TRANSFORMING BIOMASS INTO ENERGY: A PATHWAY TO SUSTAINABLE ENERGY SECURITY IN NORTHERN NIGERIA

M. G. Jegawa [(1)]
M. L. Mohammed [(2)] *
A. B. Muhammad [(2)]
J. Sanib [(2)]
B. O. Agboola [(3)]

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[1] IMT Atlantique Bretagne-Pays de la Loire, Nantes Campus, 4, rue Alfred Kastler - La Chantrerie, CS 20722, 44307 Nantes cedex 3, France
[2] Department of Energy and Applied Chemistry, Usmanu Danfodiyo University, Sokoto, Nigeria
[3] Department of Petroleum Chemistry, American University of Nigeria, Yola, Nigeria

*Corresponding Author's Email: misbahu.ladan@udusok.edu.ng

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M. G. Jegawa
IMT Atlantique Bretagne-Pays de la Loire, Nantes Campus, 4, rue Alfred Kastler - La Chantrerie, CS 20722, 44307 Nantes cedex 3,
France

M. L. Mohammed
Department of Energy and Applied Chemistry, Usmanu Danfodiyo University
Sokoto, Nigeria
misbahu.ladan@udusok.edu.ng

A. B. Muhammad
Department of Energy and Applied Chemistry, Usmanu Danfodiyo University
Sokoto, Nigeria

J. Sani
Department of Energy and Applied Chemistry, Usmanu Danfodiyo University
Sokoto, Nigeria

B. O. Agboola
Department of Petroleum Chemistry, American University of Nigeria
Yola, Nigeria

Abstract— The increasing global population has led to a significant surge in demand for fossil fuels. However, given the substantial environmental impact associated with their use, it has become essential to explore and develop alternative sources of fuel. Biomass, among other alternatives, is now becoming an important consideration as an alternative to fossil fuels. In this review, we made a critical assessment of the potentials of biomass as a source of fuel in Northern Nigeria. We took into account the opportunities and challenges of having biomass as a source for fuel, taking into consideration the geographical, climatic, and agricultural activities in Northern Nigeria. The review also explored the implications for Nigeria's bioenergy industry, as well as the challenges and limitations of establishing biomass and bioenergy industries. The role of government in terms of policy formulation was highlighted, along with suggestions for improvement. Although there will be challenges to encounter, the potential of having biomass as a source of fuel in Northern Nigeria is enormous and would be significantly beneficial socially and economically.

Keywords— Biomass, Energy, Fossil Fuel, Northern Nigeria, Pollution, Renewable Energy.

I. Introduction

In the 21st century, energy is surely one of the most pressing issues, particularly when considering its environmental impact. The heavy use of fossil fuels for our daily lives has greatly harmed the environment by contributing to global warming [1].

The functioning of a modern society relies heavily on sustainable energy, as it is the foundation for various essential activities, including transportation, manufacturing, healthcare, agriculture, and communication [2]. As evident in some research, energy is central to sustainable economic development; thus, many countries are providing special grants for energy research and development to achieve sufficiency and security. Sustainable energy is essential for achieving some of the United Nations' 17 Sustainable Development Goals (SDGs), including Goal 7, which focuses on energy transition from fossil fuels [3, 4]. Countries with growing economies, industries, and populations tend to consume more energy, resulting in an expected continued rise in global energy demand [5].

Hence, collective action and the political will to transition away from fossil fuels have gained increasing attention, primarily due to global warming caused by anthropogenic greenhouse gas emissions [6]. Through international cooperation and agreements such as the Kyoto Protocol and the Paris Agreement and the transition to renewable energy sources, technological innovations, including energy efficiency, are essential to a sustainable energy future for our planet [7]. However, the transition to alternative energy sources becomes a real challenge as the energy system of most developed and developing countries simply operates on fossil fuels [8, 9].

Renewable energy sources offer sustainable characteristics and numerous benefits, as the depletion of natural resources has made exploring alternatives an urgent necessity. They provide low environmental impact, prevent the exhaustion of fossil fuels and other natural resources, and allow for the utilization of greener alternatives, thereby improving energy security [10]. In addition to lower environmental impact, renewables also have a lesser production cost compared to the conventional fossil fuels [11]. For instance, wind and solar energy sources produce no emissions during operation, as for biomass, it releases CO_2 when burned, but this emitted CO_2 is reabsorbed by plant growth, and that is why biomass is considered a carbon-neutral energy source [12]. However, despite a recent surge in renewable energy integration, they are not a direct replacement for fossil fuels [13].

The average energy consumption per person in Nigeria (156 kWh) is significantly lower than that of some developing countries, such as Malaysia (4,114 kWh), South Africa (4,405 kWh), and Venezuela (3,413 kWh), which highlights Nigeria's heavy reliance on generators [14]. In addition to a significant portion of the citizens lacking access or connection to the grid, the country experiences frequent power outages, averaging 10-12 hours per day [15]. Furthermore, in rural areas, approximately 60% of the population remain unconnected to the grid [16].

Northern Nigeria possesses substantial renewable energy resources, such as solar, wind, hydro, and biomass. The development of renewable energy in this region can foster sustainable and inclusive socio-economic growth, generate job opportunities, attract new investments, and offer environmentally friendly energy solutions. However, despite this potential, the region's electricity generation remains heavily reliant on fossil fuels, causing energy insecurity and leaving many people without access to electricity. With vast agricultural and forest resources, Northern Nigeria has the potential to produce over 200 billion kg of biomass annually

[17]. Yet the region faces severe energy deprivation due to a lack of investment in modern energy infrastructure and favorable policies. This highlights the underutilization of biomass as a resource to improve energy access in the region. Biomass such as crop waste, forest residues, and animal manure could be converted into modern energy carriers, reducing reliance on imported fuels [18].

This study therefore assesses Northern Nigeria's biomass availability by agro-ecological zone, evaluates conversion efficiencies for localized energy solutions, and outlines policy gaps to optimize utilization.

II. Biomass dominance in Nigeria's energy landscape

The majority of households in developing countries, including Nigeria, are using solid fuels such as wood or charcoal on open fires or inefficient stoves for cooking [19]. The use of such polluting fuels and technologies results in poor health and environmental pollution and contributes to climate change [12]. Other activities, including transportation, water treatment, manufacturing, and communication, all require energy, which mostly comes in the form of electricity, to spur socio-economic development [20]. Nigeria has a total electrical energy demand of 98,000 MW, but its current production stands at only 3,900 MW, despite an installed capacity of 12,667 MW [21]. However, only 45% of Nigerians have access to this limited electricity supply [22]. The national grid's expansion to remote areas is hindered by several challenges, including scattered population, bureaucratic bottlenecks, technical difficulties, and lack of planning, among others [23].

Although not used for electricity generation, biomass accounts for 79% of Nigeria's energy use, followed by oil at 15%, natural gas at 3%, electricity at 2%, and coal at 1% [22]. Factors such as limited access to the national grid, poverty, and cultural preference for biomass utilization for cooking underscore its dominance as a primary energy source in Nigeria [24]. The huge consumption of biomass energy in Nigeria is mainly dominated by wood and charcoal for cooking purposes. However, due to limitations in local charcoal production methods, wood fuel dominates the traditional biomass consumption [25].

The breakdown of Nigeria's energy consumption by source in 2021 is presented in Figure 1 [26].

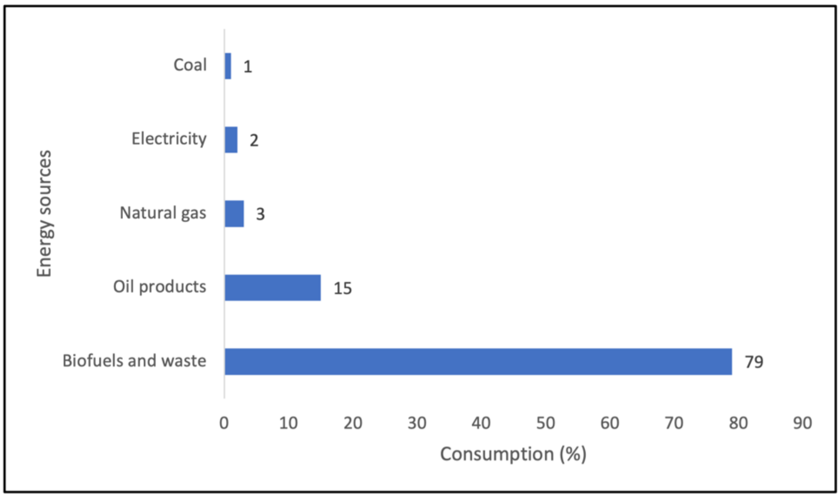

Fig. 1. Breakdown of energy consumption in Nigeria by source in the year 2021 [26]

The huge consumption of biomass energy in Nigeria is mainly dominated by wood and charcoal for cooking purposes. However, due to limitations in local charcoal production methods, wood fuel dominates the traditional biomass consumption [25]. The Northern region of the country is endowed with other renewable energy sources, which, if properly harnessed, could significantly enhance energy security and sustainability. For instance, Nigeria receives high solar irradiation, averaging around 20.1 MJ/m²/day, with the Northern regions reaching 4.1–5.8 kWh/m²/day [27]. This potential makes the region suitable for Concentrating Solar Power (CSP) projects, with estimated capacities of 88.7 GW for CSP and 210 GW for solar PV [28]. On the other hand, the wind energy potential in Nigeria is moderate and geographically concentrated, with the core Northwestern region showing a higher monthly average mean speed than other regions at 6.79 ms^{-1}. Specifically, Kano (9.27 ms^{-1}), Katsina (8.15 ms^{-1}), Sokoto (7.99 ms^{-1}), Gusau (6.52 ms^{-1}), and Kaduna (5.31 ms^{-1}) show the most potential for large and medium wind power generation, as they experience greater wind speeds at higher altitudes of 10 m and above [29]. Additionally, Nigeria possesses considerable small and large hydropower potential, which remains largely untapped. With over 278 potential small hydropower (SHP) sites with a combined capacity of 734.3 MW, only 37 MW has been explored [30].

III. Northern Nigeria's agro-ecological zones and biomass potential

To understand biomass characteristics and its distribution in Nigeria, it is important to consider the ecology and its variation. Various phenomena affect the variation of the agroecological zones in Nigeria, which include landforms, geology, soils, land use, vegetation, hydrology, climate, and wildlife; thus, a diverse selection of food crops are easily cultivated, considering the economic, nutritional, and social importance across the zones [31].

According to 2018 estimates, up to 78% of land in Nigeria is used for agricultural activities, and when broken down into different components to show the diversity of the agricultural land in the country, 37% of this agricultural land is arable and is utilized for cultivation of crops such as wheat, maize, and rice, which could be replanted every year [32]. However, in the Northern part of Nigeria, 52% of the arable land is used for farming or agriculture, which is higher than the average of 37% for the country [32]. Furthermore, 7.4% of agricultural land is dedicated to permanent crops, such as coffee, citrus, and rubber, which do not require replanting. This category also includes land for flowering shrubs, fruit trees, and nut trees. In contrast, 33.3% of the land is used for cultivation of naturally occurring crops that could take five or more years to mature, including herbaceous forage crops [33]. The different agro-ecological zones in Nigeria are as follows:

A. Sahel Savanna (Yobe, Jigawa, and Borno states)

Found in the farthest Northwest and Northeast regions of Nigeria, this zone is characterized by low rainfall of less than 600 mm (typically 3 to 4 months) and a dry season which could exceed 8 months [34]. This semi-arid zone has high evaporation rates due to heat and wind. The trees in this zone are drought-resistant and sparsely dispersed and could reach a height of 4 to 9 meters [34]. This zone is characterized by the presence of common tree species such as Acacia senegal, Commiphora africana, Acacia raddiana, and Acacia laeta. Additionally, the zone has a vast area of scarce grassland that is very short [35], such as Aristida stipoides, Schoenefeldia gracilis, and Chloris priean [36]. Crops cultivated in the Sahel region include millet, sorghum, cowpeas, pigeon peas, groundnuts, green grams, and chickpeas [37].

B. Sudan Savanna (Sokoto, Kaduna, Kano, and some parts of Borno States of Nigeria)

Covering more than 25% of Nigeria, this area exhibits higher precipitation within a range of 600 mm to 1000 mm, thereby producing more fertile soil and vegetation [34]. Although humidity in this region is usually under 40%, it could reach higher than 60% during periods of higher rainfall, and the dry season could last between 4 months and 6 months [36]. The zone is characterized by its agricultural activities, which produce vital crops such as cotton, millet, maize, and groundnuts, which are economically important crops [36]. The region has the largest population density as well as the highest number of cattle, which suggests high agricultural activities in general; alongside stunted trees, the natural vegetation is covered by short grasses of about 1 to 2 m high [36].

C. Guinea Savanna (Benue, Plateau, Nasarawa, Kwara, Niger, Kogi, and parts of Taraba States)

Located in the North Central region of the country and characterized by high annual rainfall between 1000 mm and 1500 mm, which could last for about 6 to 8 months [34]. This region has a large variation of both trees and grass, making it the most extensive vegetation in Nigeria. The region is blessed with tall trees that can reach up to 15 meters and grasses that are between 1 and 3 meters high; however, most of this vegetation is susceptible to being burnt by forest fires during the dry season [34]. Nevertheless, due to climate adaptation over time, the trees and vegetation have developed long taproots and thick barks, which make them resilient and enable them to survive forest fires [36]. Food crops such as millet, sorghum, maize, cowpea, and yam are some of the most cultivated crops in the region [38].

In addition to Nigeria's vegetation zones and features, another important aspect of understanding Nigeria is through its six geopolitical zones, presented as follows:

The North-West Zone has seven states (Jigawa, Kaduna, Kano, Katsina, Kebbi, Sokoto, and Zamfara);

The North-East Zone has six states (Adamawa, Bauchi, Borno, Gombe, Taraba, and Yobe);

The North-Central Zone has seven states, including Abuja (Benue, Kogi, Kwara, Nasarawa, Niger, Plateau, and the Federal Capital Territory (FCT));

The South-South Zone has six states (Akwa Ibom, Bayelsa, Cross River, Delta, Edo, and Rivers).

The Southeast Zone has five states (Abia, Anambra, Ebonyi, Enugu, and Imo) and

The South-West Zone has six states (Ekiti, Lagos, Ogun, Ondo, Osun, and Oyo).

Based on these geo-political zones, all the zones containing “North” in their description and name are regarded as Northern regions/states, while all the zones containing “South” in their description are regarded as Southern regions/states.

Biomass for energy consists of woody and woody biomass, herbaceous biomass, aquatic biomass; animal and human waste biomass, and biomass mixtures [18]. These biomass resources also differ based on their climatic region, with the rain forest zone expected to produce woodier biomass [39] and the savannah zones producing more crop residues [40]. This categorization of biomass is solely based on ecological or vegetation types found in Northern Nigeria as discussed earlier. Nigeria has different sources of biomass feedstock, which could be converted into energy. Figure 2 illustrates the different biomass sources and their overall contribution to Nigeria’s biomass potential [24][25].

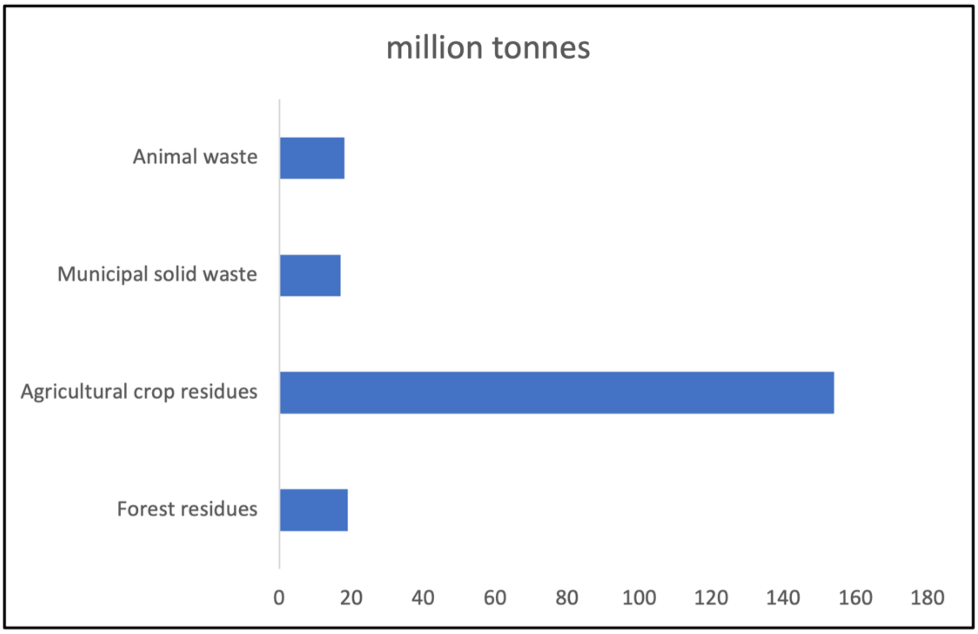

Fig. 2. Estimated annual biomass resource potential in Nigeria (Million Tonnes) [25]

IV. Distribution Of Biomass Resources In Northern Nigeria

Woody biomass consists of trees and other plantations with woody materials that are found and grown in the forest, rangelands, or woodlands [41]. These resources could include all but not limited to, the main trunk, leaves, branches, and other parts of the woody-like plant [42]. They indicate forests' ability to produce wood and sequester carbon and are essential for different applications, including paper production, construction, and energy [43]. Nigeria has established forest reserves covering an area of about 11,000,000 hectares, equivalent to 12.2% of the country's total land area [44]. With high potential for economic returns and energy production, forest residues—including logging residues (such as edgings, offcuts, sawdust, veneer log cores, slabs, bark, trimmings, and rejects)—as well as demolition wood and process residues, offer an alternative economic pathway for the country [18]. Nigeria's forest residue could be estimated at about 19 million tons, which is approximately equivalent to 8.68 Mtoe (363 PJ) [45]. Table 1 shows the forest reserves and plantations in selected Northern States of Nigeria [18].

Table 1: Forest reserves and plantations categorized by state [18]

State	Area of Forest Reserve (ha)	Area of Forest Plantation (ha)
Adamawa	10,011	2,374
Bauchi	840,280	1,200
Benue	60,175	2,234
Borno	582,820	432,052
Jigawa	92,000	3,000
Kaduna	613,484	6,146
Kano	77,702	2,186
Katsina	245,100	18,900
Kebbi	340,289	17,750
Kogi	540,360	5,000
Kwara	460,350	6,000
Niger	756,906	4,956
Plateau	402,500	6,800
Sokoto	602,631	10,943
Taraba	10,011	1,359

A. Agricultural Biomass

There are so many types of agricultural crops and their residues in Northern Nigeria, which could serve as biomass feedstock. In nature, agricultural biomass can be described as having no woody stems, and they live until the end of their growing season [46]. Most agricultural crops and grasses fall under this category, even though some crops are produced specifically as energy crops. These rain-fed crops are dispersed across Nigeria through traditional small-scale farming, feeding the country while also providing energy from their residues [47]. The most commonly produced crops in Northern Nigeria include maize, cocoyam, cassava, guinea corn, millet, rice, melon, yam, groundnut, soybeans, cotton, and cowpea. Table 2 highlights the states in Northern Nigeria with the highest production of food crops [47].

Northern Nigeria has huge potential for biomass resources from agricultural residues, and various conversion technologies could take advantage of these resources to provide cleaner energy that is cheap and reliable through a sustainable practice that conforms to international standards [12]. Agricultural residues produced in Northern Nigeria could be of two types: crop residues obtained from harvesting of target crops on the farm, such as leaves, straws, and stalks of cereals such as rice, maize, sorghum, millet, cocoa pods, cassava peelings, etc., and agro-industrial by-products derived from crop processing activities, which include coconut shells and husks, rice husks, oil seed cakes, cocoa husks, and sugarcane bagasse [48]. The crop residues, estimated at around 2.35 million tonnes, could produce an equivalent of 29 PJ of energy for Nigeria [25], and they do not provide competition for food production [49]. The majority of these residues, including maize, millet, and sorghum, occur within the months of November to March [50], while for rice, it is usually from October to December [51], and given the potential of harvest yield from agricultural crop production and residues, Northern Nigeria has a great potential to diversify its energy production by converting these residues.

Table 2: Statistics on the production of key agricultural products in Northern Nigeria [47]

Agricultural Resource	**Production Area (thousand ha)**	**Total Production (thousand metric tons)**	**State with Highest Production**	**Highest Production (thousand metric tons)**
Cowpea	2,860	3,368	Benue	428
Cassava	3,482	42,533	Benue	3,792
Maize	4,149	7,677	Kaduna	436
Cotton	399	602	Zamfara	155
Soybeans	291	356	Benue	79
Groundnut	2,785	3,799	Niger	547
Sorghum	4,960	7,141	Kano	746
Millet	4,364	5,171	Sokoto	714
Rice	2,433	4,473	Kaduna	732

B. Municipal Solid Waste (MSW)

Due to overpopulation in urban areas, MSW is generated in commercial, industrial, and household sectors. MSW could be plastics, glass, metal, paper, wood, textiles, and other biodegradables. Millions of tons of household waste are collected annually, and the majority of this waste is disposed of in landfills [52, 53]. There exists a variation of waste according to regions or cities; however, as a low-income country, the average waste generation in Nigeria is at 0.5 kg/capita/day [54]. Methane could be produced through incineration or anaerobic digestion/degradation. However, proper infrastructure and waste management systems are necessary, requiring better-designed landfills and a defined process for the collection, handling, and management of the waste [18].

C. Human and Animal Waste

There is a common cultural dislike from both public and regulatory bodies to utilize animal waste for energy production, as it can contaminate both ground and surface water resources [55, 56].

There are more widespread agricultural activities in both livestock and crop farming in the northern regions and households in Nigeria, as illustrated in Figure 3 [57]. By observation, the same is true for human waste production since the population of the Northern regions is higher that of the southern regions by almost 7 million people.

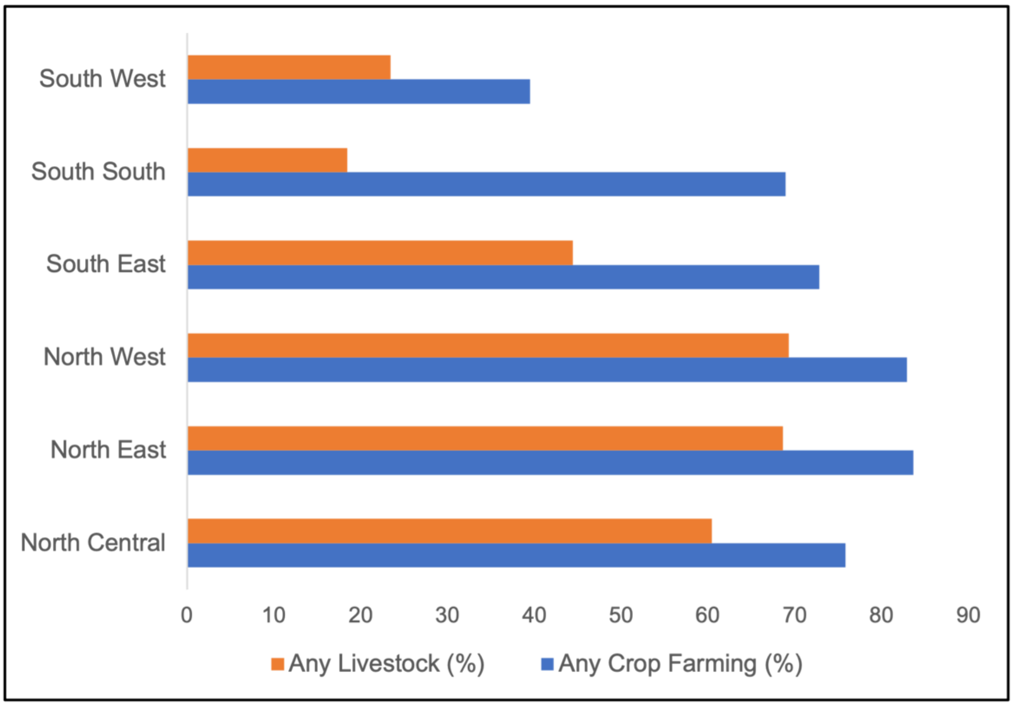

Fig. 3. The proportion of the populace engaging in agricultural pursuits in Nigeria [57]

D. Compositional Characteristics of Northern Nigeria's Crop Residues

It is noteworthy that the physiochemical properties of agricultural residues determine their energy potential. Table 3 summarizes key characteristics of Northern Nigeria's predominant crop residues, which aids in selecting more efficient conversion technologies [18].

From Table 3, maize cobs and groundnut shells offer the highest energy density, with 25,330 KJ/kg and 18,130 KJ/kg, respectively, which makes them ideal for thermochemical conversion, gasification. The average LHV of 17,279 for all the crops (Table 3) shows strong energy output from all the residues. On the other hand, rice husks and millet straws have around 14,000–16,410 kJ/kg and 15,400 kJ/kg, respectively, thus requiring supplemental fuels for efficient combustion. These findings inform policymakers to prioritize maize cobs and groundnut shells for bioenergy projects in order to maximize energy output in Northern Nigeria's existing biomass resource. Furthermore, this analysis entails strategic economic pathways for Northern Nigeria, as shown by high residue-to-product ratios for sorghum straws (RPR 0.85–7.40) and maize stalks (RPR 0.55–4.33), indicating low-cost feedstock for decentralized biomass energy systems.

V. BIOMASS TRANSFORMATION TECHNIQUES

Various techniques could be employed to convert biomass resources into biofuel; the techniques discussed in this section are chosen due to the maturity of the technology in the country, since different techniques could convert different biomass feedstock into either solid fuel like pellets, liquid fuels like biofuels, or gas fuel like biogas [18]. When it comes to biomass conversion technologies, there is no one perfect approach that solves every problem, as several factors must be analyzed to determine the best technology for deployment. These factors include the quantity of the resource, the type of biomass material that is available, and the form of energy (electricity, heat, fuel, etc.) that is required [58].

Pyrolysis is a thermal decomposition process that converts biomass into gas, char, and oil. This process has been shown to effectively utilize diverse feedstocks, including agricultural and municipal waste, to produce biochar, bio-oil, and gases, mostly methane [18]. On the other hand, thermochemical methods are recognized for their flexibility and efficiency in converting various biomass types into valuable liquid fuels, heat, and electricity [59]. The economic assessments indicate that these methods can be integrated into existing energy systems, enhancing their viability for large-scale production [59]. Gasification techniques have been used for partial oxidation of biomass at high temperature to generate syngas and other hydrocarbons such as propane or butane [18, 60]. Anaerobic digestion is a crucial biotechnological process for converting organic waste into biogas, a renewable energy source. Key factors influencing biogas yield include temperature, pH, and the composition of organic waste [61]. Biodiesel production using Jatropha curcas and vegetable oils has garnered significant attention due to its potential as a sustainable and renewable energy source. Jatropha curcas, a non-edible oilseed crop, is particularly promising since it does not compete with food resources, making it an attractive alternative to edible oils for biodiesel production [62]. Ethanol can be made by processing sugars and starches from biomass like energy crops or agricultural residues like cassava and sugarcane, which are grown in parts of Northern Nigeria [18]. The production process of ethanol typically involves pretreatment, hydrolysis, fermentation, and distillation. Yeast and bacteria are commonly used microorganisms for fermentation, with Saccharomyces cerevisiae being the most widely used yeast strain [63].

Table 3. Ultimate and Proximate Analysis of Major Crop Residues in Northern Nigeria, 2017 [18]

Crop	**Residue**	**RPR**	**Proximate Analysis (%)**			**Ultimate Analysis (%)**						**LHV (kJ/kg)**
			Ash (%)	**Volatiles (%)**	**Fixed Carbon (%)**	**C (%)**	**H (%)**	**O (%)**	**S (%)**	**N (%)**	**Cl (%)**	
Cowpea	Shells	1.20–1.90	5.9	75.3	18.8	43	5.6	43.3	0.01	0.6	0.13	17,900
Cassava	Peels	0.36–0.91	11.7	59.4	28.9	22.1	13.5	37.3	1.82	2.38		16,400
	Stalks	0.20–1.00	5.7	76	18.3	48.8	6.7	43.4	-	1.1	-	17,000
Maize	Cobs	0.20–1.80	1.6	84.3	14.1	46.2	5.4	47.2	0.2	0.9	-	25,330
	Husk	0.20–0.30	34.4	55.2	10.4	31.1	3.6	32.6	0.5	1.1	-	16,370–19,900
	Stalks	0.55–4.33	6.3	73.4	20.3	41.9	5.4	51.3	0.1	1.4	-	17,740
Soybean	Straws	0.80–3.94	4	88.8	7.2	45	6.7	45.4	-	2.9	-	17,900
Groundnut	husks/shells	0.37–1.20	3.1	68.1	28.8	49.3	7.3	39.1	0.02	1.1	-	13,785–18,130
Sorghum	Straws	0.85–7.40	8.1	73.4	18.5	39.5	7.5	43	0.2	1.1	0.6	15,400
Millet	Straws	0.95–2.00	2.7	94.1	3.2	42.7	6	33	-	0.1	-	15,400
Rice	Husks	0.17–0.35	15.8	69.3	14.9	38.2	5.9	-	0.1	0.7	-	14,000–16,410
	Straws	0.40–3.96	21.5	62.6	15.9	28.6	4	65.7	0.6	1.2	-	12,440

Key: RPR = Residue-to-Product Ratio; LHV = Lower Heating Value;"-" = Data not available

VI. ENERGY EFFICIENCY OF SMALL-SCALE CASSAVA ETHANOL PRODUCTION IN NIGERIA

The Cassakero Project is a Nigerian government initiative to replace kerosene with cassava-derived ethanol for house cooking [64]. This project offers critical insight into energy balance and practical challenges of small-scale biofuel production. The project reported a Net Energy Ratio (NER) of 1.20 with agrochemical and 1.34 without it, therefore indicating a marginal energy efficiency. Renewable energy sources, including wood fuel, organic fertilizer, and hydropower, contributed to 75-84% of total energy inputs, with a Net Energy Gain (NEG) ranging from 2.29 with agrochemicals to 3.52 MJ per liter of ethanol without agrochemicals, thus saving more energy per liter [64]. The outcome of the project showed that the ethanol conversion stage accounts for 74-83% of total energy demand because of inefficient distillation practices. NER seems to be higher without the agrochemicals at 12.25 MJ/l vs. 11.01 MJ/l, though it reduces cassava yields (10.8 vs. 20 tonnes/ha), thus highlighting a trade-off between energy efficiency and feedstock productivity. Sensitivity analysis of ±10% energy input variation validates the efficiency of the project [64].

In the case of Northern Nigeria, where cassava cultivation is limited, agricultural residues such as sorghum and millet stalks may offer higher energy returns due to lower processing demands. This reduces competition with food crops and aligns with the region's agro-ecological strengths, given limited use of agrochemicals in the region, which may result in lower crop yields but greater surplus energy, higher efficiency, and higher renewable energy contribution, as is the case with the Cassakero project.

VII. ECONOMIC VIABILITY OF BIOMASS VERSUS FOSSIL FUELS

Biomass feedstocks are locally sourced and, when compared to fossil fuels, are inexpensive and easily accessible, thereby reducing import dependence and enhancing energy security [65]. However, due to limited economies of scale, small ethanol production plants usually incur higher production costs per liter than fossil fuels, which are produced in centralized, large-scale refineries. Biomass direct combustion and biogas power generation show favorable internal rates of return (19.16% and 13.49%, respectively) and shorter payback periods (7.71 years for direct combustion) compared to fossil fuels [66]. Moreover, biomass energy systems generate rural employment and boost the local economy by retaining income in the economy and offer lower greenhouse gas emissions when burnt [66].

A. Energy Crops and Food Crops—Conflict and Symbioses In Nigeria

Biofuels are simply fuels produced from living things or their waste products. They are seen as greener and more sustainable alternatives to fossil fuels [67]. In low-income countries, producing biofuels from edible foods poses risks to food security [68]. However, biomass energy from non-edible substrates has garnered increased attention as it provides benefits such as clean energy production, better use of agricultural waste, improved health, and more job opportunities [69, 70].

As highlighted in the preceding sections of this article, the Northern regions of Nigeria have enormous potential to produce bioenergy from agricultural residues, municipal solid wastes, forest residues, etc. Energy or agricultural crops produced as feedstock for biofuel production include crops such as oil plants (such as Jatropha), corn, sorghum, rapeseed, sugarcane, grasses (switchgrass, miscanthus, alfalfa, reed canary grass, etc.) [71], and trees (willow, poplar, eucalyptus, and paulownia), which can reproduce after being felled and can be harvested every 3-5 years [72]. It is noteworthy that Northern Nigeria has vast land areas suitable for intensive and mechanized cultivation of food and energy crops compared to the regions in the south [69]. While maize, millet, wheat, rice, potatoes, sugarcane, and sorghum could all be used for ethanol production, cassava is the most profitable feedstock, followed by sugarcane in Nigeria, mainly due to the country's established expertise in producing these crops [67].

Jatropha, a second-generation energy crop, could be cultivated in all ecological zones of Nigeria. It is non-edible and therefore does not compete with food; it has highly resilient growth capabilities, and it can grow very well even in harsh weather conditions and low rainfall as found in most Northern States in Nigeria [73].

A continuous large-scale production of important energy crops for bioenergy production will cause demand for food crops to rise; consequently, the prices of these crops will also rise [74]. This trend of energy crops for biofuel production must be carefully analyzed, as most Nigerian farmers struggle to cultivate enough food crops for themselves. Utilizing land and water resources for energy crops could exacerbate issues, increase poverty, and limit access to food [67]. After all, more than 60% of the country's population lives below the poverty level [75], primarily due to low income and poverty [76]. As biofuel production could compromise food security, it is essential to assess poverty and how biofuel production could impact the four pillars of food security: availability, access, stability, and utilization [67].

VIII. ENVIRONMENTAL IMPLICATIONS OF BIOENERGY PRODUCTION

While biomass is often promoted as a renewable energy source, its production can lead to significant environmental degradation. For instance, expansion of energy crops or agro-residues for ethanol production may lead to the conversion of forests and grasslands, and this directly affects biodiversity and increases carbon emissions, vegetation loss, and soil disturbance [78]. Although the use of agrochemicals can boost harvest yields, such practices could degrade soil health over time and affect water resources [79].

Biomass energy production can result in substantial greenhouse gas emissions, particularly during the cultivation, harvesting, and processing stages [80]. A number of pollutants, including carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM), could be produced during combustion and upstream processes, though specific emissions depend on the type of biomass and combustion method used [81]. For example, studies on biomass electricity generation systems indicate that agricultural residues have a higher greenhouse gas emission with 291.25 gCO2e/kWh; while forestry and industrial wastes have lower emissions with 43 gCO2e/kWh and 45.93 gCO2e/kWh, respectively; and dedicated energy crops gave 208.41 gCO2e/kWh [82].

Therefore, long-term sustainability of bioenergy production requires careful strategic planning and management as it cuts across several dimensions, like environmental, economic, and social factors [83]. Hence, life cycle assessments (LCA) are crucial for evaluating the environmental footprint of bioenergy production, including greenhouse gas emissions, land use, and water consumption. These assessments help identify the potential for carbon dioxide removal, which can range from 45 to 99%, depending on the bioenergy process used [84]. Economic sustainability involves ensuring that bioenergy production is cost-effective and competitive with other energy sources. This requires careful management of supply chains and the use of optimization techniques to enhance efficiency [85]. While social sustainability focuses on the impact of bioenergy production on communities, including job creation and energy access. A multidimensional approach that considers cultural, institutional, and technical factors is necessary to address these social aspects effectively [86].

IX. Opportunities and Challenges

The Nigerian Government Biomass Program (2005) was a deliberate intervention aimed at encouraging the utilization of biomass resources for automotive applications. The program primarily focused on exploring potential biomass-derived fuels, such as bioethanol and biodiesel, as alternatives to conventional fuels in the automotive sector. Its objectives included reducing reliance on imported gasoline and minimizing environmental pollution from fossil fuels [77]. The policy aimed at raising domestic production of biofuel to 100% in 2020 along with other key projections, such as increasing 1.3 billion liters of ethanol (E-10 blend) from 2010 to 2 billion liters by 2020 and increasing 480 million liters of biodiesel from 2010 to 900 million liters by 2020.

In 2007, Nigeria launched an ambitious biofuel initiative to supply the domestic market with a 10% ethanol blend with gasoline (E10) [88] with an audacious amount of over US$ 3.86 billion investment for 19 ethanol biorefineries in the country [89]. Yet, there is not any operational large-scale commercial bioethanol plant in the country [90].

Northern Nigeria has huge potential for biomass resources from crops, forest residues, and various conversion technologies that could take advantage of these resources to provide cleaner energy. Hence, there should be a clear collaboration between the government and relevant institutions for the development of the biofuel industry in Northern Nigeria, since the region has the highest established potential for ethanol production in the country (Figure 4) [40]. The government can establish a clear framework and direction, while the institutions play a central role in research, development, and implementation. At both domestic and international levels, government involvement is crucial. Their strategies will help ensure the implementation and sustainable development of initiatives, tackling issues such as raw material shortages, high costs, and competition with traditional fossil fuels [90]. Meanwhile, institutions play a vital role in determining the industries' success, as they provide the necessary rules and structure for the bioenergy market to develop, promote collaboration between stakeholders, reduce uncertainties, and facilitate efficient resource allocation [91].

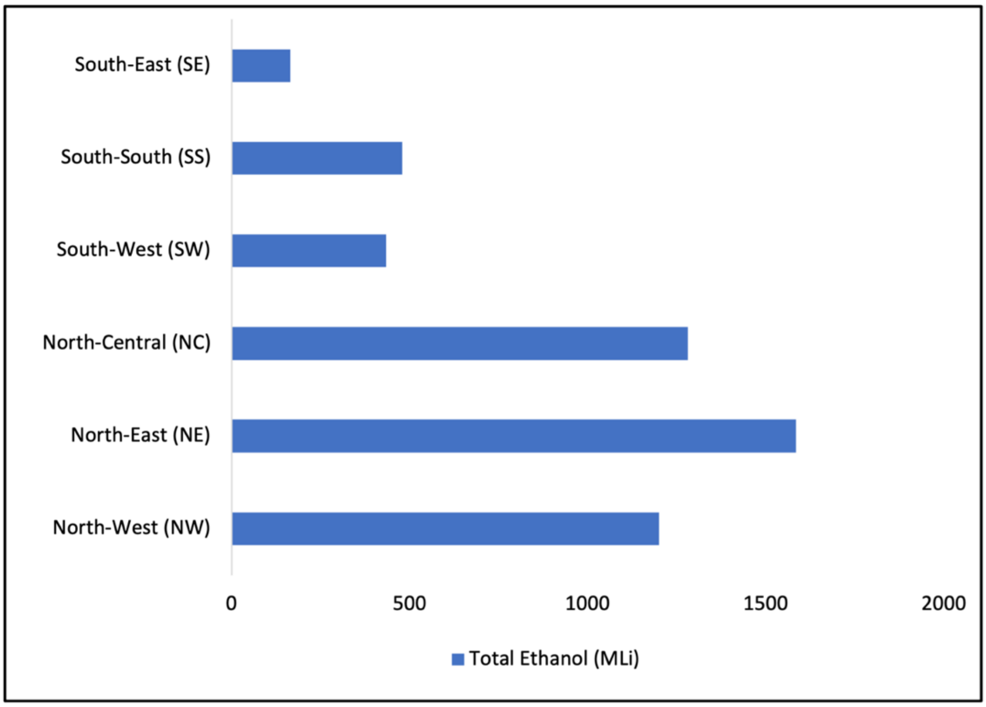

Fig. 4. Ethanol production potential by region – Nigerian Energy-Food Model [40]

X. Conclusion

Reliable and affordable energy is essential for economic growth and progress, and its importance to other aspects of modern civilization cannot simply be overstated. In Northern Nigeria, there is a significant potential in the exploration of biomass as a renewable energy source. With vast arable landmass and extensive agricultural activities, there exist numerous opportunities for sustainable energy development that could alleviate the poverty rate in the region, provide job employment, infrastructure development, and basic social needs such as electricity and water supply. Furthermore, following a sustainable strategy and cultivating energy crops presents a viable solution to meet energy demands without encroaching on food crop production, thereby eliminating conflicts between food and biofuel production.

Government policies and established relevant institutions play a pivotal role in accelerating and implementing the biofuel policy, actualizing it, and continuing its development to transition Nigeria's fossil-based energy systems and encourage its utilization. The current policies have laid the groundwork, but still, biofuels are not being used on a large scale, at least not even half their potential, and there exist several barriers and confusing frameworks for management and implementation of the initiatives. Other areas of improvement include the provision of relevant incentives and the reduction of bureaucratic processes to hasten the decision-making processes and investment in the sector.

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