 a	1650,000	14.24[a]	23.50
Coconut	Shells	0.28[a]	0.25[c]	71,250	18.09[c]	1.28
Cowpea	Shells	2.6[a]	1.75[a]	4567,500	19.44[a]	88.80
Sweet Potato	Straw	4.03[a]	0.50[a]	2015,000	14.24[a]	28.70
Soybean	Straw	0.758[a]	2.50[a]	1895,000	12.38 [a]	23.46

Source: Adapted from [a]Ezealigo et al. (2021); [b]Okafor et al. (2022); [c]Jekayinfa et al. (2020)

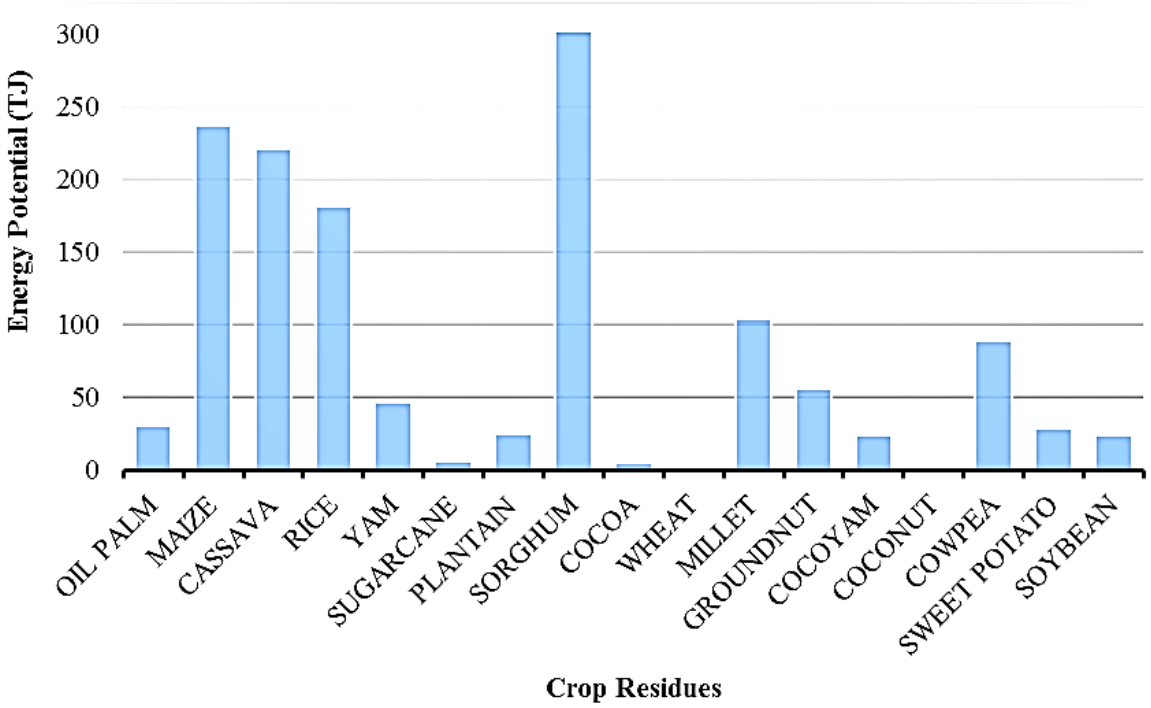


Figure 1: Energy Potential of Agricultural Residue in Nigeria

Table 1 and Figure 1 reveal substantial variation in the energy potential of agricultural residues in Nigeria, with sorghum stalk of 305.54 TJ, maize residues of 236.84 TJ, and cassava peels of 220.95 TJ dominating due to their high production volumes and favourable residue-to-product ratios. These findings align with recent studies highlighting cereal and tuber residues as major bioenergy resources in sub-Saharan Africa Oyedepo et al. (2019), Adewuyi (2020) and reports by the International Energy Agency IEA (2023), which emphasize their underutilization in developing economies. Despite this high potential, biomass resources in Nigeria remain underexploited due to supply chain inefficiencies, competing uses, and limited technological deployment Adekanye (2025); Okoro et al. (2024), alongside continued reliance on inefficient traditional combustion systems (Tshikovhi and Motaung, 2023, Makepa and Chihobo, 2025).

The variation in residue characteristics necessitates feedstock specific conversion pathways, with lignocellulosic residues suited for thermochemical processes and high moisture residues for biochemical conversion (Awasthi et al., 2023, Sarker et al., 2023). Furthermore, effective biomass utilization requires integrated resource management and supportive policy frameworks, as emphasized by the International Renewable Energy Agency (IRENA, 2021). In Nigeria, the absence of a structured biomass policy continues to hinder large-scale deployment (Tambari et al., 2020). Overall, while Nigeria possesses significant biomass energy potential, bridging the gap between availability and utilization will require improved logistics, technological investment, and policy support, consistent with broader African energy transition trends (IRENA, 2021, IEA, 2023). Numerous researches have been carried out regarding the applications of biomass for energy production in Nigeria including circular bioeconomy (CBE) (Igbokwe et al., 2022), biomass residues and their potential for bioenergy (Ezealigo et al., 2021), agro-bioenergy potential to reduce emissions and mitigate climate change (Elum et al., 2017), the potential for different crops to be used as resources of energy (Jekayinfa et al., 2020), renewable energy for environmental protection: Nigeria's palm oil production life cycle inventory for safeguarding the environment with renewable energy (Anyaoha and Zhang, 2021).

Many emerging economies including Nigeria have enormous quantities of forest and agriculture wastes that are now underutilized and might be converted into charcoal briquettes for industrial and residential use (Japhet et al., 2020). The suitability of the loose agricultural residues (biomass) material for briquetting will be determined by the nature and type of biomass, since this will have an impact on the final quality of the briquette. Ben-Iwo et al. (2016)

reported that the agricultural wastes differ in moisture content, bulk density, particle dispersion, and particle size depending on the age of the agro - waste, state of harvest, physical composition, and length of storing and harvesting procedures. Furthermore, Oyegoke et al. (2023) in their study reported that in Nigeria the overall average of the total Agricultural waste generated was estimated to be 12.06 Mt. This amount of agricultural waste is generated yearly in our country and is frequently inadequately managed. It is visible in our immediate environment, including on the farms, roadways, at dump sites, and in residential areas where it is used as fuel. The sustainable development of our communities could be improved further if we take into consideration safer alternatives to current waste management methods.

According to Babayemi et al. (2016), the substantial biomass wastes in Nigeria were rice husks, corn cobs, rice straws, sawdust, groundnut shells, corn straws, sugar cane fibre, bamboo stalk, coffee stalk, and cotton stalk. Agricultural biomass is becoming a rapidly increasing problem as decomposed waste agricultural biomass produces environmental pollution while open burning by the farmers (a common practice in Nigeria) generates CO_2 and other dangerous pollutants. As a result, a considerable portion of it is left or burned in the field after harvesting. Domestic energy resource scarcity and environmental pollution make it attractive to find out environmentally friendly and alternative renewable energy resources to substitute fossil fuels. Despite high availability, resource utilization efficiency remains low, with a large proportion of biomass either wasted or openly burned.

3.2 Technologies of Biomass Conversion

The various methods of converting biomass into useful energy sources are shown in figure 1. Agricultural wastes can be converted to fuel via mechanical conversion, chemical conversion, thermochemical conversion, physicochemical conversion and biochemical conversion technology. The processes employed for thermochemical conversion include combustion, pyrolysis, carbonization, gasification, and liquefaction. Carbonization is a biomass thermochemical conversion employing heat to start the process of breakdown of organic materials, splitting down their hydrocarbonaceous bonds to convert them into a more potent type of energy at a temperature of 400–800^{o}C (Amer and Elwardany, 2020). According to the study, biomass thermochemical transformation begins with the breakdown of organic materials by cracking the hydro carbonaceous bonds in order to change them into more abundant forms of energy. Ibitoye et al. (2021a) opined that the characteristics of the feedstock and the processing conditions have a significant impact on the yield of carbonization.

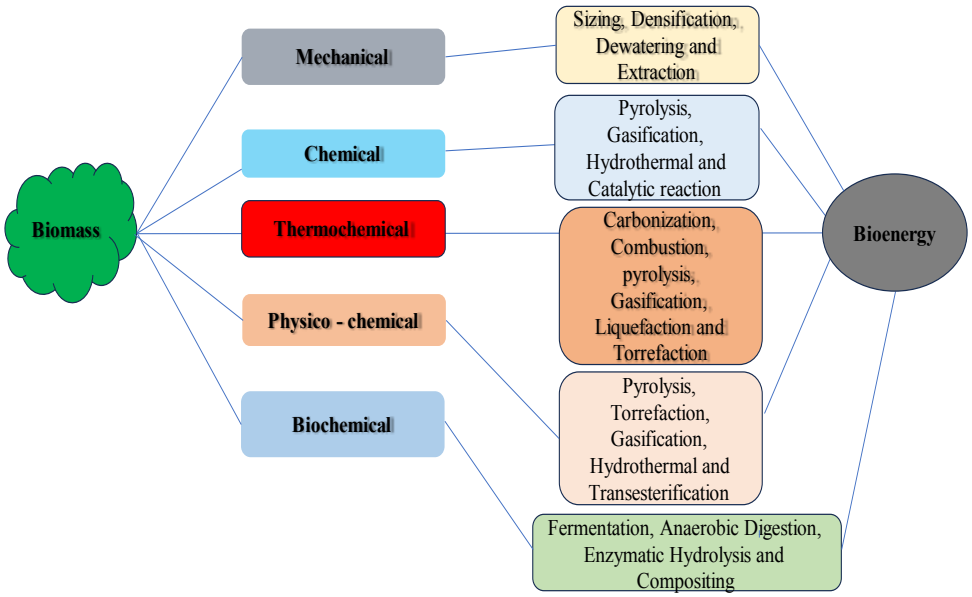


Figure 2: Biomass Conversion Pathways

Mechanical Conversion

The need for fuel pellets has sparked a renewed interest in using diverse biomass resources. The quality of fuel pellets is determined by density, mechanical stability, hydrophobicity and energy content. These properties are regulated by biomass type, pretreatment, formulations, compaction processes and environmental factors such as temperature, pressure and relaxation time (Sarker et al., 2023). Mechanical conversion processes of biomass involve physically transforming the structure of biomass. They consist of cutting, chipping, crushing, grinding, milling, mechanical sieving and densification. Jekayinfa et al. (2020) explained that densification is a method of pressing raw biomass to form solid fuels such as briquettes and pellets. Briquettes or pellets are formed at a high temperature if no binder is employed. Several studies have explored biomass briquetting. Jekayinfa et al. (2019) examined the influence of process and material factors on the water resistance of maize cob briquettes. The water resistance of the generated briquettes ranged between 32.6 and 94.8% for die temperatures ranging from 90 to 120°C, hold times ranging from 7.5 to 15 minutes, and die pressures ranging from 9 to 15 MPa. A higher die temperature increased the water resistance of biomass briquettes. Additionally, extending the hold duration enhanced the water resistance of the briquettes. They concluded that briquettes made with particle sizes smaller than 2.5 mm have a stronger water resistance characteristic than those made with particle sizes larger than 2.5 mm.

In their study, Orisaleye et al. (2019) investigated the effects of geometrical factors (channel depth and helix angle) and operational variables (friction coefficient, mass flow rate, and speed) on the performance and design of the briquetting machine using a plug flow theory-based pressure model. The pressure model investigations revealed that a short screw channel and very small helix angle caused substantial pressure buildup along the screw extruder biomass briquetting machine. High friction at the barrel-material interface, low friction at the screw-material interface, high screw speed, and a high mass flow rate all contributed to rapid pressure build up along the screw extruder of the biomass briquetting machine. Ibitoye et al. (2021b) explained that mechanical conversion of biomass (densification) is a process of compacting particles to produce solid fuels using pressure-driven methods such as extrusion, screw press, piston press, hydraulic piston press, roller press, and pallet press and densification processes are classified as high-pressure, medium-pressure, or low-pressure compactions. Briquetting, pelletizing, bailing, and cubing are some common densification procedures. These techniques provide solid fuels with appropriate physical, mechanical, chemical, thermal, and combustion properties, providing significant benefits in both home and industrial settings.

According to Bychkov et al. (2019), mechanical treatment should examine the underlying processes rather than just generating fine and ultrafine particles. Active surface radicals can be developed, hydrothermal chemical reactions can occur, and mechano-composites can be formed during mechanical conversion process of biomass. When applying mechanical treatment, it is critical to take into account interphase processes, surface growth, size effects, crystal structure change, and amorphization.

Chemical Conversion

Chemical conversion mechanisms can be used to produce different biofuels from waste biomass through anaerobic digestion, fermentation and transesterification. Anaerobic digestion (AD) is the process of transforming organic-biodegradable waste, such as agricultural plant waste, food waste, sewage sludge, animal waste, secondary crop waste, and others, into a valuable energy source while reducing their volume (Moustakas et al., 2020). Jekayinfa et al. (2020) stated that anaerobic digestion is a process of converting moist organic matter into biogas in the absence of oxygen. Research on production of biogas in biodigesters has been conducted by Adebayo et al. (2018), their study revealed that biogas and methane yields drop as Organic Loading Rate (OLR) increases, with the highest yields of 0.45 L/goS and 0.25 LCH4/goS at 2.5goTS/L.d. The average methane content in a Continuous Stirred Tank Reactor (CSTR) with digested cow slurry was 57%. A 140-day CSTR experiment resulted in the development of a kinetic model based on the first-order mass balance equation that might be beneficial for anaerobic digestion of animal dung at thermophilic temperatures.

Ayodele et al. (2019) examined the power generating potential of hydrogen gas derived from steam reforming biogas in six South Western Nigerian locations and reported an estimate of 0.411 million tons of hydrogen gas could potentially be obtained, resulting in 19.46 million kWh annually. The method additionally achieved 94.33% ecological efficiency, indicating that biogas steam reforming has a positive environmental impact. Fermentation is the conversion of carbohydrates to ethanol by microbes. Otaraku et al. (2019) studied cassava fermentation for ethanol production utilizing decaying oranges and palm wine microbes. The results showed that a 35%-45% starch-

wet base was created. When zymomonasmobis was mixed with 10g of starch in 90ml of distilled water, the most alcohol volume was produced. Saccharomyces cerevisiae and zymomonasmobis were combined to generate the highest ethanol volume. The mathematical model equation developed had a great relationship with the findings from the experiment.

Transesterification involves removing alcohol from one ester and replacing it with another using an acid or base catalyst (Jekayinfa et al., 2020). The technique produces biodiesel from fatty acid methyl esters. Several scholars have conducted laboratory studies on biodiesel generation using various oils. Ishola et al. (2020) demonstrated that biodiesel can be produced from Nigerian palm oil employing batch reactors. Using methanol and a potassium hydroxide catalyst, the biodiesel yielded 62.5%, indicating that it is possible for large manufacturing. The biodiesel has a density of 0.884 g/cm^3, a cetane number of 48.91, and a flashpoint of 208 °C, fulfilling the ASTM D975 Standard Specification for diesel fuels. Effiom (2023) examined how process parameters affect biodiesel production using palm kernel shell oil (PKSO) and eggshell catalysts. The optimal conditions for maximizing biodiesel yield were identified as a 3% catalyst concentration, a reaction time of 150 minutes, a reaction temperature of 65°C, a methanol/oil molar ratio of 12:1, and an agitation speed of 300 rpm. Key fuel properties of the biodiesel, including density, kinematic viscosity, flash point, fire point, cloud point, pour point, free fatty acid content, aniline point, diesel index, API gravity, cetane number, and fuel calorific values were in the ranged of 0.8461 – 0.8831 kg/m³, 5.31 – 7.84 mm²/s, 97 – 141°C, 107 – 150°C, 4.14 – 6.5°C, 1.5 – 4.5°C, 0.318 – 0.931 mg KOH/kg, 45 – 52°C, 31.83 – 41.17, 28.165 – 33.258, 28.8313 – 41.1519, and 16 – 18%, respectively. These values fall within the standard limits for diesel fuels, and highlight the significant influence of process parameters on biodiesel production.

Aworanti et al. (2019) aimed to identify optimal process factors for establishing an efficient and cost-effective method for converting palm oil sludge (POS) into biodiesel. They used a combination of POS, methanol, and potassium hydroxide (KOH) as a catalyst, applying the One-Factor-at-a-Time technique to determine the best process variables for maximum biodiesel yield. The optimal variables found were a 12:1 molar ratio, 1.5wt% catalyst loading, and a 30-minute reaction time, resulting in a biodiesel yield of 61.2%. The produced biodiesel met EN 14214 and ASTM 6751 standards, with a density of 857.0 kg/m^3, kinematic viscosity of 5.38 mm^2/s, flash point of 180°C, pour point of -5°C, and an acid value of 0.17 mg KOH/g. Mayorga Betancourt et al. (2020) focused on transesterification of palm kernel oil to produce fatty acid methyl ester (FAME) biodiesel with KOH as a catalyst. The optimal conditions were determined to be 50°C, a 5.5 methanol/oil molar ratio, and 0.8 KOH%. FTIR spectroscopy, gas chromatography, and ASTM quality control procedures were used to analysed the FAME's cold, transport, and combustion characteristics. The reaction rate was calculated, and a reaction mechanism was proposed based on the experimental findings.

Thermochemical Conversion

Thermochemical conversion is the production of energy from agricultural biomass by the application of heat and chemical reactions. Thermochemical conversion technologies currently in use include carbonization, pyrolysis, gasification, liquefaction, and combustion (Tursi, 2019). Biomass thermochemical conversion involves heat application to decompose organic materials, cracking hydrocarbonaceous bonds, and converting them into energy through processes like combustion, pyrolysis, carbonization, co-firing, gasification, and liquefaction (Brigagão et al., 2019). Pyrolysis is the fundamental basis of all thermochemical conversion methods, and the process involves chemical reactions which produce solid "char," liquid "bio-oil," and gas "biogas" under oxygen-free or oxygen-limiting environments. The gases and bio-oil are derived from the volatile biomass component, whereas char is predominantly composed of fixed carbon (Jameel and Keshwani, 2017). The proportions of the different pyrolysis products differ depending on the process of pyrolysis (fast, slow, or conventional) and the parameters of the reaction.

Pyrolysis is the process of heating biomass in the absence of air and it is categorized into fast and slow pyrolysis based on the applied heating rate. Fast pyrolysis has high heating rates and lower residence time, increasing bio-oil yield. Slow pyrolysis has lower heating rates, resulting in higher solid yields or char. Slow pyrolysis is further subdivided into carbonization and torrefaction and this subdivision depends on the operating temperature of the process and the residence time. Basu (2018) stated that carbonization is an alternative to torrefaction, and is a process that employs higher temperatures and longer residence times to produce a highly carbonaceous product. The final product from any of the two slow pyrolysis processes is commonly referred to as "char," whilst charcoal is used exclusively for carbonization products. Purwanto et al. (2018) reported that charcoal is a highly carbonaceous

substance that is meant to be used as a fuel and can be employed as a reductant in the metallurgical production during the melting and sintering operations.

Carbonization (pyrolysis) is the heat degradation of lignocellulosic agricultural biomass in an inert environment in the absence of oxygen. Biochar, bio-oil, and gases are the end products of carbonization. The products of carbonization (pyrolysis) are determined by the process's operating temperature, residence time, reactor type, and heating rates (Sá et al., 2020). According to Amer and Elwardany (2020), carbonization is the process of transforming waste biomass into carbon/energy-rich charcoal. Char is formed by a carbonization process in which biomass is burned to high temperatures in an inert environment until absorbed volatiles are released, hence increasing its heating value and energy content (Amer and Elwardany, 2020). Majority of the energy generated from agricultural waste in Nigeria is through combustion techniques. Nigeria's ineffective combustion technologies waste energy, especially in rural areas where cooking using biomass through combustion is the practice. Some studies carried out by different researchers revealed that the combustion of agricultural waste (biomass) result in inefficient energy in the process. Among the researchers are; Bello et al. (2015) who in their study found out that sawdust stove, charcoal stove, and three-stone stove operating on firewood, in turn, had efficiencies of 52.64%, 64.38%, and 34.56%, respectively. Gujba et al. (2015) also noted that the efficiency of fuelwood, charcoal, and agricultural residue used for cooking were 18%, 22%, and 10%, respectively. These figures are lower than the efficiencies of kerosene, liquefied petroleum gas, and electric stoves, which range from 55% to 95%. It is consequently necessary for the nation to embrace advanced combustion technology (Ofori et al., 2018).

In Nigeria, carbonization, pyrolysis, and torrefaction remain at the laboratory scale. Ola and Jekayinfa (2015) and Ola and Jekayinfa (2014) studied sandbox (*Hura crepitans*) shells, discovering that variations in temperature, heating time, and feedstock particle size significantly influenced biochar yield. Fuwape and Faruwa (2016) conducted torrefaction on wood samples from *Pinus carrebea* and *Leucaena leucocephala*, examining how temperature affected the physical and combustion properties of the products. Garba et al. (2014) and Adeleke et al. (2019) performed torrefaction studies on rice straw and woody biomass (Melina and Teak wood), respectively, exploring the impact of different temperatures and residence times. Farrow et al. (2018) analyzed the characteristics of char produced from cassava peelings, while Onifade et al. (2017) conducted a characterization of bio-oil derived from palm fruit fiber and physic nut shell. Similarly, Okekunle et al. (2019) evaluated pyrolysis products obtained from different wood sources, including *Gmelina arborea*, *Anogeissus leiocarpa*, *Parkia biglobosa*, and *Adansonia kilima*.

Physicochemical Conversion

Physicochemical conversion of biomass refers to a set of integrated processes that combine chemical and physical treatments to transform organic feedstocks, such as agricultural wastes, food waste, and wood chips, into value added products including energy, chemicals, and biofuels. By combining mechanical, thermal, and chemical methods, this conversion pathway improves biomass decomposition and makes it easier for it to be broken down into smaller parts that can be further refined into advanced materials or used more effectively for energy production. Physicochemical conversion uses multistage processing techniques intended to promote biomass decomposition, increase downstream energy recovery efficiency, and maximize total product yields, in contrast to exclusively biochemical or thermochemical approaches (Durak, 2023, Woźniak et al., 2025). Chen et al. (2024), explain that physicochemical characterization of biomass is essential for effective conversion, as physical pretreatment methods such as size reduction and mixing play a critical role in feedstock preparation. These processes increase surface area, improve homogeneity, and enhance heat and mass transfer, thereby improving reaction efficiency, reducing energy demand, and supporting uniform chemical conversion (Das et al., 2023, Chen et al., 2024).

Chemical techniques such as catalysis, solvent extraction, and supercritical fluid technology are integral to physicochemical biomass conversion, enabling efficient transformation of biomass into fuels and valuable chemicals (Wu, 2025). Key processes include liquefaction, supercritical fluid extraction, transesterification, and solvolysis, which operate under relatively moderate conditions and offer high selectivity and product yields across diverse biomass feedstocks (Li et al., 2024a). Although the integration of physical and chemical methods enhances conversion efficiency and versatility, these processes often require significant energy input and extensive pretreatment, increasing operational complexity and cost and potentially offsetting their environmental benefits at large scale (Khandaker et al., 2025, Kashif et al., 2025).

Bio - chemical Conversion

Biochemical conversion processes, including fermentation, anaerobic digestion, enzymatic hydrolysis and compositing, breakdown of biomass organic matter without oxygen under relatively mild operating conditions. Adeoye et al. (2023), Sarker et al. (2025) reported that biochemical conversion of biomass involves using biological agents, such as microorganisms and enzymes, to break down organic materials into biofuels or other valuable products. This process typically employs pathways such as anaerobic digestion and fermentation. Wu (2025), stated that biochemical conversion is more sustainable and environmentally friendly option than thermochemical processes because it uses biological agents instead of heat, and it can handle wet biomass, operate under ambient temperature and pressure, and exhibit greater selectivity for desired products. The biochemical method is effective for energy recovery from biomass because it uses the entire biomass without the need to isolate specific macromolecules (Wu, 2025). As a result, biochemical conversion operates under relatively mild conditions. Typical biochemical conversion routes include anaerobic digestion and fermentation (Li et al., 2024b). These pathways enable the transformation of biomass into a range of valuable products, including bioethanol, biogas, hydrogen, and other chemical compounds. Wang et al. (2024), give example of biochemical conversion as, anaerobic digestion which is widely employed for the production of methane-rich biogas, which serves as a renewable energy source obtained from organic waste materials. In contrast, fermentation is mainly utilized for converting sugars into bioethanol, a commonly used biofuel (David et al., 2023, Devi et al., 2023, Tong et al., 2024). Most advanced technologies remain at laboratory or pilot scale, with limited industrial deployment in Nigeria.

3.3 Obstacles and Future Prospects

Obstacles for Biomass as Alternative Energy Source

There are several obstacles that may hinder utilizing biomass for energy in Nigeria. These include:

i. Inadequate transfer of technology and localization: Energy technology equipment is largely imported due to limited technology transfer and undeveloped manufacturing industries, resulting in significant foreign exchange spending (Benti et al., 2021). In rural areas, there is a lack of equipment and infrastructure for preserving and converting biomass for energy generation and cooking application.
ii. Food insecurity: Energy crops, such as sugar cane, corn, and maize, are essentially food crops. Using them for energy production creates competition with food production, which is crucial for feeding the people and reducing food prices (Prasad and Ingle, 2019).
iii. Land availability and right: The bioenergy industry requires large land for the energy corps to plant. Furthermore, the Land Use Act of 1978 grants land ownership on state governors in Nigeria (Olujobi et al., 2022). They hold the land in their states in trust for the people. Without the consent of the state Governors, this could hinder large-scale farming and limit the availability of essential resources for bioenergy production by private investors and the Federal Government (Olujobi et al., 2022).
iv. Air and waste pollution: Smoke from burning agricultural waste and wood is a significant contributor to poor air quality and health hazards. Using biomass and firewood as a cooking fuel exposes women to fumes, which can cause respiratory problems (Bede-Ojimadu and Orisakwe, 2020). According to Olujobi et al. (2021), untreated animal manure used for biofuel can significantly harm the environment when present in large quantities. Feedlots generate waste that is more concentrated than raw domestic sewage, and if this waste contaminates the water supply, the effects can be catastrophic.
v. Inadequate collaboration among institutions: Nigeria's waste disposal data is often unavailable or unpublished by environmental regulatory bodies due to insufficient waste management regulations and political will, as well as the Federal Government's commitment to converting waste into energy for industries (Adekola, 2020).
vi. Initial cost of investment: Renewable energy technology seems to be more lucrative than typical fossil fuel generation since it is a new technology but it may require significant investments to get started (Breyer et al., 2022).

Future Prospects of Biomass as Alternative Energy Source

Biomass, as renewable energy may provide significant prospects if adopted by all stakeholders, including governments, commercial corporations, civil society, and non-governmental organizations. Implementing and enforcing policies for sustainable energy for all (SE4All) can lead to prospects such as job creation, technological advancement, economic growth, and attracting foreign investors (Levi-Oguike et al., 2019). Employing renewable energy can help reduce greenhouse gas emissions. Nigerians are meeting the Kyoto Protocol's goal of lowering fossil fuel emissions through biomass adoption, but they are also seeking a reform of energy policy owing to worries about the outlook, security, and variety of energy sources used for power generation (Onwumelu, 2023). Atta et al.

(2016) opined that energy from waste disposal plants might play an insignificant but crucial part in generating power and providing heat to communities. With fossil fuel costs rising in recent years, the prospects for biomass waste components for energy shall continue to rise.

Converting waste to energy will enhance air quality, reduce emissions, and support the acquisition of carbon credits and compliance with international climate agreements, among other benefits (The World Bank 2013, as cited in Ibrahim et al. (2021)). This ecological waste management strategy will put an end to the uncontrolled collection and dumping of waste. It will significantly advance Nigeria's energy integration and help subsidize future energy access (Olujobi and Olujobi, 2020). Given a decline in fossil fuel reserves and the negative environmental impacts associated with fossil fuels, biomass-based energy production in Nigeria has the potential to become economically viable. Biomass, produced mostly from plants, can sustain itself as long as fertile soil, water, sunlight, and carbon dioxide are available (Herrmann et al., 2018). Biomass is gaining popularity as a renewable energy source due to its low cost, domestic production, and environmental benefits. It is easier to sustain than other energy sources since the majority of resources come from waste materials, which is less expensive to acquire. This makes biomass an option for energy production since it minimizes greenhouse gas emissions and supports green pasture growth. However, a better knowledge of the economic and environmental consequences of bioenergy pathways is required for their efficient usage in the energy industry and local prosperity

4.0. Conclusion

This review demonstrates that Nigeria possesses significant biomass resources capable of contributing to national energy needs. However, a substantial gap exists between resource availability and actual utilization. The study highlights that overcoming technological, economic, and policy barriers is essential for unlocking biomass potential. A transition toward modern biomass conversion technologies, supported by strong institutional frameworks, is necessary for sustainable energy development. Biomass is a renewable energy source that can be used to heat, chill, produce power, and transport fuel. Nigeria has 77.8% of its land accessible for biomass energy production, yielding an estimated 2.33 EJ of energy from biomass resources. Using bioenergy in Nigeria may reduce dependence on oil. In Nigeria's energy sector, biomass which includes agricultural residues, wood and animal dung is essential. It is mostly utilized in rural areas for cooking and heating, and can also be used for power production, but its full potential is still mostly unrealized. One of the main obstacles is the lack of modern technologies and infrastructure for biomass conversion. Traditional biomass utilization methods often result in inefficient energy production and pollution of the atmosphere. The adoption of advanced technologies such as biomass carbonization, gasification and biofuel can enhance energy efficiency and reduce environmental impacts.

Nigeria has significant potential for biomass as an alternative fuel energy source, but challenges include the need for policy frameworks and financial incentives. The government should establish supportive policies like feed-in tariffs, tax incentives, and research grants to encourage investments in biomass projects. Collaboration between public and private sectors is crucial for a favourable environment. Nigeria's abundant agricultural resources can serve as sustainable feedstock for biomass production, contributing to waste management, rural development, and job creation. Realizing biomass's potential requires a comprehensive approach, including technological advancements, policy reforms, capacity building, and public awareness campaigns.

References

Adebayo, A., Jekayinfa, S. & Ahmed, N. 2018. Kinetic Study Of Thermophilic Anaerobic Digestion Of Cattle Manure In A Continuously Stirred Tank Reactor Under Varying Organic Loading Rate. *Arpn Journal Of Engineering And Applied Sciences* 13**,** 1-8.

Adejumo, I. O. & Adebiyi, O. A. 2020. *Agricultural Solid Wastes: Causes, Effects, And Effective Management. In Strategies Of Sustainable Solid Waste Management,* 5 Princes Gate Court, London, Sw7 2qj, United Kingdom, Intechopen Limited

Adekanye, T. 2025. Opportunities And Challenges In Utilizing Biomass Energy For Carbon Neutrality In Nigeria: A Comprehensive Review. *Academia Green Energy,* 2.

Adekola, A. A. 2020. A Critical Policy Review On Environmental Protection In Nigeria. *Lapai International Journal Of Management And Social Sciences,* 12**,** 117-135.

Adeleke, A., Odusote, J., Paswan, D., Lasode, O. & Malathi, M. 2019. Influence Of Torrefaction On Lignocellulosic Woody Biomass Of Nigerian Origin. *Journal Of Chemical Technology And Metallurgy,* 54**,** 274-285.

Adeoye, A. O., Lawal, O. S., Quadri, R. O., Malomo, D., Aliyu, M. T., Dang, G. E., Emojevu, E. O., Maikato, M. J., Yahaya, M. G. & Omonije, O. O. 2023. Sustainable Energy Via Thermochemical And Biochemical Conversion Of Biomass Wastes For Biofuel Production. *Transportation Energy And Dynamics.* Springer.

Adewuyi, A. 2020. Challenges And Prospects Of Renewable Energy In Nigeria: A Case Of Bioethanol And Biodiesel Production. *Energy Reports,* 6**,** 77-88.

Akorede, M., Ibrahim, O., Amuda, S., Otuoze, A. & Olufeagba, B. 2017. Current Status And Outlook Of Renewable Energy Development In Nigeria. *Nigerian Journal Of Technology,* 36**,** 196-212.

Amer, M. & Elwardany, A. 2020. Biomass Carbonization. *In:* Mansour, A., S., Serhad (Ed.) *Renewable Energy-Resources, Challenges And Applications.* Intechopen, London, United Kingdom.

Anyaoha, K. E. & Zhang, L. 2021. Renewable Energy For Environmental Protection: Life Cycle Inventory Of Nigeria's Palm Oil Production. *Resources, Conservation And Recycling,* 174**,** 1 - 11.

Atta, A., Aminu, M., Yusuf, N., Gano, Z., Ahmed, O. & Fasanya, O. 2016. Potentials Of Waste To Energy In Nigeria. *Journal Of Applied Sciences Research,* 12**,** 1-6.

Awasthi, M. K., Sar, T., Gowd, S. C., Rajendran, K., Kumar, V., Sarsaiya, S., Li, Y., Sindhu, R., Binod, P. & Zhang, Z. 2023. A Comprehensive Review On Thermochemical, And Biochemical Conversion Methods Of Lignocellulosic Biomass Into Valuable End Product. *Fuel,* 342**,** 127790.

Aworanti, O., Ajani, A., Agarry, S., Babatunde, K. & Akinwunmi, O. 2019. Effect Of Process Variables On The Transesterification Process Of Palm Oil Sludge To Biodiesel. *Biotechnology Journal International,* 23**,** 1-14.

Ayodele, T., Alao, M., Ogunjuyigbe, A. & Munda, J. 2019. Electricity Generation Prospective Of Hydrogen Derived From Biogas Using Food Waste In South-Western Nigeria. *Biomass And Bioenergy,* 127**,** 1-13.

Babayemi, J. O., Ogundiran, M. B. & Osibanjo, O. 2016. Overview Of Environmental Hazards And Health Effects Of Pollution In Developing Countries: A Case Study Of Nigeria. *Environmental Quality Management,* 26**,** 51-71.

Basu, P. 2018. *Biomass Gasification, Pyrolysis And Torrefaction: Practical Design And Theory*, Elsevier Science Academic Press, 32 Jamestown Road, London Nwi, Uk 1- 583.

Bede-Ojimadu, O. & Orisakwe, O. E. 2020. Exposure To Wood Smoke And Associated Health Effects In Sub-Saharan Africa: A Systematic Review. *Annals Of Global Health,* 86**,** 1-27.

Bello, R., Adegbulugbe, T. & Onilude, M. 2015. Characterization Of Three Conventional Cookstoves In South Eastern Nigeria. *Agricultural Engineering International: Cigr Journal,* 17**,** 122 - 129.

Ben-Iwo, J., Manovic, V. & Longhurst, P. 2016. Biomass Resources And Biofuels Potential For The Production Of Transportation Fuels In Nigeria. *Renewable And Sustainable Energy Reviews,* 63**,** 172-192.

Benti, N. E., Gurmesa, G. S., Argaw, T., Aneseyee, A. B., Gunta, S., Kassahun, G. B., Aga, G. S. & Asfaw, A. A. 2021. The Current Status, Challenges And Prospects Of Using Biomass Energy In Ethiopia. *Biotechnology For Biofuels,* 14**,** 1-24.

Bonechi, C., Consumi, M., Donati, A., Leone, G., Magnani, A., Tamasi, G. & Rossi, C. 2017. *Biomass: An* Overview Dalena, F., Basile, A., Rossi, C., Eds. *Bioenergy Systems For The Future, Woodhead Publishing: Cambridge, Uk, 2017;***,** 3-42.

Bp 2021. Bp Statistical Review Of World Energy 2021.Bp P.L.C. 1 St James's Square London Sw1y 4pd Uk 70th Edition, 1-76.

Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A. S., Aghahosseini, A., Gulagi, A., Solomon, A., Keiner, D. & Lopez, G. 2022. On The History And Future Of 100% Renewable Energy Systems Research. *Ieee Access,* 10**,** 78176-78218.

Brigagão, G. V., Araújo, O. D. Q. F., De Medeiros, J. L., Mikulcic, H. & Duic, N. 2019. A Techno-Economic Analysis Of Thermochemical Pathways For Corncob-To-Energy: Fast Pyrolysis To Bio-Oil, Gasification To Methanol And Combustion To Electricity. *Fuel Processing Technology,* 193**,** 102-113.

Brodny, J., Tutak, M. & Bindzár, P. 2021. Assessing The Level Of Renewable Energy Development In The European Union Member States. A 10-Year Perspective. *Energies,* 14**,** 3765.

Bychkov, A., Podgorbunskikh, E., Bychkova, E. & Lomovsky, O. 2019. Current Achievements In The Mechanically Pretreated Conversion Of Plant Biomass. *Biotechnology And Bioengineering,* 116**,** 1231-1244.

Chen, J., Ma, X., Liang, M., Guo, Z., Cai, Y., Zhu, C., Wang, Z., Wang, S., Xu, J. & Ying, H. Physical–Chemical–Biological Pretreatment For Biomass Degradation And Industrial Applications: A Review. Waste, 2024. Mdpi, 451-473.

Dairo, O. U., Adeleke, A. E., Shittu, T., Ibrahim, N. A., Adeosun, O. J. & Iyerimah, R. B. 2018. Development And Performance Evaluation Of A Low-Cost Hydraulic-Operated Biomass Briquetting Machine. *Fuoye Journal Of Engineering And Technology,* 3**,** 1-6

Das, N., Jena, P. K., Padhi, D., Kumar Mohanty, M. & Sahoo, G. 2023. A Comprehensive Review Of Characterization, Pretreatment And Its Applications On Different Lignocellulosic Biomass For Bioethanol Production. *Biomass Conversion And Biorefinery,* 13**,** 1503-1527.

David, A. J., Abinandan, S., Vaidyanathan, V. K., Xu, C. C. & Krishnamurthi, T. 2023. A Critical Review On Current Status And Environmental Sustainability Of Pre-Treatment Methods For Bioethanol Production From Lignocellulose Feedstocks. *3 Biotech,* 13**,** 233.

Devi, A., Bajar, S., Sihag, P., Sheikh, Z. U. D., Singh, A., Kaur, J., Bishnoi, N. R. & Pant, D. 2023. A Panoramic View Of Technological Landscape For Bioethanol Production From Various Generations Of Feedstocks. *Bioengineered,* 14**,** 81-112.

Dioha, M., Dioha, I. & Olugboji, O. 2016. An Assessment Of Nigeria Wind Energy Potential Based On Technical And Financial Analyses. *Journal Of Sustainable Energy,* 7**,** 53-57.

Dodo, U. A., Ashigwuike, E. C. & Eronu, E. M. 2021. Renewable Energy Readiness In Nigeria: A Review Focusing On Power Generation. *Uniabuja Journal Of Engineering And Technology* 1**,** 115-144.

Durak, H. 2023. Comprehensive Assessment Of Thermochemical Processes For Sustainable Waste Management And Resource Recovery. *Processes,* 11**,** 2092.

Effiom, S. O. 2023. Effect Of Process Parameters On Biodiesel Yield Produced From Palm Kernel Shell Oil (Pkso) Using Eggshell As Catalyst. *International Journal Of Frontiers In Engineering And Technology Research,* 4**,** 001-017.

Elum, Z. A., Modise, D. M. & Nhamo, G. 2017. Climate Change Mitigation: The Potential Of Agriculture As A Renewable Energy Source In Nigeria. *Environmental Science And Pollution Research,* 24**,** 3260-3273.

Ezealigo, U. S., Ezealigo, B. N., Kemausuor, F., Achenie, L. E. K. & Onwualu, A. P. 2021. Biomass Valorization To Bioenergy: Assessment Of Biomass Residues' Availability And Bioenergy Potential In Nigeria. *Sustainability,* 13**,** 1 -23.

Farrow, S., Eterigho, E. & Colin, S. 2018. Pyrolysis And Char Burnout Characteristics Of Cassava Peelings As Potential Energy Source. *Chemical And Process Engineering Research* 57**,** 59-66.

Fuwape, J. A. & Faruwa, F. A. 2016. Combustion Characteristics Of Torrefied Wood Samples Of Pinus Carrebea And Leucaena Leucocephala Grown In Nigeria. *Pro Ligno,* 12**,** 21-29.

Garba, M. U., Oloruntoba, J. M., Isah, A. G. & Mohammed, A. 2014. Production Of Solid Fuel From Rice Straw Through Torrefaction Process. *International Journal Of Science And Engineering Investigations,* 4**,** 1-6.

Gideon, M., Duniya, E. K. & James, M. A. 2023. Instantaneous Conversion Of Agricultural Plant Residues As Organic Fertilizer And It Application On Maize Cultivation: A Comparative Study With Npk And Manure. *Chemrxiv,* 1**,** 1 - 14.

Gujba, H., Mulugetta, Y. & Azapagic, A. 2015. The Household Cooking Sector In Nigeria: Environmental And Economic Sustainability Assessment. *Resources,* 4**,** 412-433.

Herrmann, R., Jumbe, C., Bruentrup, M. & Osabuohien, E. 2018. Competition Between Biofuel Feedstock And Food Production: Empirical Evidence From Sugarcane Outgrower Settings In Malawi. *Biomass And Bioenergy,* 114**,** 100-111.

Ibitoye, S. E., Jen, T.-C., Mahamood, R. M. & Akinlabi, E. T. 2021a. Generation Of Sustainable Energy From Agro-Residues Through Thermal Pretreatment For Developing Nations: A Review. *Advanced Energy And Sustainability Research,* 2**,** 1-15.

Ibitoye, S. E., Jen, T.-C., Mahamood, R. M. & Akinlabi, E. T. 2021b. Densification Of Agro-Residues For Sustainable Energy Generation: An Overview. *Bioresources And Bioprocessing,* 8**,** 1-19.

Ibrahim, I. D., Hamam, Y., Alayli, Y., Jamiru, T., Sadiku, E. R., Kupolati, W. K., Ndambuki, J. M. & Eze, A. A. 2021. A Review On Africa Energy Supply Through Renewable Energy Production: Nigeria, Cameroon, Ghana And South Africa As A Case Study. *Energy Strategy Reviews,* 38**,** 100740.

Ichu, B. C., Nwogu N.A, Agulanna A.C. & H.O, N. 2020. Potentials Of Biomass Briquetting And Utilization: The Nigerian Perspective. *Pacific International Journal,* 3**,** 07-12.

Iea 2020. *World Energy Outlook 2020*, Iea, Paris Https://Www.Iea.Org/Reports/World-Energy-Outlook-2020, Licence: Cc By 4.0.

Iea 2023. Renewable Energy Market Update - June 2023. *Iea, Paris*

Igbokwe, V. C., Ezugworie, F. N., Onwosi, C. O., Aliyu, G. O. & Obi, C. J. 2022. Biochemical Biorefinery: A Low-Cost And Non-Waste Concept For Promoting Sustainable Circular Bioeconomy. *Journal Of Environmental Management,* 305.

Irena 2021. Renewable Capacity Statistics 2021.

Ishola, F., Adelekan, D., Mamudu, A., Abodunrin, T., Aworinde, A., Olatunji, O. & Akinlabi, S. 2020. Biodiesel Production From Palm Olein: A Sustainable Bioresource For Nigeria. *Heliyon,* 6**,** 1-12.

Jameel, H. & Keshwani, D. R. 2017. Thermochemical Conversion Of Biomass To Power And Fuels. *In:* Cheng, B. (Ed.) *Biomass To Renewable Energy Processes.* 2nd Edition Ed. Boca Raton: Crc Press.

Japhet, J., Luka, B., Maren, I. & Datau, S. 2020. The Potential Of Wood And Agricultural Waste For Pellet Fuel Development In Nigeria—A Technical Review. *International Journal Of Engineering Applied Sciences And Technology,* 4**,** 598-607.

Jekayinfa, S. O., Orisaleye, J. I. & Pecenka, R. 2020. An Assessment Of Potential Resources For Biomass Energy In Nigeria. *Resources,* 9**,** 1-41.

Jekayinfa, S. O., Orisaleye, J. I., Pecenka, R. & Onifade, T. B. 2019. Effect Of Densification Variables On Water Resistance Of Corn Cob Briquettes. *Agronomy Research* 17**,** 1722–1734.

Kashif, M., Sabri, M. A., Aresta, M., Dibenedetto, A. & Dumeignil, F. 2025. Sustainable Synergy: Unleashing The Potential Of Biomass In Integrated Biorefineries. *Sustainable Energy & Fuels,* 9**,** 338-400.

Keles, S., Bilgen, S. & Kaygusuz, K. 2017. Biomass Energy Source In Developing Countries. *Journal Of Engineering Research And Applied Science,* 6**,** 566-576.

Khandaker, T., Islam, T., Nandi, A., Anik, M. A. A. M., Hossain, M. S., Hasan, M. K. & Hossain, M. S. 2025. Biomass-Derived Carbon Materials For Sustainable Energy Applications: A Comprehensive Review. *Sustainable Energy & Fuels,* 9**,** 693-723.

Kihombo, S., Ahmed, Z., Chen, S., Adebayo, T. S. & Kirikkaleli, D. 2021. Linking Financial Development, Economic Growth, And Ecological Footprint: What Is The Role Of Technological Innovation? *Environmental Science And Pollution Research,* 28**,** 61235-61245.

Koutoudjian, G., Diniz, L., Cespedes, R. & Undp, V. G. 2021. About Irena The International Renewable Energy Agency (Irena) Is An Intergovernmental Organisation That Supports Countries In Their Transition To A Sustainable Energy Future, And Serves As The Principal Platform For International Co-Operation, A Centre Of Excellence, And A Repository Of Policy, Technology, Resource And Financial Knowledge On Renewable Energy. *Irena Promotes The. Irena Promotes The,* 24.

Kovalyshyn, S., Kaygusuz, O. & Guney, M. 2019. Global Energy Demand And Woody Biomass. *Journal Of Engineering Research And Applied Science,* 8**,** 1119-1126.

Kraus, N. & Kraus, K. 2021. Digitalization Of Business Processes Of Enterprises Of The Ecosystem Of Industry 4.0: Virtual-Real Aspect Of Economic Growth Reserves. *Wseas Transactions On Business And Economics,* 18**,** 569-580.

Levi-Oguike, J., Sandoval, D. & Ntagwirumugara, E. Blockchain Technology And Renewable Energy Access: A Case For Sub-Saharan Africa. 2019 Ieee 5th International Conference For Convergence In Technology (I2ct) Pp1-6, 2019. Ieee, 1-6.

Li, G., Wang, R., Pang, J., Wang, A., Li, N. & Zhang, T. 2024a. Production Of Renewable Hydrocarbon Biofuels With Lignocellulose And Its Derivatives Over Heterogeneous Catalysts. *Chemical Reviews,* 124**,** 2889-2954.

Li, X., Wang, Z., He, Y., Wang, Y., Wang, S., Zheng, Z., Wang, S., Xu, J., Cai, Y. & Ying, H. 2024b. A Comprehensive Review Of The Strategies To Improve Anaerobic Digestion: Their Mechanism And Digestion Performance. *Methane,* 3**,** 227-256.

Lubwama, M., Yiga, V. A., Muhairwe, F. & Kihedu, J. 2020. Physical And Combustion Properties Of Agricultural Residue Bio-Char Bio-Composite Briquettes As Sustainable Domestic Energy Sources. *Renewable Energy,* 148**,** 1002-1016.

Makepa, D. C. & Chihobo, C. H. 2025. Sustainable Pathways For Biomass Production And Utilization In Carbon Capture And Storage—A Review. *Biomass Conversion And Biorefinery,* 15**,** 11397-11419.

Malico, I., Pereira, R. N., Gonçalves, A. C. & Sousa, A. M. 2019. Current Status And Future Perspectives For Energy Production From Solid Biomass In The European Industry. *Renewable And Sustainable Energy Reviews,* 112**,** 960-977.

Matemilola, S., Elegbede, I., Kies, F., Yusuf, G., Yangni, G. & Garba, I. 2019. An Analysis Of The Impacts Of Bioenergy Development On Food Security In Nigeria: Challenges And Prospects. *Environmental And Climate Technologies,* 23**,** 64-83.

Mayorga Betancourt, M. A., Lopez Santamaria, C. A., Lopez Gomez, M. & Gonzalez Caranton, A. R. 2020. Experimental Analysis Of Biodiesel Synthesis From Palm Kernel Oil: Empirical Model And Surface Response Variables. *Reaction Kinetics, Mechanisms And Catalysis,* 131**,** 297-317.

Moustakas, K., Parmaxidou, P. & Vakalis, S. 2020. Anaerobic Digestion For Energy Production From Agricultural Biomass Waste In Greece: Capacity Assessment For The Region Of Thessaly. *Energy,* 191**,** 1-34.

Nerini, F. F., Broad, O., Mentis, D., Welsch, M., Bazilian, M. & Howells, M. 2016. A Cost Comparison Of Technology Approaches For Improving Access To Electricity Services. *Energy,* 95**,** 255-265.

Odimegwu, C. 2019. A Derivation Of Passive Guidelines For Achieving Thermal Comfort In The Design Of Residential Buildings In Warm Humid Climate Of Abia State, Nigeria. *International Journal Of Development Strategies In Humanities, Management And Social Sciences,* 9**,** 1 - 15.

Ofori, S. N., Fobil, J. N. & Odia, O. J. 2018. Household Biomass Fuel Use, Blood Pressure And Carotid Intima Media Thickness; A Cross Sectional Study Of Rural Dwelling Women In Southern Nigeria. *Environmental Pollution,* 242**,** 390-397.

Okafor, C. C., Nzekwe, C. A., Ajaero, C. C., Ibekwe, J. C. & Otunomo, F. A. 2022. Biomass Utilization For Energy Production In Nigeria: A Review. *Cleaner Energy Systems,* 3**,** 1-12.

Okekunle, P. O., Itabiyi, O. E., Bello, M., Adeleke, A. G., Olayanju, A. & Olapade, O. Biofuel Yields From Sawdust Pyrolysis Of Different Woods In A Fixed Bed Reactor. *Proceedings Of The International Conference Of Mechanical Engineering, Energy Technology And Management,* International Conference Centre, University Of Ibadan, Ibadan, Nigeria Pp 4-7, 2019. 4-7.

Okoro, P. A., Chong, K. & Röder, M. 2024. Enabling Modern Bioenergy Deployment In Nigeria To Support Industry And Local Communities. *Biomass And Bioenergy,* 190**,** 107403.

Ola, F. & Jekayinfa, S. 2014. Pyrolysis Of Sandbox (Hura Crepitans) Shell And Characterization Of The Solid Product. *Science Focus,* 19**,** 52-58.

Ola, F. & Jekayinfa, S. 2015. Pyrolysis Of Sandbox (Hura Crepitans) Shell: Effect Of Pyrolysis Parameters On Biochar Yield. *Research In Agricultural Engineering,* 61**,** 170-176.

Oliy, G. B. & Muleta, D. T. 2020. Characterization And Determination Of Briquette Fuel Prepared From Five Variety Of Corn Cob. *International Journal Of Sustainable And Green Energy,* 9**,** 59-64.

Olujobi, O., Ufua, D., Olokundun, M. & Olujobi, M. 2021. Conversion Of Organic Wastes To Electricity In Nigeria: Legal Perspective On The Challenges And Prospects. *International Journal Of Environmental Science And Technology,* 19**,** 1-12.

Olujobi, O., Ufua, D., Olokundun, M. & Olujobi, O. 2022. Conversion Of Organic Wastes To Electricity In Nigeria: Legal Perspective On The Challenges And Prospects. *International Journal Of Environmental Science And Technology,* 19**,** 939-950.

Olujobi, O. J. & Olujobi, O. M. 2020. Comparative Appraisal Of Anti-Corruption Laws: Lessons Nigeria Can Learn From Norway, United Kingdom And United States'anti-Corruption Strategies. *International Journal Of Management (Ijm),* 11**,** 338-347.

Onifade, T., Wandiga, S., Bello, I., Jekanyinfa, S. & Harvey, P. 2017. Conversion Of Lignocellulose From Palm (Elaeis Guineensis) Fruit Fibre And Physic (Jatropha Curcas) Nut Shell Into Bio-Oil. *African Journal Of Biotechnology,* 16**,** 2167-2180.

Onwumelu, D. C. 2023. Biomass-To-Power: Opportunities And Challenges For Nigeria. *World Journal Of Advanced Research And Reviews,* 20**,** 001-023.

Orisaleye, J. I., Ojolo, S. J. & Ajiboye, J. S. 2019. Pressure Build-Up And Wear Analysis Of Tapered Screw Extruder Biomass Briquetting Machines. *Agricultural Engineering International: Cigr Journal,* 21**,** 122-133.

Otaraku, I. J., Oji, A. & Obi, C. 2019. Modelling And Optimization Of Ethanol Production From Cassava (Manihot Esculenta). *International Journal Of Scientific Research In Chemistry (Ijsrch)* 4**,** 1-6.

Oyedepo, S. O., Dunmade, I. S., Adekeye, T., Attabo, A. A., Olawole, O. C., Babalola, P. O., Oyebanji, J. A., Udo, M. O., Kilanko, O. & Leramo, R. O. 2019. Bioenergy Technology Development In Nigeria-Pathway To Sustainable Energy Development. *International Journal Of Environment And Sustainable Development,* 18**,** 175-205.

Oyegoke, T., Obadiah, E., Adah, F., Oguche, J. E., Timothy, G. T., Mantu, I. A. & Ado, A. D. 2022. Trends Of Progress In Setting Up Biorefineries In Developing Countries: A Review Of Bioethanol Exploration In Nigeria. *Journal Of Renewable Energy And Environment,* 9**,** 37-52.

Oyegoke, T., Oyegoke, A. F., Fasanya, O. O. & Ibrahim, A.-A. G. 2023. State Of Agro-Wastes Management In Nigeria: Status, Implications, And Way Forward. *In:* Ajay, P., Ashwini Kumar, Ravi Kant Mittal, Rajesh Goel (Ed.) *Waste Recovery And Management.* Crc Press Boca Raton.

Prasad, S. & Ingle, A. P. 2019. Impacts Of Sustainable Biofuels Production From Biomass. *In:* Ingle, M. R. A. A. P. (Ed.) *Sustainable Bioenergy.* Elsevier.

Purwanto, H., Zakiyuddin, A. M., Rozhan, A. N., Mohamad, A. S. & Salleh, H. M. 2018. Effect Of Charcoal Derived From Oil Palm Empty Fruit Bunch On The Sinter Characteristics Of Low Grade Iron Ore. *Journal Of Cleaner Production,* 200**,** 954-959.

Raturi, A. K. 2019. Renewables 2019 Global Status Report [Accessed Online: 20/04/2024], Https://Www.Ren21.Net/Wp Content/Uploads/2019/05/ Gsr_2019_Full_Report_En.Pdf.

Rea 2021. Rural Electrification Agency: Projects And Initiatives. 22 Freetown Street, Wuse Ii Abuja, Nigeria. Info@Rea.Gov.Ng.

Sá, L. C., Loureiro, L. M., Nunes, L. J. & Mendes, A. M. 2020. Torrefaction As A Pretreatment Technology For Chlorine Elimination From Biomass: A Case Study Using Eucalyptus Globulus Labill. *Resources,* 9**,** 1- 25.

Sarker, T., Ethen, D., Asha, H., Islam, S. & Ali, M. R. 2025. Transformation Of Municipal Solid Waste To Biofuel And Bio-Chemicals–A Review. *International Journal Of Environmental Science And Technology,* 22**,** 3811-3832.

Sarker, T. R., Nanda, S., Meda, V. & Dalai, A. K. 2023. Densification Of Waste Biomass For Manufacturing Solid Biofuel Pellets: A Review. *Environmental Chemistry Letters,* 21**,** 231-264.

Seo, M. W., Jeong, H. M., Lee, W. J., Yoon, S. J., Ra, H. W., Kim, Y. K., Lee, D., Han, S. W., Kim, S. D. & Lee, J. G. 2020. Carbonization Characteristics Of Biomass/Coking Coal Blends For The Application Of Bio-Coke. *Chemical Engineering Journal,* 394**,** 1-10.

Shaaban, M. & Petinrin, J. 2014. Renewable Energy Potentials In Nigeria: Meeting Rural Energy Needs. *Renewable And Sustainable Energy Reviews,* 29**,** 72-84.

Tambari, I. T., Dioha, M. O. & Failler, P. 2020. Renewable Energy Scenarios For Sustainable Electricity Supply In Nigeria. *Energy And Climate Change,* 1**,** 1-32.

Tong, K. T. X., Tan, I. S., Foo, H. C. Y., Lam, M. K., Lim, S. & Lee, K. T. 2024. Advancement Of Biorefinery-Derived Platform Chemicals From Macroalgae: A Perspective For Bioethanol And Lactic Acid. *Biomass Conversion And Biorefinery,* 14**,** 1443-1479.

Tshikovhi, A. & Motaung, T. E. 2023. Technologies And Innovations For Biomass Energy Production. *Sustainability,* 15**,** 12121.

Tursi, A. 2019. A Review On Biomass: Importance, Chemistry, Classification, And Conversion. *Biofuel Research Journal,* 6**,** 962 - 979.

Ugwu, C. O., Ozor, P. A., Ozoegwu, C. G., Ndukwe, A. & Mbohwa, C. Biomass Resources In Nigeria And The Conversion Pathways. Proceedings Of The International Conference On Industrial Engineering And Operations Management, Nsukka, Nigeria 746-756, 2022. 746-756.

Undp 2022. Sustainable Development Goals. *United Nations Development Programme.*

United, N. 2015. Transforming Our World: The 2030 Agenda For Sustainable Development. *New York: United Nations, Department Of Economic And Social Affairs,* 1**,** 41.

Wang, C., Feng, D., Xia, A., Nizami, A.-S., Huang, Y., Zhu, X., Zhu, X., Liao, Q. & Murphy, J. D. 2024. A Comparative Life Cycle Assessment Of Electro-Anaerobic Digestion To Evaluate Biomethane Generation From Organic Solid Waste. *Renewable And Sustainable Energy Reviews,* 196**,** 114347.

Woźniak, A., Kuligowski, K., Świerczek, L. & Cenian, A. 2025. Review Of Lignocellulosic Biomass Pretreatment Using Physical, Thermal And Chemical Methods For Higher Yields In Bioethanol Production. *Sustainability,* 17**,** 287.

Wu, R. 2025. Biomass Conversion Technologies: Transforming Organic Matter Into Energy And Materials. *Biomass Based Products.* Intechopen.

Yirijor, J., Adazabra, A. N. & Mcbagonluri, F. 2023. Fabrication And Characterization Of Charcoal Briquettes Fuel From A Blend Of Coconut Husk And Corncob. *Journal Of Energy Research And Reviews,* 13**,** 14-24.

Zubairu, A. & Abba, G. S. 2014. Production And Characterization Of Briquette Charcoal By Carbonization Of Agro-Waste. *Energy Power,* 4**,** 41-47.