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Review

Solid Biofuel Production from Biomass: Technologies, Challenges, and Opportunities for Its Commercial Production in Nigeria

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Abstract: Producing durable and efficient solid biofuels should be an important consideration in Nigeria's present economy due to the numerous advantages associated with it. It offers the benefit of energy generation, particularly in rural areas, and could potentially replace fossil fuels. However, the adoption and production of solid biofuels at commercial scale in Nigeria is limited by some challenges, including the lack of a developed supply chain structure, inadequate facilities, and air pollution. The present study summarizes the types of solid biofuel production technologies deployed in Nigeria as well as the biomass feedstock utilized in the production of fuel briquettes and pellets. While opportunities exist in the gasification of biomass in Nigeria, direct combustion is a readily applicable fuel conversion process that can be utilized to generate electricity from solid biofuel. The major challenges surrounding the full adoption of solid biofuel production and utilization in Nigeria are highlighted. Among others, promotion of clean energy alternatives, investments and financial incentives, sustainable renewable energy policy and energy transition plan, and legislative backing are identified as factors that could accelerate the commercial production and adoption of solid biofuel in Nigeria.

Keywords: bioeconomy; biomass; energy; densification; solid biofuel; energy transition

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1. Introduction

Clean, sustainable, and affordable energy is of great current interest as environmental and health-related issues arising from the use of fossil fuels continue to affect the global community. The past few decades have witnessed significant global interest from researchers, industry, and other stakeholders in energy transition from the use of fossil fuels to renewable energy systems in meeting both industrial and household energy needs [1–3]. The global interest in renewable energy systems could be attributed to its cost effectiveness, particularly its sustainability as a clean and affordable energy system for regions highly deficient in reliable energy supply [4]. Sub-Saharan Africa (SSA), for instance, has the lowest electricity access rate in the world, with about 600 million people lacking access to electricity. About 890 million of its population depend on traditional fuel for cooking, and economic growth has been severely impeded over the years due to lack of access to energy [4,5]. Sustainable energy demand in sub-Saharan Africa can be reliably met using renewable resources which are readily available and abundant in the region [6]. The abundant renewable resources in the region along with the decreasing costs associated with renewable energy technologies could be a major driving factor in the development and deployment of commercial-scale sustainable energy systems in the region.

In terms of renewable energy availability in SSA, about 81% of the total primary energy demand in the region is supplied by solid fuels [7] due to the vast availability of the resource. In its drive to meet its growing energy demand, biomass has continued to be an essential energy resource for the region. The categories of biomass available in the region include forest and forest product residues, agricultural residues, animal manure, and municipal solid wastes (MSW). While most of this biomass is usually burnt in the open, some of the biomass like coconut husk, wood shavings, and palm nut shells are mostly used in their natural form for direct combustion in traditional cooking stoves, e.g., three-stone fire. The traditional combustion of biomass for cooking and heating purposes has been linked with the incomplete combustion of biomass, leading to the emission of hazardous pollutants including CO. The long-term usage of biomass in its traditional form could lead to severe health problems, such as respiratory disease, chronic pulmonary diseases, or lung cancer [7]. Semi-solid biomass like sewage sludge and animal manure are poorly managed, with most of them discharged into the environment, including water bodies. The management of MSW is no different in this regard within the SSA countries as they are usually collected, illegally dumped in open locations, and allowed to decay naturally or are burnt when dried. This results in the necessity but also the opportunity of their further processing and application in biomass energy technologies within the region [8].

To improve the utilization of biomass for direct combustion, researchers and stakeholders have focused mostly on the densification of available biomass feedstock, which is considered to be one of the most promising and viable bioenergy pathways for SSA countries [9–11]. As an important route for solid biofuel production, biomass densification involves configuring biomass into a predetermined uniform shape by reducing the bulk volume via increased bulk density. This improves the handling, transportation, and storage of the loose biomass in its densified form. Densification of biomass generally entails the rearrangement of feedstock particles into sizes, deformation, and interlocking of particles via mechanical means. Biomass from various sources including animal waste, crop residues, forest product residues, and MSW has been densified into briquettes and pellets with varying degrees of success [12–14]. Considering the vast availability of raw biomass and the possibility of dedicated energy crops thriving in SSA, sustainable solid biofuel could potentially play a significant role in closing the energy gap within the region, particularly in rural communities. The SSA region is anticipated to experience significant increase in its economic and human population, resulting in, among many other things, an increase in energy demand for domestic and industrial uses. About 54% of the total energy demand is expected to come from residential sector and this demand is expected to continue to rise [15,16]. Regarding household energy demand, solid biomass is expected to provide more than 80% of the total energy in most SSA countries, particularly in rural and semi-urban areas which are often agriculture-based economies [17]. This necessitates carefully concerted efforts in developing and growing the renewable energy sector, particularly with respect to densified biofuels.

This study explores advancements in biomass densification within the context of Nigeria, with a specific emphasis on both the technologies employed for biomass densification and the biomaterial feedstock effectively utilized in solid biofuel production. This paper discusses the challenges impacting the commercial production and widespread adoption of solid biofuels in this country. In addition, opportunities for the development and promotion of the bioenergy sector are examined using the example of Nigeria, one of the fastest-growing economies in SSA.

2. Biomass Situation in Nigeria

Several countries in the sub-Saharan African (SSA) region share similar climatic and weather conditions as well as a similar biomass availability and utilization status [17–19]. This study focuses on the situation of biomass densification in Nigeria. Nigeria is located in West Africa (Figure 1) between latitudes 3°15′ and 13°30′ N and longitudes 2°59′ and 15°00′ E. The country has a wide range of untapped renewable energy resources including biomass, hydropower, solar, and wind energy, with potential to sustainably meet the energy needs of its population (Figure 2). Loose biomass is the cheapest and most readily accessible biomaterial in Nigeria, and it is widely used in its traditional form for heating purposes, including cooking. This, however, presents severe long-term health implications as well as environmental impacts. Nonetheless, processed biomass can play a pivotal role in reducing Nigeria's energy dependence on fossil fuels, diversifying its energy supply, and improving energy security for its people. This is mostly due to the vast availability and easy accessibility of biomass in the country [18–20]. In addition, energy from biomass can be used in combination with other renewable energy sources including hydropower and photovoltaic systems for heating and electricity [4].

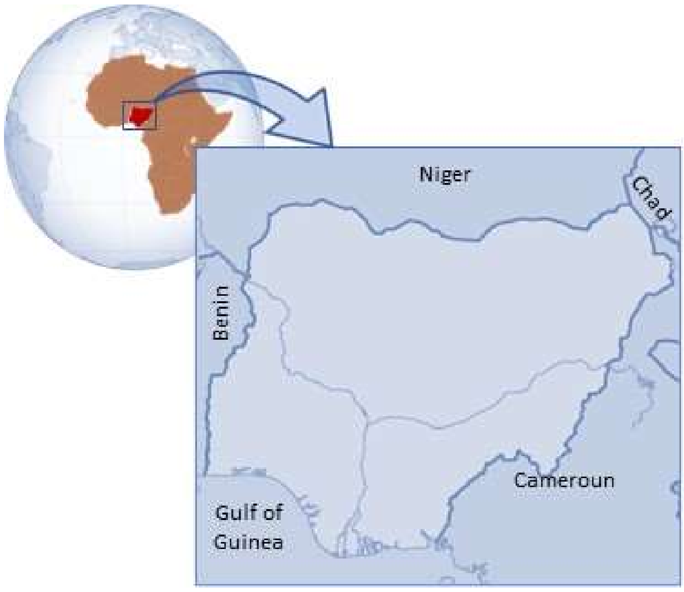

Figure 1. Map showing location and borders of Nigeria.

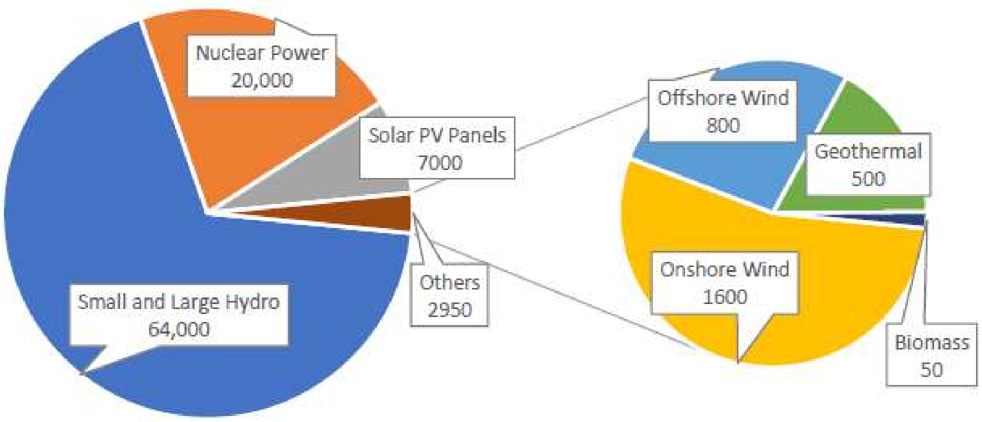

Figure 2. Potential of renewable energy sources in Nigeria (MW) as of 2017 [21].

Previous studies have shown significant biomass potential in Nigeria, with its quantity, quality, and distribution being dependent on the geographical location [17,20–24]. The feedstock categories in the country include agricultural residues emanating from crop management or post-harvest crop processing, e.g., straw, stalks, husks, stover, bagasse, leaves, and small branches; forest product processing residues, e.g., wood shavings, fiber, and sawdust, off-cut, and wood chips; and livestock manure as well as slurries from livestock. Nigeria is estimated to produce about 144 million tons of biomass per year, with most Nigerians, especially those in the rural areas, using biomass and waste from wood, charcoal, and animal dung in their traditional form to meet their household energy needs. Jekayinfa et al. [22], in their recent study, provided detailed data on the availability of different biomass types in Nigeria as well as an estimation of their technical energy potential. The biomass types identified include forest residues, agricultural residues, human and animal wastes, aquatic biomass, municipal solid waste, and energy crops. The authors reported a production value of 11,192,000 tons for maize with a residue-to-product ratio (RPR) of 0.20 to 0.30, 59,485,900 tons for cassava with an RPR of 0.36–0.91 for the peels, and about 1,497,800 tons of sugarcane with an RPR of 0.05–1.16.

The authors suggested that forest residues available as feedstock for solid biofuel production in Nigeria are estimated at 4.478 m tons, while wastes generated from animal production are estimated to be 82 kg/day. Their study suggests an annual generation of 36.5 million tons of municipal solid waste in Nigeria, while agricultural wastes are estimated at approximately 215 million tons. Readers are referred to Jekayinfa et al. [22] for more detailed data on biomass availability in Nigeria.

One of the challenges of the supply and utilization of biomass in Nigeria is the lack of a well-developed logistic infrastructure for the collection and distribution of this resource in an organized manner. While these biomass types are readily available and abundant in the country, they are widely dispersed. In addition, the lack of a well-defined and sustainable energy policy could also have contributed to the limited development in this sector. For a detailed description of the climatic conditions, population, and biomass availability and supply in Nigeria, readers are referred to the literature [20–23,25].

3. Solid Biofuel Production Technologies in Nigeria

Globally, there are several available technologies to produce solid biofuels. They have been classified into low-, medium-, and high-pressure compaction technologies [26]. Low-pressure compaction techniques utilize pressures of less than 5 MPa with a binder to produce densified fuel. Medium-pressure technologies utilize pressures ranging from 5 to 100 MPa for the production of solid biofuel and utilizes a heating device. High-pressure compaction occurs at pressures reaching or exceeding 100 MPa and require sophisticated equipment. High-pressure technologies include screw extruder briquetting machines, piston press briquetting machines, roll press densification equipment, and pelleting machines.

In Nigeria, the technologies, which have been utilized to produce briquettes, have mostly been used at laboratory scale with pressures falling within the low to medium range. The technologies that are utilized and have been reported in the literature are shown in Table 1—categorized based on the machine type. It was observed that most technologies utilize uniaxial or multiaxial hydraulic presses with closed die to produce briquettes. In addition to this, most of the briquetting operations utilize some form of binder in the solid biofuel production process. There is very little research and/or equipment relating to the high-pressure densification technologies such as the screw extruder briquetting machine, mechanical piston-press briquetting machine, hydraulic piston-press briquetting machine, pelleting machine, and roll press briquetting machine. Table 1 not only provides information on machine types but also presents details on available biomass types in Nigeria that have been utilized successfully with specific machine types for the production of solid biofuels.

Many studies reported in the literature were primarily experimental but showed potential for scale-up for commercial or industrial production. Lamido et al. [27] noted that there is a huge opportunity to solve the problem of unemployment in Nigeria through the development of biomass briquetting businesses. While Nigeria has a significant amount of biomass resources to support the commercial production of solid biofuel [28], Danjuma et al. [29] noted that Nigeria has suffered policy decay, which gives probable reason for the unpopularity of biomass densification technologies for solid biofuel production.

Table 1. Production technologies for renewable solid biofuels produced in Nigeria.

Machine Type	Solid Biofuel Produced and Material Utilized	Machine Description and Production Capacity	Mode of Operation and Comments	References
Hydraulic presses with single or multiple molds				
Hydraulic compression press with cylindrical mold	Briquettes from agglomerated charcoal fines and pine sawdust	Products were produced with applied pressure of 5 MPa	Binder was required. Manually operated press located at Federal Research Institute of Nigeria, Ibadan, Nigeria.	[30]
Uniaxial hydraulic compression press with cylindrical mold	Elephant grass briquettes	Press operated with compaction force of 355.03 N	Manually operated press. High moisture product.	[31]
Hydraulic briquetting machine with 3 molds	Bio-coal briquettes of groundnut husk	Press operated with compaction force of 276.36 N. Compaction pressure of 5 MPa.	Manually operated press. Binder was required.	[32]
	Composite briquettes of coal and corncobs			[33]
	Coal and cassava stalks			[34]
Lightweight hydraulic press with 4 molds	Water hyacinth and sawdust briquettes	Molds have diameter of 80 mm for briquette production	Manually operated press. Binder was required.	[35]
Hydraulic briquetting press with 4 molds	Rice husk, sawdust, and composite rice husk-sawdust briquettes	Cylindrical molds with press operated with a 3-ton hydraulic jack. Production capacity ranged between 20 and 30 kg/h. Compaction pressure ranged between 0.4 and 0.6 MPa.	Manually operated press. Binder was required.	[36]
	Composite briquettes of orange peels and corncobs	Compaction pressure up to 15 MPa	Manually operated press. Binder was required.	[37]
Hydraulic briquetting press with 12 molds	Composite briquettes of coal-banana leaves, and coal-banana pseudostem	Compaction force of 60 N and compaction pressure of 7 MPa	Manually operated. Binder was required.	[38]
Hydraulic briquetting press with replaceable molds	Torrefied corn husk, sawdust, and cassava peel briquettes	Capacity to produce 576 briquettes in 8 h. Working pressure of 15 MPa.	Manually operated. Binder was required.	[39]
Hydraulic briquetting press with 20 molds	Palm kernel granules	Press capacity of 10 tons. Briquettes of 28 mm diameter and 50 mm length. Compaction force of 215.3 N.	Manually operated. Binder was required.	[40]
Hydraulic briquetting press with 6 molds	Briquettes from elephant grass and spear grass	Molds produce briquettes with diameter of 39 mm. Working pressure of 5 MPa.	Manually operated. Binder was required. Press located at National Centre for Energy Research and Development, University of Nsukka, Nigeria.	[41]
	Composite briquettes of pine-needle dust and coal	Rectangular briquettes of 86 × 62 mm cross section. Working pressure of 5 MPa.		[42]

Table 1. *Cont.*

Machine Type	Solid Biofuel Produced and Material Utilized	Machine Description and Production Capacity	Mode of Operation and Comments	References
Hydraulic briquetting press with 20 molds	Dokanut and Docent groundnut shells	Working pressure ranged between 0.2 and 10 MPa	Manually operated. Binder was required.	[43]
Hydraulic briquetting press with 36 molds	Sawdust briquettes	Press capacity was 20 tons. Each mold was 100 × 70 × 150 mm.	Binder was required. Manually operated.	[44]
Hydraulic press with 4 molds	Corncob and rice husk briquettes	Compaction pressure of 2.10 MPa. Square cross-section briquettes with dimension of 75 mm.	Manually operated. Binder was required.	[45]
	Briquettes from corncob, groundnut shell, melon shell, cassava, and yam peels			[46]
Hydraulic press with single die	Corncob briquettes	Maximum compaction pressure of 25 MPa Cylindrical die of 50 mm. Heated die.	Manually operated. No binder required	[47–49]
	Sawdust briquettes			[50]
Hydraulic press with pelleting mold	Rice husk pellet	Operating pressure range of 28 to 34 MPa. Pellet of 12 mm diameter and 20 mm length.	Manually operated. Wet compaction.	[51]
Mechanical presses with single or multiple molds				
Motorized vibratory briquetting machine with 2 molds	Rice husk briquettes	Tapered cylindrical molds producing hollow briquettes	Motorized press. Binder was required.	[52]
Power screw operated presses with single or multiple molds				
Horizontal axis power screw operated press	Wastepaper and coconut husk admixtures	Press produces briquettes with average of 73 mm diameter and 37 mm length	Manually operated	[53]
Vertical axis power screw-operated press with 4 molds	Maize stalk briquettes	Press produces briquettes with 70 mm diameter and 50 mm length. Compaction force was 205.8 N.	Manually operated	[54]
Vertical axis power screw-operated press with 2 molds	Rice husk, sawdust, and maize stalk briquettes	Press produces briquettes with diameter of 70 mm. Working pressure of 0.42 MPa.	Manually operated	[55]
Power-screw-operated press	Water hyacinth briquettes	Cylindrical mold with diameter of 230 mm	Manually operated. Binder was required. Mold can be used as stove.	[56]
Dual-operated screw briquetting press	Carbonized melon seed shells	Machine capacity was 0.0025 kg/s and 0.0055 kg/s for manual and motorized operation, respectively. Briquette force was 47.13 N and power requirement was 0.785 kW. Produces briquettes with diameter of 25 mm.	Operation can switch between manual and motorized. Binder was required.	[57]

Table 1. *Cont.*

Machine Type	Solid Biofuel Produced and Material Utilized	Machine Description and Production Capacity	Mode of Operation and Comments	References
Motorized briquetting machine	Groundnut shell briquettes	Pressure exerted is 10 MPa	Motorized press. Binder was required.	[58]
	Groundnut shell and wastepaper admixture			[59]
Solid biofuel equipment based on screw extrusion				
Screw-type pelleting machine	Pellets from palm kernel shell, palm fiber, empty fruit bunch	Capacity of 5 kg/h. Operating pressure of 1.2 kPa.	Electrically powered. Binder required.	[60,61]
	Pellets from blends of coal and palm kernel shell			[62]
Screw extruder briquetting machine with heated die	Water hyacinth briquettes	Machine has a capacity of 120 kg/h and efficiency of 85%. Produces 90 briquettes per hour. Produces 50 mm diameter briquettes with 200 mm length and 10 mm center hole.	No binder was required. Electrically operated.	[63]
Screw extruder briquetting machine	Briquettes from blend of water hyacinth and groundnut shell	Machine has a capacity of 72 g/h and power consumption of 1.3 kW. Produces briquettes with 50 mm diameter. Efficiency of 90%.		[64]
Screw extruder briquetting machine	Sawdust briquettes	Operating pressure of 2000 Pa. Die temperature of 450 °C.	Motorized machine. Heated die requiring dried biomass. No binder was required.	[65]
Screw extruder briquetting machine	Sawdust	Machine consists of a power unit, speed reducer gear assembly, extrusion assembly, and control panel. Die temperature of 300 °C.	No binder was required. Electrically operated.	[66]
Screw extruder briquetting machine	Rice husks and sugarcane bagasse briquettes	Machine produces briquettes of 56 mm with 100 mm length. Power rating of 949.5 W. Efficiency of 60%. Capacity of 60 briquettes in 30 min.	Binder was required. Electrically powered motorized machine.	[67]
Screw extruder briquetting machine	Municipal solid wastes	Throughput capacity of 2605.4 kg/h. Power rating of 5 hp. Minimum and maximum operating temperature of 327 and 412 °C.	No binder required. Motorized machine.	[68]
Screw extruder briquetting machine	Sawdust, rice husk, and palm fruit shell briquettes	Machine has capacity of 0.5 kg/s.	Motorized and electrically driven. Binder was required.	[69]

Table 1. *Cont.*

Machine Type	Solid Biofuel Produced and Material Utilized	Machine Description and Production Capacity	Mode of Operation and Comments	References
Screw extruder briquetting machine	Sawdust	Design capacity of 100 kg/h. Power rating of 30 kW. Heated die.	Electrically powered. No binder was required.	[70]
Mechanical piston briquetting machine				
Mechanical piston-type briquetting machine	Sawdust and rice husk briquettes	Machine produces briquettes with rectangular cross section. Machine has a capacity of 0.2 kg/s.	Motorized and electrically operated. Binder was required.	[71]

4. Potential Utilization of Solid Biofuels for Domestic Energy Generation

Domestic energy consumption is a significant factor in the energy sector in Nigeria. The household sector is the most significant consumer of primary energy sources used mainly for cooking [72]. Table 2 shows the choice of domestic energy in rural and urban regions of Nigeria. It is clear that the commonly used fuel for household energy is solid biomass. This has remained consistent, as there is limited access to clean energy in these areas. Clean energy is becoming increasingly available in urban regions of Nigeria, as is shown in Table 2.

Table 2. Choice of cooking fuel in Nigeria [72].

Domestic Energy Source	Availability/Utilization (%)								
	2008			2013			2018		
	National	Urban	Rural	National	Urban	Rural	National	Urban	Rural
Electricity/gas	1.6	3.7	0.5	2.7	5.3	0.7	14.7	26.8	4.0
Kerosene	25.6	51.6	11.3	25.5	47.6	8.7	15.0	24.3	6.8
Wood/charcoal	67.4	41.3	83.6	67.2	43.9	84.9	67.6	47.4	85.5
Agric. waste/dung	1.0	0.7	1.1	1.9	0.2	3.2	1.0	0.3	1.6
% Solid biofuel used	70.1	42.1	85.6	69.1	44.1	88.1	68.6	47.7	87.0
Electricity coverage (%)	50.3	84.8	31.4	55.6	83.6	34.4	59.4	82.7	38.9

In rural areas, the commonly utilized traditional stove is the three-stone fire which is available throughout the Nigeria due to its simple design based on three stones with similar sizes upon which the pot is set, and fire is made between the stones. Another traditional stove is the charcoal stove which is made of metal and consists of an open combustion chamber which is separated from the ash chamber by a grate. The cooking pot is supported directly above the combustion chamber [73]. These traditional stoves have relied heavily on firewood, and sourcing for firewood contributes to deforestation, as it requires felling of trees for the purpose of fuel.

Solid fuels obtained from other sources are considered as a suitable replacement for firewood. Deforestation can be reduced through the densification of underutilized agricultural and forestry residues to produce pellets and briquettes for energy generation. In rural communities, solid biofuels based on such densified biomass can be easily used for the heat generation required for cooking. Kabir et al. [74] noted that the prevalence and large extent of the use of traditional cooking stoves and related cooking characteristics exert huge pressure on the environment and households. There are, however, different improved cooking stoves that have been developed and could utilize solid biofuels for generating energy for cooking. Table 3 gives an overview of efforts made in Nigeria to develop cooking stoves. Many of the cooking stoves use biomass in their loose form but have the potential to utilize densified fuels as feedstock. Fajola et al. [75], however, noted that, in practice, there is low awareness and information about cooking stoves with improved efficiency, which has limited their deployment.

Table 3. Conventional and improved cook stoves developed and utilized in Nigeria.

Stove Type	Fuel Used	Design Details	Performance	Emission Characteristics	References
Inverted downdraft gasifier cooking stove	Wood shavings	Diameter of 180 mm and height of 600 mm	Fuel conversion rate (FCR) was 1.89 kg/h.	Not determined	[76]
	Wood chips, corncobs, coconut shells, palm kernel shells		FCR of 1.60 to 1.82 kg/h. SGR between 85.89 and 102.25 kg/m^2h. Efficiency of 20.76%.		[47]
Ceramic-insulated biomass multi-cooking system	-	-	Insulating properties of ceramics for Inyi clay and its utilization in production of improved cookstove were investigated	Not determined	[77]
Top-lit updraft cooking stove	Wood chips	280 mm diameter and 400 mm height	Efficiency in cold and hot start was similar. Energy efficiency of the cookstove reached 89%.	Not determined	[78]
	Wood chips, coconut shell, and rice husk briquettes		Performance was significantly influenced by type of fuel. Wood chips had better performance than rice husk briquette and coconut shell. Lowest specific fuel consumption (SFC) was 8.54 kJ/kg.	Not determined	[79]
Batch-fed natural draft cooking stove	Charcoal	126 mm diameter and 521 mm height. Ceramic insulated.	Thermal efficiency between 17.2 and 33%. Boiling time was 0.172 to 0.354 h/kg of water.	Not determined	[80]
			Thermal efficiency was 25% with SFC of 0.213 h/kg.		[81]
Natural convection rocket-type biomass stove	Sawdust briquette and fuelwood	190 mm diameter and 500 mm height	Briquette burning rate of 20.5 g/min and fuelwood burning rate of 16.8 g/min. Thermal efficiency was 14.5% for briquettes but 31.1% for fuelwood.	Fuelwood emitted more particulate matter than briquette. Mean CO emission was also higher using fuelwood.	[82]

Table 3. *Cont.*

Stove Type	Fuel Used	Design Details	Performance	Emission Characteristics	References
Metal shield stove, clay charcoal stove, and metal charcoal stove	Fuelwood (metal shield stove) and wood charcoal (metal and clay charcoal stoves)	Mass of metal shield stove, metal charcoal stove, and clay charcoal stove were 0.75, 1.15, and 3.05 kg, respectively	Thermal efficiency of metal shield stove, metal charcoal stove, and clay charcoal stove were 11.64%, 20.02%, and 17.06%, respectively	Not determined	[83]
Sawdust/rice husk stove and charcoal metal stove	Sawdust and charcoal	Charcoal stove was 150 mm wide and 230 mm high. Sawdust stove had 140 mm diameter and 160 mm height.	Thermal efficiency of sawdust stove was 52.64% but 64.38% for charcoal stove	Not determined	[84]
Natural draft gasifier biomass cooking stove	Sawdust, wood, groundnut husk, and charcoal	Fiber insulated. Height of 460 mm, reactor diameter of 160 mm.	Thermal efficiency was 32.18, 80.10, 38.73, and 50.33% for charcoal, sawdust, wood, and groundnut husk, respectively	CO emission was highest in wood. Emission of CO reduced with time. CO emissions ranged between 150 and 850 ppm.	[85]
Forced draft biomass cooking stove	Charcoal	Insulated with fire clay (sawdust 50%, kaolin 40%, and ball clay 10%)	Efficiency ranging between 52 and 61.4% with a heat utilization of 40.65%. Stove operates between 1.40 and 1.66 kW.	Not determined	[86]
Portable improved cooking stove	Wood	Ceramic combustion chamber with metal casing. Combustion chamber of 120 mm diameter.	Burning rate and firepower were 6.7 g/min and 2192 kW during cold start, and 3.9 g/min for hot start. Thermal efficiency was 66%.	Not determined	[87]
Envirofit improved stove	Fuelwood	-	The fuelwood consumption was reduced by up to three times when improved cooking stove was used compared with the tripod stove	Significant reduction in mean particulate matter concentration. Lung function of cooking stove users improved.	[75]
Fuelwood cooking stove	Hardwood and softwood		The fuelwood stove had the highest thermal efficiency, highest average firepower, and lowest SFC compared to a 3-stone stove and traditional metal stove	There was little to no smoke generation. CO generated per kg of dry wood consumed ranged between 245 and 310.8 mg/m^3.	[88]

Table 3. *Cont.*

Stove Type	Fuel Used	Design Details	Performance	Emission Characteristics	References
Improved wood fuel clay cooking stoves	Fuelwood	External diameter of 450 mm and height of 380 mm	Improved stoves had firepower between 7.72 and 8.59 kW. Thermal efficiency ranged between 13.8 and 35%.	Not determined	[89]
Improved clay-lined cooking stoves	Charcoal	Two stoves: pyramidal and rectangular stoves	SFC ranged from 28,302 kJ/kg-s to 36,092 kJ/kg-s. Thermal efficiencies were 49.57% and 13.49% for pyramidal and rectangular cooking stoves.	Not determined	[90]
Modular briquette cooking stove	Water hyacinth briquettes	Stove diameter of 390 mm and a height of 750 mm. Chimney added to increase air flow to burner.	Thermal efficiency was 70.51% for water hyacinth briquettes and between 15 and 52% for other fuels.	Not determined	[91]
Enhanced biomass gasifier cooking stove	Palm kernel shell	It has four compartments, which perform various functions related to stove performance	Cooking stove had better performance than kerosene stove and compared favorably with the gas stove. Thermal efficiency of 36.98%.	Lower CO emissions compared to other stoves	[92]
Updraft biomass gasifier cooking stove	Sawdust	Reactor diameter of 300 mm and height of 850 mm	Performance of stove depended on loading capacities	Not determined	[93]

5. Potential for Industrial Utilization of Solid Biofuel in Nigeria

There is a lot of focus on the development of technologies for domestic utilization of solid biofuels and related technologies such as cooking stoves. However, there is a huge potential for application of solid biofuels in several industrial processes [27]. These include boilers for steam generation for different industries. They can also be used in distilleries, bakeries, and drying processes in food industry. There is also the opportunity for its use in the textile industry, manufacturing of clay products, and agro-industries. The generation of electricity from solid biofuels has not been explored in Nigeria. Electricity generation from solid biofuel would be beneficial to the rural communities who have limited access to electricity. To generate electricity from solid biofuel locally in Nigeria, more efforts need to be dedicated to fuel conversion processes and incorporation with the existing centralized power production units. The fuel conversion processes that can be utilized are combustion and gasification [94]. There are several studies that have investigated the economic viability of implementing gasification technology in Nigeria for off-grid electricity generation [95–98]. It has been noted that there are resources and technologies available to sustainably deliver electric power to certain regions in a cost-effective manner. Akhator and Obanor [99] noted that there is a huge potential for the application of downdraft biomass gasifiers for use in internal combustion engines in Nigeria. While this opportunity exists, significant research would need to be directed to producing densified solid biofuels suitable for use in gasifiers from the readily available biomass resources in Nigeria.

On the actual development of gasification technologies, not much research has been conducted. The few studies on gasifiers in Nigeria focus on the use of loose biomass including wood chunks, wood shavings, and rice husk at laboratory scale and have not been deployed for power generation in practice. Akhator et al. [100] developed a small-scale downdraft gasifier with thermal capacity of 5 kW and feedstock conversion rate of 1.25 kg/h. Salisu [101] evaluated the performance of a downdraft gasifier using rice husk. Ojolo and Orisaleye [102] also developed a small-scale downdraft gasifier, which was evaluated using wood shavings and palm kernel shells. Bukar et al. [103] considered the development of a blower for downdraft gasifiers. Akinyemi and Olaiya [104] attempted to design a reactor for fluidized gasification of sawdust. However, there has been no report of the use of gasification technologies in off-grid electricity generation in practice.

6. Challenges of Solid Biofuel Production and Utilization

Producing and utilizing quality solid biofuel would support the development of a sustainable bioeconomy in Nigeria. Developing a sustainable solid biofuels sector will serve to produce a possible replacement for fossil fuels, which will consequently reduce the country's reliance on non-renewable fuels. Solid biofuels in the form of briquettes (with and without binders) and pellets can be produced through the right combination of different waste materials such as agricultural, forest, and other forms of biomass residues [105–108]. Despite the enormous benefits and advantages, the commercial production of solid biofuels has been limited by some challenges, hence delaying their full adoption in Nigeria. The most important challenges are discussed in the following sections.

6.1. Indoor Air Pollution

One of the key challenges is the exposure to indoor air pollution while burning solid biofuels. Inhaling the ash particles, soot, carbon dioxide, and gases from burning solid biofuels is detrimental to human health, with children and women mostly affected. When these toxic substances or pollutants in the form of fine particulate matter (FPM) are inhaled, they easily find their way into the respiratory system. With long-term exposure, the lungs can be affected leading to different lung diseases and disorders including cognitive decline, arterial disease, chronic obstructive pulmonary disease, pneumonia in children, and in some cases, death [109]. This is one of the major challenges limiting the large-scale production and utilization of biofuel in Nigeria.

6.2. Durability

Another factor hindering the full adoption of solid biofuel production is the durability of the produced fuels. Generally, the durability of solid biofuels determines the transportation, handling, and combustion features, which in turn dictates their acceptability and utilization. The addition of calcium and phosphorus-based additives [110,111] when making solid biofuels can reduce the level of pollutant emission and enhance the overall durability of the fuels by increasing carbon retention and strengthening biomaterial stabilization. The durability of solid biofuels can also be enhanced by improving the binders' variables, including quantity, texture, and particle size, and reducing the content of extractives, fat, and lignin in the binders [112,113].

6.3. Infrastructure

Inadequate infrastructure is also one of the key problems facing the full-scale production of solid biofuels in Nigeria. Our findings revealed that the success of any solid biofuel business mostly depends on the availability of adequate facilities including fuel storage facilities, pelletizing or briquetting and pretreatment equipment, stockyard, and waste unloading area [114–116]. For instance, appropriate storage facilities are required for the safe storage of the solid biofuels prior to being transported to the location of use. In addition, equipment required for briquetting and pelletizing process lines should be readily available.

6.4. Supply Chain

Furthermore, the lack of a developed supply chain structure has been one of the bottlenecks affecting the overall efficiency and standardization of solid biofuel processing systems in Nigeria, limiting their production at industrial scale and thus reducing adoption. For instance, if there is no synergy among the responsible parties including the fuel users, forest owners, biomass suppliers, and others [117,118], the production of high-grade fuels can be delayed, inefficient, or of low quality since there is no proper coordination.

7. Opportunities in Solid Biofuel Production and Utilization Sector

Sustaining and maximizing the existing opportunities in the solid biofuel sector could create new job opportunities, which in turn could enhance the growth and development of the economy [119]. Furthermore, improvements in access to energy in rural areas as well as reduction in dependence on fossil fuels are also part of the existing opportunities which solid biofuel production and utilization offers. Finally, this is also expected to mitigate the effects of climate change in rural communities in Nigeria. The production of cost-effective and low-emission solid biofuels from biomass and other renewable energy sources provides opportunities for the generation of energy for domestic use and industrial applications [120–122].

The existing opportunities can be sustained in many ways. Firstly, adequate financing can be made available for investment in solid biofuel production and utilization in Nigeria, especially in local areas. Furthermore, availability of governmental support in the form of subsidies would encourage the production and utilization of solid biofuels in Nigeria. Fostering increased awareness and public education on solid biofuel production, along with highlighting the subsequent advantages resulting from its commercialization, will contribute to the long-term sustainability of opportunities within the sector. Public health can also be improved by reduced indoor air pollution through the adoption of efficient and clean solid biofuel combustion technologies.

8. Policies Governing the Production and Utilization of Solid Biofuels in Nigeria

Over the years, government policies have been implemented to accelerate the commercial production and adoption of sustainable solid biofuels in Nigeria (Table 4). A good example is the NREEEP program initiated by the Nigerian government in 2015 to enhance the generation of energy in Nigeria through the production and utilization of solid biofuels. By 2030, based on the initiative from the Nigerian government, one of the objectives of the policy is to add substantial renewable energy capacity to the existing policies. By this, the amount of energy generated from solid biofuels can be significantly enhanced, paving the way for its commercialization. It is projected that Nigeria's energy mix will contain about 10% renewables (Federal Republic of Nigeria, Ministry of Power, 2015) [123]. The NEMP and NEP policies were initiated by the Energy Commission of Nigeria (ECN) to oversee the continuous production and utilization of solid fuels for efficient energy generation. In 2021, the Nigerian government passed and signed the Climate Change Act. The Act was designed to provide a framework for the realization of low carbon emissions both by the government and private sector, and promote the development and implementation of effective climate change mitigation and adaptation strategies. While this move is in the right direction, there has been no visible action by the government through its agencies aimed at achieving the goals of the Act. Developing a framework for implementing this Act could significantly accelerate the development of a sustainable bioeconomy in the country driven by solid biofuel production. Similarly, past initiatives, as presented in Table 4, suffered the same fate of lack of the government's willingness to follow through on its documented policies. While the initiatives presented all had the potential to transform the bioeconomy of the country, no noticeable effort by the government was recorded to drive their implementation.

Table 4. Government and private policy for the commercial production and adoption of solid biofuel in Nigeria.

S/N	Policy/Initiatives	Objective(s)	Year	References
1	National Renewable Energy and Energy Efficiency Policy (NREEEP)	(a) Increase in grid-renewable energy supply by 2030.	2015	[123]
2	National Biofuel Policy and Incentives (NBPI)	(a) More attention on crops as feedstock—cassava sugarcane, oil palm, and others. (b) Tackling the food vs. energy conflict. (c) Development and promotion of solid biofuel industry using agricultural products.	2007	[20,123–127]
3	Strategic Education and Sensitization Programs (SESP), Technological and socio-political	(a) Creating more awareness programs and campaigns for Nigerians on the potential health, environmental, and economic benefits from using solid biofuels. (b) Providing instructional manuals and guides on the proper installation and usage of solid-biofuel-making machines. (c) Making available the technical standardization and specifications for effective production and performance.		[125,126]
4	National Energy Policy (NEP)	(a) Steady increase in the production of solid biofuel materials/crops since 2004 after the initiation of NEP. (b) Production grew by 19% for cassava between 2004 and 2011, 59% for maize and 70% for sugarcane.	2003, updated in 2013; 2018	[22,128,129]
5	Renewable Energy Master Plan (REMP)	(a) Reducing GHG emissions. (b) Transition to clean and environmentally friendly energy sources. (c) Exploiting renewable energy sources to meet the proposed energy needs of the country. (d) Expanding the role of renewable energy in its energy mix.	2005, update in 2011	[129–131]
6	Investment policy and legislative issues, Clean energy alternatives	(a) Developing new markets for solid biofuels. (b) Tax exemptions. (c) Providing avenues for easy setup of solid biofuel businesses in any part of Nigeria. (d) Upholding the existing forestry policies.		[126,132,133]
7	National Policy on Climate Change and Response Strategy (NPCC-RS)	(a) Mitigation and adaptation measures. (b) Establishing research and development programs necessary to strengthen research institutes. (c) Promoting low carbon and enhancing economic growth.	2012	[134]
8	National Energy Master Plan (NEMP)	(a) Coordinating the implementation of government policies. (b) Enhancing the performance in the energy sector through proper coordination.	2014	[135]

It is believed that the development and utilization of solid biofuels can be realized at industrial scale in Nigeria if the investment risks associated with the solid biofuel enterprise are reduced, and the regulatory and policy uncertainties are addressed. To this end, appropriate government policies could accelerate the commercial production and adoption of solid biofuel in Nigeria.

Common commercial solid biofuels include briquettes, pellets, firewood, and charcoal. Most of the materials used for making solid biofuels are derived from bioenergy crops, wood industry wastes, plantation and forestry residues, industrial processing residues from agriculture, and agricultural wastes [136]. Solid biofuel initiatives could be adopted, not only in the rural areas but also in the urban areas of Nigeria. Important considerations to drive this include the development and transfer of appropriate solid biofuel technologies, as well as market development. The Nigerian bio-economy can be greatly developed and enhanced with the provision of the right technology, which entails improving the efficiency of the existing local, low-cost solid biofuel production machines [137], and fabricating sophisticated and advanced fuel-making machines that can stand the test of time, and facilitate large-scale production of quality solid biofuels.

9. Advancing Nigeria's Energy Transition through Solid Biofuel Production

Economic development, as rightly pointed out by Iglinski et al. [138], can often result in adverse environmental effects without intentional efforts to mitigate them. A common consequence is the degradation of the natural environment through emissions into the atmosphere, surface and groundwater, and soil. The pressing need to safeguard the environment has given rise to energy transition policies, particularly in developed and developing societies. Energy transition is defined as "the gradual and complete shift to a fossil fuel-free, low-carbon society" [139]. This transformative process not only fosters the creation of a sustainable renewable energy sector [140] but also generates new employment opportunities and business opportunities.

While energy transition has gained momentum globally, countries such as Nigeria have grappled with fundamental energy provision for their population, which in the case of Nigeria is over 200 million people. The delay in formulating an energy transition policy by the government of Nigeria may be attributed to the multidimensional nature of this process, involving technological, economic, social, institutional, and legislative factors [141]. Considering that energy transition promotes energy security, equitable and fair access to energy, and environmental sustainability [142], it becomes imperative for developing nations like Nigeria to channel more efforts, including institutional support, towards fostering the commercial production of biomass energy, particularly from briquettes, to attain energy access and sustainability for their population.

The development and implementation of energy transition policies in developing economies such as Nigeria could achieve three crucial goals. Firstly, it can reduce reliance on environmentally unsustainable fuels like fossil fuels, paving the way for the establishment and expansion of a renewable energy mix to ensure stable energy availability. Secondly, it can mitigate the risk of energy scarcity, potentially enhancing economic, social, and overall livelihoods of the population. Thirdly, it can yield positive environmental and socio-economic effects, aligning with the sustainable development goals of the United Nations [141,143–145]. Moreover, it would facilitate the diversification and decentralization of energy production, which would contribute to enhanced energy security for the population [146].

It is important to note that energy transition processes are significantly influenced by institutional factors and legislative backing [146]. Therefore, it is crucial for the Nigerian government to lead the way in facilitating the promotion of commercial briquette production while encouraging entrepreneurs and investors to drive the business and infrastructure aspects. Streamlining regulations governing investment in these processes is essential as it would foster greater economic and investment efficiency by minimizing bureaucratic obstacles common in government agencies. To avoid the pitfalls of past government energy interventions presented in Table 4, Nigeria should ensure that the process is spearheaded by competent and experienced officials. It is pertinent that the Nigerian government, through its relevant government institutions, develop an energy transition plan with milestones and measurable implementation strategies. This will position the country favorably in the global energy transition landscape, drawing lessons from other nations at earlier stages of their energy transformation.

Pietrzak et al. [146] in their study underscore the significance of the prosumer energy market in the energy transition process, emphasizing the need for government legislation to incentivize prosumers in the drive towards the commercialization of bioenergy products. In Nigeria, numerous households already generate and consume electrical energy through solar or fossil fuel generators. Offering favorable legislative incentives for prosumers in the biomass energy sector to generate and sell energy could expedite the construction of low-energy infrastructures, stimulate the growth of small- and medium-scale biomass briquetting companies, and ultimately foster energy independence from centralized access.

As the shift from fossil fuels to renewable energy sources is anticipated to significantly improve the country's natural environment, renewable energy from biomass remains one of the top three renewable energy sources, alongside wind and solar energy [147]. Implementing sustainable energy transition policies that prioritize biomass energy holds great promise for Nigeria for environmentally friendly and economically sustainable energy solutions.

10. Conclusions

Sub-Saharan African countries including Nigeria have a wide variety of biomass types in abundance. Although Nigeria has experienced several societal challenges including security, economy, environmental, and energy challenges, there has been a strong research interest in the development of biomass densification technologies for the production of sustainable solid biofuels. This is considered a viable renewable energy option for the country. While these attempts may not be sophisticated, researchers have focused on utilizing technologies appropriate for the technological capabilities of rural dwellers. This attempt, however, has yet to transition from laboratory studies to commercial production, which has been a major hurdle for stakeholders. This move has been stunted or impeded mostly by a lack of workable government policies, research funding, public awareness and interest in biomass energy, and lack of investments and financial incentives. While the government has in the past developed several policies with the potential to develop the bioenergy sector, implementation has been lacking. To reverse this trend, the government will have to develop a proper renewable energy policy implementation framework; invest more in research, training, and development; raise public awareness of the benefits associated with the use of renewable energy systems; and provide incentives for its use. Significantly, this could not just provide energy for the population but also help in the development of a new bioeconomy, thus leading to economic growth, especially for rural dwellers.

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Abbreviations

ECN	Energy Commission of Nigeria
FCR	Fuel conversion rate
FPM	Fine particulate matter
GHGs	Greenhouse gases

MSW	Municipal solid wastes
NREEEP	National Renewable Energy and Energy Efficiency Policy
NBPI	National Biofuel Policy and Incentives
NEMP	National Energy Master Plan
NEP	National Energy Policy
NPCCRS	National Policy on Climate Change and Response Strategy
REMP	Renewable Energy Master Plan
SESP	Strategic Education and Sensitization Programs
SFC	Specific fuel consumption
SGR	Specific gasification rate
SSA	Sub-Saharan Africa

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