



A REVIEW OF PERFORMANCE OF SOLID BIO FUEL FOR HEATING APPLICATIONS

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Abstract

The rise in global population and urbanization has led to a surge in waste production, turning into a critical problem due to inadequate management and improper disposal. The review targets research findings on the conversion of agricultural wastes into briquette, which is an alternative energy to fossil. This review work provides a way of evaluating the efforts at reducing or even eliminating the menace and nuisance of these agro-wastes. Also, it highlights an alternative energy source (solid bio- fuel) that is environmentally friendly thereby reducing environmental pollution associated with agricultural wastes. Briquette production can help meet the growing energy needs of people, significantly boosting the development of developing countries. Additionally, briquettes offer advantages over fuel wood, such as higher heat intensity, ease of use, and reduced storage space requirements. Researchers agree that the production of briquette from wastes would go a long way to not only improve our wastes management approach for better public health and environmental sustainability but also boost or strengthen our country's economy as well as job creation, and the opportunity for exportation of solid bio fuel to neighboring countries. Furthermore, deforestation will be prevented as the use of briquette will be replace with firewood or wood fuel thereby conserve trees that would have been cut for fuel purpose.

Keywords: Bio solid fuel, Density, Agricultural waste and Briquette quality parameter

1.0 Introduction

From pre-colonial times till the present, agriculture has dominated the economies of Sub-Saharan African nations (Lutz *et al.*, 2019; Robert *et al.*, 2022). Agriculture has

been essential to the economic and population survival of many African nations. Between 60 and 70 percent of Nigerians work in agriculture or closely related fields, accounting for a sizable portion of the

country's GDP (NBS, 2022). Wastes are always produced during harvest, which follows the cultivation of agricultural produce throughout developing nations. Rice husk, groundnut shells, corn cobs, corn stalks, tomato wastes, sorghum stalks, bean shells, sugarcane bagasse, and numerous other waste materials are among them (Oyegoke *et al.*, 2022). The wastes that have accumulated over time have been causing pollution of the land, air, and water, which can harbor deadly microbes that contaminate the environment and release toxic gases into nearby homes, among other negative effects on the environment (Ogundele *et al.*, 2018). Currently, the techniques used to manage these wastes are typically burning them outdoors or dumping them on farms where they will eventually decompose. These approaches not only squander a tremendous number of resources but also cause pollution and environmental deterioration. Nonetheless, some of these agricultural wastes can be burned directly to produce fuel (Robert *et al.*, 2022)

Briquettes belong to the class of bio energy; they are solid bio fuels made by compacting particles, or biomass leftovers, under pressure at different pressures. Briquettes are easily used, transported, and stored because of their higher density, reduced moisture content, consistent size, and shape, which are all generated through compaction (Oyegoke *et al.*, 2023). Briquettes are considered a superior fuel due to their clean-burning qualities and long-term storability without degradation. Briquettes manufactured from free-of-cost raw materials, like agricultural wastes, can serve as a substitute for coal, charcoal, electricity, wood, and gas as a source of energy for homes and businesses.

Fuel wood is currently the main energy source for the rural population because other energy sources, such as gas, electricity, and kerosene, either extremely scarce or quite inadequate and are beyond of reach for the majority of people. Fuel wood collection has a negative impact on sustainable forest resource management and conservation. Depending on the ingredients used to manufacture the briquettes, they may burn cleaner than firewood or charcoal, converting waste materials into fuel.

Producing briquettes can help satisfy the growing energy demands of urban and industrial sectors, potentially providing a significant economic boost to developing countries. Moreover, briquettes offer advantages over fuelwood, including higher heat intensity, cleanliness, ease of use, and requiring less storage space. (Aransiola *et al.*, 2019). Briquettes made from biomass can be used to supplement or replace a variety of other energy-generating sources, including hydro, nuclear, solar, thermal, and many more (Olujobi *et al.*, 2022). It has the ability to enhance Nigeria's waste management strategy as well. It will contribute to the diversification of the country's energy mix, the progressive improvement of the power supply issue, the generation of direct and indirect employment, and foreign direct investment. The ability of the raw materials to bond together when compressed—for which fiber-rich materials are good—is another crucial selection criterion. However, the choice of raw materials is primarily based on what is readily available in the areas where the briquettes are made. If these materials are soaked in water and partially decompose, the fibres in the material are able to create strong bond. The fuel properties of agro-waste

briquettes differ depending on the type, and since they can be produced from a wide range of agro-residues, it is crucial to select briquettes with the best fuel properties or positive attributes. These careful selections will ensure the efficient and effective use of these wastes (Aransiola *et al.*, 2019).

The sustainability of this, as well as the current strain on biomass supplies, the detrimental effects on the environment, and the issues with energy supply might all be mitigated by implementing comprehensive alternative energy technologies for decentralized applications, which is why it is appealing. Therefore, there is paucity of information of exploring natural resources which are often considered as wastes and constitute environmental pollution. Consequently, the study reviews the available materials common to Nigeria environment, binder and evaluation of the briquette quality (Aransiola *et al.*, 2019; World Health Organization 2020). Thus, managing biomass waste properly in the process of making briquette fuel adds value to the effective and sustainable use of biomass waste. In an effort to satisfy growing energy demands with a reduced carbon footprint, the scientific community, politicians, and business supporters have recently focused on biomass conversion to various types of bio-energy (Ganesan *et al.*, 2020). Three pathways—biochemical, chemical, and thermochemical—are used to classify the biomass conversion technologies that are currently available on the market (Chin *et al.*, 2019; Olujobi *et al.*, 2022). Furthermore, many families have already embraced the method of creating solid fuels by densifying the wet pyrolyzed biomass materials in order to meet their energy needs

for heating and cooking (Gill *et al.*, 2018). Furthermore, these solid matters called briquettes burn longer and are less expensive than charcoal. However, the performance of solid biofuels for heating applications remains a critical concern, as their variable energy density, moisture content, and combustion efficiency hinder their widespread adoption and optimization. Despite growing interest in biofuels as a sustainable alternative, a comprehensive understanding of their performance characteristics is lacking, limiting their potential to replace traditional fossil fuels. This knowledge gap necessitates a review of existing research on performance evaluation of solid biofuels for heating applications, to identify key challenges, areas for improvement, and opportunities for enhancement, ultimately informing strategies for sustainable energy development.

2.0 Raw material/waste

Waste is any item or substance that has to be disposed of because it is no longer useful due to being damaged, worn out, contaminated, or in some other way spoiled. Only a small portion of Nigeria's annual production of about 35 million tons of solid trash is said to be collected (Bakare, 2020). Waste can be in any form such as Wood off cuts, wood bark, and sawdust from wood processing are the main components of wood waste. Wood wastes from planing or polishing the wood also include ordinary shavings. Because of the intensity of wood processing, sawmills produce a large amount of wood waste (Oyewo *et al.*, 2023a). Due to their flammability, wood waste and dust can catch fire. If there is a lot of sawdust in the vicinity, this could result in an explosion. Sawdust can be collected in bags or cyclones, or it can be

removed manually and collected by local exhaust ventilation systems to reduce this risk. Wastes provide a number of issues, including air pollution from smoke during incorrect trash burning, loss of aesthetic value, environmental damage, and offensive odors. Like most developing nations, Nigeria produces trash on a daily basis as a result of the strong demand for its products for a variety of purposes. Because waste is not properly managed, this endangers human health and the environment. Agricultural waste is produced yearly in most communities, and it is frequently mismanaged. It is evident the roadside, landfills, and residential areas. Examining safer alternatives for improving garbage management could help make our communities safer and environmentally friendly (Oyewo *et al.*, 2023b).

In developing nations, sawdust—a woody biomass residue after saw-milling operations by wood-based industries—is a plentiful resource that could eventually take the role of firewood in households' energy demands (Robert *et al.*, 2022) but because of their high moisture content and poor energy density, only a small percentage of the wastes are used as fuel (Njenga *et al.*, 2013). As a result of a rise in their fixed carbon content, it has been shown that wood biomass, such as sawdust, has higher calorific values at higher pyrolysis temperatures (Suspata *et al.*, 2013). Thus, employing carbonized sawdust as a fuel source could overcome the disadvantages associated with non-carbonized sawdust. Furthermore, to increase the caloric value of faecal char and sawdust, also known as sawdust char, carbonized sawdust may be a good material to combine the two. Moreover, the significance of agriculture to humanity

and its sustenance cannot be overemphasized both in developed and in developing nations like Nigeria. The negative implications of how its wastes are currently managed cannot be overlooked for the sake of eco-friendly and good public health. It is therefore vital to correct these current practices and unfold alternative approaches to better manage the waste (Oyewo *et al.*, 2022).

Excreta are a highly abundant biomass that is produced every day in the world in amounts of about 9.5 million m³ (Mateo-Sagasta, 2015). But because of low sewage system coverage and inadequate handling of faecal sludge, treating faecal matter and ensuring its safe disposal remains difficult in many developing nations (WHO 2020). Faecal that have been dried are pyrolyzed to create bio char, and finally densified under pressure to sterilize it for use in the manufacturing of briquettes. When feces are pyrolyzed at temperatures higher than 300C, the following outcomes are possible: (i) total pathogen eradication (Mateo-Sagasta, *et al.*, 2015); (ii) reduction of oxygen-containing functional groups and an increase in aromatic carbon content, which reduces smoke and CO₂ emissions (Szymajda *et al.*, 2021). However, because energy-rich aliphatic hydrocarbons degrade at higher pyrolysis temperatures, this process also reduces the caloric values of feces (Ward *et al.*, 2014). For instance, in Lagos, a city in Nigeria with approximately five million residents, around 1,000 metric tonnes of fecal sludge are generated, but only a fraction, 20-50%, is transported to treatment facilities. Utilizing these sludges for briquette production offers an alternative treatment and recycling method, alongside the commonly practiced biogas production (Yusuf *et al.*, 2020).

2.1.2 Recycling of waste

Recycling involves repurposing unwanted or discarded materials to create new products. Felfil (2011) states that recycling reintegrates these materials or energy back into the production cycle. Beyond replacing virgin materials, recycling provides numerous sustainability benefits. Hassan *et al.*, (2017) highlight its role in conserving oil, reducing greenhouse gas emissions, and saving energy. The five common methods for recycling agricultural waste are anaerobic digestion, re feeding, land application, composting, and incineration (Owoyemi *et al.*, 2016).

Reusing and recycling wood aids in the conservation of natural resources. By repurposing wood waste, pressure on forests is alleviated, allowing time for regeneration and the replacement of harvested trees. Given the much request for timber products, forests

are vulnerable to overexploitation and potential loss. Forests play a crucial role in environmental stability by absorbing carbon dioxide through photosynthesis and emitting oxygen. Repurposing trees reduces the need for excessive harvesting and allows them to continue their vital environmental functions. Additionally, wood waste can be utilized as a substitute for coal in steam generation (Obiri *et al.*, 2014). Although the reuse of waste material for charcoal briquettes and electricity generation has shown promise in developed countries, its adoption remains limited in developing nations like Nigeria (Ohimain *et al.* (2014)

2.1.3 Products from waste recycling

Recycling of waste will not only protect the environment but also save costs or reduce expenses for disposal. A few products from waste recycling are shown in Table 2.1.

Table 2.1: Agro-wastes in the production of bio fuels

Waste use	Bio fuel produce	Key finding made	Reference
Rice husk	Syngas	Calorific value of 4.46 MJ/ m ³ at 800 ⁰ c	Bazargan <i>et al.</i> , 2019
Groundnut peel and shell	Bioethanol	From 100 g of peels and shells of groundnut, 7.89% and 3.94% of ethanol were recovered, and the FT-IR spectral confirmed that the bio-liquid obtained from the samples was bioethanol.	Ajetunmobi <i>et al.</i> , 2020
Food wastes and human excreta	Biogas	The potential of utilizing the palm oil mill effluent for the production of biogas was established.	Ohimain <i>et al.</i> , 2014

Sawdust and animal dung	Bio solid fuel	Agricultural by product good for producing durable and excellent briquette	Szymajda <i>et al.</i> , 2021
Groundnut peel and shell	Bio ethanol	From 100 g of peels and shells of groundnut, 7.89% and 3.94% of ethanol were recovered, and the FT-IR spectral confirmed that the bio-liquid obtained from the samples was bio ethanol	Ajetunmobi <i>et al.</i> , 2020

3.0 Evaluation of briquette quality

3.1 Physio- Combustion properties of solid bio-fuel

To assess the suitability of a briquette for combustion, several factors must be considered:

- **Ignition Time:** The average time it takes for the briquette to ignite is crucial as it indicates the ease of starting the combustion process.
- **Cooking Time:** The duration needed for cooking with a particular briquette or the briquette requirement for completing a specific application.
- **Soot and Ash Production:** The amount of soot and ash generated is important as it directly affects the heat supply to the application.
- **Odor:** The smell produced during combustion, which is significant for household cooking and industrial heating application (Krizan *et al.*, 2020)

To comprehensively evaluate and classify briquettes as a high-quality product, several key parameters beyond heating value are considered. These include moisture content, ash content, bulk density, durability, shatter resistance, calorific value, volatile matter content, and fixed carbon content. These factors collectively provide a detailed understanding of the briquette's physical and chemical characteristics, enabling manufacturers to compare and categorize their products based on stringent quality standards. By assessing these parameters, producers can ensure their briquettes meet the required specifications for optimal performance, efficiency, and environmental sustainability, ultimately guaranteeing a superior product that meets industry benchmarks (Krizan *et al.*, 2020).

3.2 Physico- Chemical properties of fuel

3.2.1 Moisture content

One significant factor influencing the final product's density is its moisture content. Furthermore, a lower calorific value will

result from the higher moisture content (Miranda *et al.*, 2015). But as the briquettes burn out quickly without producing enough energy, much lower moisture content also results in lower quality (Ajadi *et al.* 2020). In addition, stability will be diminished by moisture contents below 4% or 5% (Tumuluru *et al.* 2011). Many earlier researchers have recommended that the ideal moisture content be about 8% since it will overcome previously mentioned problems (Chin & Siddiqui, 2014).

3.2.2 Heating value

According to Oyelami *et al.* (2023), The energy density of solid biofuel briquettes, typically expressed in megajoules per kilogram (MJ/kg), is a critical factor in their performance. A higher energy density translates to more efficient combustion, greater heat output, and lower fuel usage. The type of biomass, moisture levels, compression pressure, and binder quality all impact the energy density of briquettes. By refining these elements, manufacturers can boost energy density, leading to enhanced fuel efficiency, lower emissions, and increased energy output. Moreover, high-energy-density briquettes can fetch a higher market price, making them more appealing to customers. Nonetheless, fluctuations in energy density can compromise fuel consistency and reliability, highlighting the importance of quality control measures to ensure a high-quality fuel product. By focusing on energy density, solid biofuel manufacturers can produce a superior product, elevating the performance and efficiency of heating systems while providing a dependable source of renewable energy. The heating values of the fuel briquettes are determined based on the temperature

differential between the maximum and minimum temperatures using the following formula as presented in Equation 3.1 (ASTM Standard Test Method. 2013).

$$Q = \frac{(C_H + C_{cal})(T_b - T_a)}{W_b} \quad (1)$$

Where, Q = Calorific value of the fuel briquette (kJ/kg)

W_b = Weight of the fuel briquette sample (kg)

C_{cal} = Heat capacity of the bomb calorimeter (kJ/°C)

$T_b - T_a$ = The difference temperature (°C)

C_H = Heat capacity of water (kJ/°C).

3.2.3 The percentage of ash content

Briquette percentage ash content is a crucial factor in solid biofuel performance, representing the residual inorganic matter left after combustion. A lower ash content is desirable, as high ash levels can lead to reduced fuel efficiency, increased emissions, and fouling of heating equipment. Ash content is influenced by biomass type, moisture levels, and contaminants present in the feedstock. Briquettes with high ash content can cause slagging, corrosion, and maintenance issues, ultimately leading to decreased system performance and increased operating costs. Conversely, briquettes with low ash content (typically <5%) exhibit improved combustion efficiency, reduced emissions, and minimized equipment wear. To optimize ash content, producers can implement quality control measures, such as feedstock screening and processing

techniques like washing or torrefaction. By minimizing ash content, solid biofuel producers can deliver a cleaner, more efficient, and higher-performing fuel product, enhancing the overall performance and reliability of heating applications. percentage of ash content is calculated as presented in Equation 2 (ASTM Standard Test Method. 2020):

$$\text{Percent of Ash Content} = \frac{B}{A} \times 100 \quad (2)$$

3.2.3 Fixed carbon

This factor defines the total amount of solids remaining once the carbonization process has been completed. It should be a higher value of carbon content in the feedstock to produce long-lasting and stable briquettes (Enweremadu *et al.* 2004).

3.2.4 Calorific value

Briquette calorific value is a critical parameter in solid biofuel performance, representing the amount of energy released per unit mass of fuel during combustion. A higher calorific value indicates a more energy-dense fuel, resulting in improved combustion efficiency, increased heat output, and reduced fuel consumption. Factors influencing briquette calorific value include biomass type, moisture content, densification pressure, and binder quality. Optimizing these factors can enhance calorific value, leading to improved fuel performance, reduced emissions, and increased energy efficiency. Additionally, high-calorific value briquettes can command a premium price in the market, making them more attractive to end-users. However, variability in calorific value can impact fuel consistency and reliability, emphasizing the need for quality control measures to ensure a stable and high-

performing fuel product. By prioritizing briquette calorific value, solid biofuel producers can deliver a superior fuel product, enhancing the overall performance and efficiency of heating applications. (Enweremadu *et al.* 2004). The briquette's energy content is determined by its calorific value (Romallosa 2017). The calorific value of the briquette is reported between 14–17 MJ.kg⁻¹ Gill *et al.* (2018),

3.3 Physio-Mechanical properties

The physical and mechanical of the briquettes determined included density, stability, compressive strength, hardness, shatter resistance, thermal efficiency and mechanical durability (Krizan *et al.*, 2020).

3.3.1 Shatter resistance

The hardness of the briquettes determined by dropping briquettes of known weight and length from 1 meter height to a concrete floor ten times. Tabil and Sokhansanj (1996) and Adapa *et al.* (2003) considered shatter resistance of > 80% as acceptable. First, the weight of the disintegrated briquette is read, and the material loss (%WL) is calculated using Equation (3) (Madhava *et al.*, 2012). Next, the percentage of shatter resistance (% SR) is evaluated using Equation (4)

$$\% \text{ WL} = \frac{W_1 - W_2}{W_1} \times 100 \quad (3)$$

$$\% \text{ SR} = 100 - \% \text{ WL} \quad (4)$$

Where:

W_1 = weight of briquette before shattering, g

W_2 = weight of briquette after shattering, g

% WL = percentage weight loss, %.

3.3.2 Stability

Briquette stability is a critical factor in solid biofuel performance, referring to the ability of densified biomass briquettes to withstand physical stress, moisture absorption, and thermal degradation without disintegrating or deforming. Oyelami *et al.* (2023) reported that unstable briquettes may break apart during handling, storage, or combustion, leading to reduced fuel efficiency, increased emissions, and equipment damage. Factors influencing briquette stability include biomass composition, moisture content, densification pressure, and binder type. High-stability briquettes exhibit minimal swelling, shrinkage, or cracking, maintaining their structural integrity and energy density. Techniques to enhance briquette stability include optimizing densification conditions, using suitable binders, and applying surface treatments. By ensuring briquette stability, solid biofuel producers can guarantee consistent fuel quality, improved combustion performance, and reduced maintenance requirements, ultimately enhancing the overall efficiency and reliability of heating applications. According to Oyelami *et al.* (2024a), increase in length and diameter are calculated using Equation (5) and (6) respectively.

$$\% \text{ increase in length} = \frac{L_F - L_0}{L_0} \times 100 \quad (5)$$

Where: L_0 = Length of briquette immediately after removal from the mould, mm

$$(\%) \text{ increase in diameter} = \frac{D_F - D_0}{D_0} \times 100 \quad (6)$$

Where: D_0 = Diameter of briquette immediately after removal from the mould, mm

D_f = Diameter of briquette 96 hours after removal from the mould, mm.

3.3.3 Compressive strength

Briquette density stands out as a paramount parameter due to its direct correlation with the briquette's energy content (Krizan *et al.*, 2020). The eventual density of the product is determined by various factors such as the density of the feedstock and binding agent, operational pressure, temperature, and water content. It's worth noting that the total energy content per unit varies depending on the density achieved (Oyelami *et al.*, 2014b).

According to Anozie *et al.* (2021), the strength is evaluated with Equation (7), $N \text{ mm}^{-1}$.

$$CS = \frac{3 \times \text{fracture point load (N)}}{L_1 + L_2 + L_3} \times 100 \quad (7)$$

Where:

L_1 = Length of briquette at point 1, mm L_2 = Length of briquette at point 2, mm L_3 = Length of briquette at point 3, mm.

3.3.4 Density

According to Olujobi *et al.* (2020), briquette density is a critical factor in solid biofuel performance, significantly impacting combustion efficiency, energy output, and handling logistics. Density, typically measured in kilograms per cubic meter (kg/m^3), affects the briquette's energy density, with higher densities indicating more energy per unit volume. Factors influencing briquette density include biomass type, moisture content, densification pressure, and binder quality. Optimizing density can enhance combustion efficiency, reduce emissions, and increase energy output, while also improving storage and transportation

efficiency. Conversely, low-density briquettes may exhibit reduced combustion performance, increased emissions, and decreased energy efficiency. By targeting optimal density ranges (typically 1,100-1,400 kg/m³), solid biofuel producers can create a high-quality fuel product that balances energy density, handling convenience, and combustion performance, ultimately enhancing the overall efficiency and effectiveness of heating applications. Equation (8) is used to calculate the density of the briquette.

$$\text{Density} = \frac{\text{weight of briquette}}{\text{volume of briquette}} \times 100 \quad (8)$$

3.3.5 Hardness

Hardness is a crucial property of solid biofuels that significantly impacts their performance in heating applications. It refers to the fuel's resistance to mechanical stress, impact, and abrasion, influencing handling, storage, and combustion behavior. Harder biofuels are more challenging to grind and mill, increasing processing costs and energy consumption, while also potentially causing clogging or bridging issues in fuel feed systems. Furthermore, hardness affects combustion efficiency, with harder fuels burning less efficiently and producing increased emissions (Oyelami *et al.*, 2014b). The moisture content, density, particle size, and biomass type all impact hardness, making it essential to understand and control these factors. Torrefaction, palletization, and additives can improve hardness, enhancing fuel efficiency, reducing maintenance, and increasing overall system performance. Therefore, evaluating and optimizing hardness is vital for ensuring reliable and efficient operation of solid biofuel heating systems (Križan, 2017).

3.3.6 Water penetration resistance

Water penetration resistance is essential for the storage and transportation of briquettes in humid environments or after exposure to rain. A common method for assessing the water resistance of biomass briquettes is a water-immersion test conducted in a laboratory. Researchers like Fadele *et al.* (2021) and Anozie *et al.* (2021) evaluated water resistance by submerging briquettes in a water bath for two minutes and then using Equation (9) to calculate the percentage of water absorbed. Other methodologies, such as immersing briquettes in water for 30 seconds at room temperature (Orisaleye *et al.*, 2019), have also been reported using Equation 9 (Anozie *et al.*, 2021).

$$\% \text{ water absorbed by briquette} = \frac{M_a - M_b}{M_b} \times 100 \quad (9)$$

3.4 Elemental analysis

Elemental analysis, particularly proximate analysis, is essential for determining the elemental composition of the briquettes. For energy materials, Carbon (C), Hydrogen (H), and Oxygen (O) are crucial elements. Equations provided by Jigisha *et al.* (2007) enable the estimation of biomass elemental composition for Oxygen (C) (Equation 10), Hydrogen (H) (Equation 11), and Carbon (C) (Equation 12) at a 95% confidence interval.

$$C = 0.637F_c + 0.455V_m \quad (10)$$

$$H = 0.052F_c + 0.062V_m \quad (11)$$

$$O = 0.304F_c + 0.476V_m \quad (12)$$

Where C, H, and O are Carbon, Hydrogen, and Oxygen.

4.0 Conclusions and future studies

4.1 Conclusions

The improper disposal of agricultural waste poses evident dangers and contributes to environmental pollution, which can adversely impact human health. The organic nature of agricultural waste increases the risk of disease outbreaks due to the attraction of vectors to decaying waste. However, there are significant economic opportunities in harnessing the substantial volume of agricultural waste generated, particularly in developing countries like Nigeria. Energy production, whether in the form of fuel (liquid, gaseous, or solid) or electricity, offers an efficient means of disposing of or utilizing biomass. Another promising avenue is the conversion of agricultural waste into useful materials and chemicals, such as adsorbents, which are crucial for pollution control, water treatment, and various chemical process industries. Exploring the conversion of agricultural biomass into chemicals presents numerous opportunities that warrant thorough exploration (Oyelami *et al.*, 2014a).

In this context, biomass briquettes emerge as a superior alternative energy source compared to traditional wood fuel. Clean energy adoption in households not only enhances human health but also mitigates the impacts of climate change, benefiting millions of people, particularly women and children, who would otherwise spend considerable time collecting fuel daily. Embracing biomass briquettes would facilitate improved access to life-changing products for end-users, leading to increased sales, economic stability, job creation, and enhanced tax revenue for the government, consequently bolstering Nigeria's economy. Furthermore, the adoption of biomass briquettes aligns with Nigeria's commitment

to reducing emissions by 20% to 45%, as outlined in its Nationally Determined Contributions (NDC). Overall, this transition promises to elevate the standard of living and productivity of end-users while safeguarding the environment for future generations.

4.2 Future recommendations

It is recommended that there should be promotion of the conversion of agro-waste into valuable products, such as solid bio fuel, for economic benefits. Thus, initiation of widespread awareness campaigns to highlight the economic value of agricultural waste and educate citizens on the dangers of waste burning is necessary. Incorporate this education into the basic school curriculum to ensure continuous awareness.

Furthermore, there should be significant initial capital investment for setting up process plants, along with tax breaks and other government incentives, to incentivize investors to engage in agro-waste conversion projects, thereby fostering sustainable development and economic growth.

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