BIO-BRIQUETTES PRODUCTION FROM AGRICULTURAL RESIDUES: A REVIEW OF BINDERS, METHODS AND CHARACTERIZATION

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ABSTRACT

This review investigates the utilization of waste biomass as a feedstock for bio-briquette production, focusing on materials derived from agricultural crops. The study explores different bio-briquette production methods, including pyrolyzed densification using a binder, direct densification with binders, and binderless briquetting. The selection and impact of binders on briquette properties are discussed, considering factors like availability, cost, moisture content, and desired energy content. Furthermore, the study delves into the characterization of bio-briquettes, analyzing their physical, mechanical, chemical, and thermal properties. Key parameters evaluated include density, durability, moisture content, ash content, volatile matter content, fixed carbon, heating value, ignition time, and burning rate. Overall, this study underscores the potential of waste biomass-based bio-briquettes in addressing energy demands sustainably and mitigating environmental impacts, supporting the transition towards a greener and more environmentally friendly future. The insights gained from this research can serve as a valuable guide for policymakers, researchers, and stakeholders in advancing the adoption of bio-briquettes in Africa as a cleaner and more sustainable energy solution which stated in banana nut which is 29.49Mj/kg, Banana peels/corn cobs 26.36Mj/kg, Corn starch waste 10.30Mj/kg, Banana Leave 17.70Mj/kg, Baggasse and Cofe Husk 11.13Mj/kg, Baggasse 18.38Mj/kg, Hazelnut shell 18.89Mj/kg, and Durian Peel 6274.29kcal/kg.

Keywords: *Biomass, Pyrolysis, Densification, Binders, Bio-briquettes*

INTRODUCTION

Rapid industrial progress and population growth has caused sudden increase of energy consumption and depletion of traditional fossil fuels (Shen, 2020; Drożyner, et al 2013). The widespread utilization of fossil fuels to meet the energy demands in industrial, residential, and transportation sectors results in significant levels of greenhouse gas emissions. These emissions contribute to environmental pollution, global warming, and climate change (Sarker et al., 2021).

More than 700 million Africans (82%) use solid biomass fuels, such as wood, charcoal, dung and agricultural residues, for their primary cooking needs. Dependence on solid biomass, especially wood is also associated with forest degradation and deforestation, where unsustainable harvesting is practiced. Solid biomass fuels beyond firewood and charcoal can be derived from by-products of agricultural production and forest residues, are becoming increasingly important (Japhet et al, 2020). Briquettes are fuels whose energy conversion occurs through direct burning and are used for heating and cooking, for domestic or industrial use, best used in fixed bed chambers, due to their physical structure (Marreiro, et al., 2021).

The development of briquettes made from agricultural waste, which will increase efficiency in the domestic sector, and potentially replace conventional polluting fuels such as firewood (Arévalo, et al., 2017). Bio-briquettes provide a solution that is mostly made of green waste and other organic materials, and is commonly used for electricity generation, heat, and cooking fuel. Producing bio-briquettes can also intensively help to address the increasing demand for energy (Sanchez et al., 2021).

2.0 WASTE BIOMASS AS A FEEDSTOCK FOR BIO-BRIQUETTE PRODUCTION

The biomass materials primarily consist of organic remnants resulting from human activities, such as agroforestry residue, industrial and municipal bio-wastes, as well as naturally grown resources like energetic crops or wild grasses. When it comes to biomass briquetting, materials derived from vegetables or plants are the preferred option for densification, while animal-derived biomass, like cow dung, is commonly used as a binding agent. The preference for vegetable or plant biomass is mainly due to its widespread availability compared to animal-derived biomass. In Table 1, we can observe the global quantities of selected biomass sourced from agricultural crops that were burned in 2009 and 2019 (Obi et al., 2022).

The figures 1 and 2 below show more on biomass good for briquetting, and biomass classification origin.

Breadfruit waste b. Forest residue c. Wood fibre

3. IMPORTANCE OF UTILIZING WASTE BIOMASS AS A RENEWABLE RESOURCE

At present, our society confronts two significant challenges: the depletion of resources and the accumulation of waste. These issues result in soaring costs for raw materials and the implementation of increasingly expensive and stringent waste disposal regulations (Pfaltzgraff et al., 2013). Consequently, inadequate management of agricultural and agro-industrial waste biomass contributes to climate change, contamination of water and soil, and local air pollution, posing a threat to the well-being of plant and animal life. Additionally, this waste biomass holds substantial value in terms of both material and energy recovery (Kaur et al., 2014).

4. BINDERS IN BIOMASS BRIQUETTING

Biomass generally comprises inherent natural binding or stabilizing components, such as lignin and proteins. When the densification process takes place at elevated temperatures and pressures, these substances are discharged and triggered, leading to an increased level of particle bonding within biomass briquettes (Mani et al., 2006; Oyelaran et al., 2015).

Nevertheless, there are instances where the biomass might lack a substantial amount of natural binder (lignin), or the densification process necessitates extra binders to attain the desired strength and resilience of the briquettes. Briquette binders can be broadly classified into two types: organic and inorganic. Moreover, within each category, they can be further subdivided based on their specific compositions (Anukam et al., 2021).

4.1 Classification of Bio-briquette Binder

As previously stated, briquette binders can be categorized into three main classes: organic binders, inorganic binders, and composite binders. Zhang, et al (2018) Noted that organic binders are known for their favorable binding properties, which encompass high impact and abrasion strength, as well as excellent water resistance. However, it is important to note that at high temperatures, organic binders tend to decompose easily, leading to poor thermal stability and reduced mechanical strength. (Han, et al., 2014). Organic binders are primarily characterized by their widespread availability, affordability, high heating value, and low ignition temperature. There are four main types of organic binders, which include: biomass (agricultural wastes, forestry biomass, etc.), tar pitch and petroleum bitumen (coal tar pitch, tar residues, etc.), lignosulphonate, and polymer binders (resins, polyvinyl, and starch). Miao, et al. (2019) Noted that organic binders could further be divided into hydrophobic binders (e.g., asphalt, and coal tar) and hydrophilic binders (e.g., biomass) based on their reaction to water. The limited commercial application of organic binders in biomass briquetting is primarily attributed to their poor thermal stability (Yun, et al 2014).

4.2 Binder Selection

The selection of binders in biomass briquetting is influenced by several factors, such as availability, cost and properties of the raw materials, moisture content of the mixture, densification pressure, and the desired energy content of the briquettes (Olugbade et al., 2019). In developing communities, the primary considerations for binder selection are often the cost and availability. The type and quantity of binders used in biomass briquetting have a direct impact on the resulting briquette properties, including combustion and mechanical characteristics (Lubwama et al., 2020). Moreover, the extent of their influence on briquette properties can vary significantly among different binders. For instance, a study investigating the effects of different binders on carbonized corncob briquette properties revealed that briquettes produced with corn starch exhibited better moisture content, relaxed density, and compressive strength compared to those with corn starch and gelatin (Aransiola et al., 2019).

Therefore, in the commercial production of biomass briquettes, it is crucial to evaluate the impact of the type and quantity of binders on the resulting briquette properties. This consideration extends to the energy requirement for briquetting and the overall cost of the process. Despite the positive effects of adding binders in the densification of loose biomass, some binders may have negative impacts on certain briquette properties (e.g., reduced density, deposit formation, emissions) and could potentially compete with other uses, including food and industrial applications (Obernberger et al., 2004).

4.3 Common Biomass Briquette Binders

As previously mentioned, binders play a crucial role in the biomass densification process, aiming to enhance the compressive strength, resistance to abrasion, and in certain instances, the energy content of briquettes. Various types of raw materials necessitate specific types of binders because of their distinct underlying material bonding mechanisms (Zhang et al, 2018). Binders that are widely used in biomass briquette production are discussed below.

4.3.1 Glycerol

Crude glycerin, a by-product generated during biodiesel production, has proven to be a successful binding agent in biomass briquetting, leading to noteworthy improvements in the properties of the briquettes. While crude glycerin can be refined into valuable chemicals suitable for applications in the pharmaceutical, food, and cosmetics industries, the purification procedure tends to be costly and inefficient due to the presence of a diverse array of impurities often found in it (De Almeida et al, 2020).

On the contrary, the glycerin market has reached a state of saturation, and disposing of it in landfills is not environmentally sustainable. Consequently, the price of glycerin has continued to decrease, making it economically attractive for utilization as a binder in biomass briquette production. Glycerin has also found applications in biomass pellet production. This includes issues like a high tendency to absorb moisture, reduced energetic value, and compromised aesthetics and durability. (De Almeida et al, 2020).

4.3.2 Starch

Starch is a white powder primarily derived from different crops, such as cereals, rhizomes, and roots. It exists in the form of semi-crystalline granules that possess unique characteristics specific to each crop source (Bertoft et al., 2017). Due to its high-energy content and favorable chemical and structural properties, starch serves as an outstanding binding agent in biomass densification processes. As a result, it continues to be the most commonly utilized binder for biomass briquettes, as noted in the literature (Lubwama et al., 2020). Nonetheless, the commercial use of starch in briquetting has been limited due to certain drawbacks, such as its high cost, low resistance to coking, and lack of water-proof properties (Zhang et al., 2018). Although starch binders generally enhance the physical and mechanical properties of briquettes, Lubwama et al. (2020) reported that they can inhibit heat transfer in carbonized composite briquettes made from rice husks, coffee husks, and groundnut shells. This highlights the necessity for a more comprehensive assessment of the effects of binders on both the physico-mechanical and thermal properties of briquettes, which is currently lacking in the existing literature.

4.3.3 Algae

Algae, a diverse group of photosynthetic and heterotrophic single-celled organisms found in freshwater and seawater ecosystems, offer significant advantages for cultivation. They exhibit an impressive production rate, approximately 50 times faster than most terrestrial biomass (Haykiri et al., 2013). Algae's potential as a biomass binder stems from its high protein and lignin content (Nagarajam et al., 2021). The binding capability of algae is attributed to the combination of two of its constituents, chitin, and proteins, which act as natural binding agents. Algae biomass possesses several attractive qualities that make it viable for use as a binder in biomass briquettes, including the possibility of year-round cultivation, adaptability to diverse climates and unsuitable agricultural areas, and positive effects on the environment (Savage et al., 2013). Researchers have explored using algae both as a binding agent and as the primary feedstock, producing briquettes after drying (Rawat et al., 2021). However, during carbonization, the inorganic content of the algae can become concentrated. To this end, Amarasekara et al. (2017) successfully produced briquettes from naturally grown algae biomass collected from lakes without the addition of binders, indication g that algal biomass holds potential as both a raw material and a binding agent for briquette production.

4.3.4 Molasses

Molasses is a cost-effective liquid by-product that results from the final stage of sugar extraction from cane or beets through repetitive crystallization, discharged by the centrifuge. It is a dense, non-transparent, and brown to dark brown liquid that dissolves completely in hot and cold water. Molasses typically contains carbohydrates within the range of 48 to 53% and has a water content lower than 25% (Mordenti, 2006). Notably, molasses exhibits excellent stability and shelf life due to its high osmotic potential, which is linked to its antimicrobial properties.

As a binder, molasses is known for its capacity to effectively promote bonding mechanisms among fine particles. This is attributed to its sucrose and gum content, including starch. Its bonding properties have been widely utilized in the feed industry for the preparation of compound feed, and more recently, it has found applications in the bioenergy sector (Zhang et al., 2021).

5. BIO-BRIQUETTING METHODS

According to Maninder et al. (2012), there are three methods in bio-briquette processing namely

(i) Pyrolyzed densification using a binder, (ii) Direct densification of biomass using binders, and

(iii) Binderless briquetting.

5.1 Pyrolyzed Densification using Binder

The briquette production method described here involves a sequential process of first pyrolyzing the biomass and then mixing it with a binder before densifying it. This approach has been explored in existing studies, including the research conducted by Irhamni et al. (2019). Their study focused on Durian Peel bio-briquettes that underwent carbonization at 400°C, resulting in a caloric value of 5040 cal/g and a 55-minute flame test. The findings indicated that these briquettes met the fuel standards suitable for household use.

Furthermore, Lubwama and Yiga (2018) also investigated the carbonization process and its impact on briquette properties. They observed that the carbonization process led to Furthermore, Lubwama and Yiga (2018) also investigated the carbonization process and its impact on briquette properties. They observed that the carbonization process led to briquettes that have reduced moisture adsorption. This quality is crucial as it increases the shelf life and storage stability of the briquettes by preventing them from rotting and decomposing over time. Flow chart process for pyrolyzed densification using binder as shown in figure 3.

5.2 Direct Densification with Binders

The densification process in biomass briquetting involves two main aspects: (1) compacting the materials to increase their density, and (2) conglomerating the material to ensure the resulting product, known as briquettes, remains compressed and retains its shape under steady conditions. This process offers several benefits, such as elevating the material's calorific value by reducing its volatile matter, transforming it into a stable and easily transportable fuel, and enabling efficient storage while also reducing emissions (Kaur et al., 2017). Bio-briquettes utilize a binder agent, commonly referred to as a "binder," which is often a partially decomposed fibrous organic material. The binder serves the purpose of releasing the necessary fibers that physically hold the briquettes together, providing cohesion and structural integrity to the final product shown in figure 4.

5.3 Binderless Briquetting

Binderless briquetting is a technique used to produce briquettes without the need for binders. This method relies on the natural lignin component present in lignocellulosic plants, which acts as a natural glue, binding the cellulose fibers together. As a result, briquettes are either directly densified or pyrolyzed without the addition of any external binder (Oladeji, 2015). The process involves applying high compaction pressure to achieve densification.

Kaur et al. (2017) explain that the application of high pressure on the biomass leads to increased mechanical interlocking and enhanced adhesion/cohesion forces, resulting in the formation of intermolecular bonds in the contact area. In a study conducted by Alchalil et al. (2021), the characteristics of bio-briquettes made from rice husk and coffee pulp were investigated at different pressures (100, 150, and 200). The research utilized samples of carbonized rice husk, directly densified coffee pulp, and a mixture of both agricultural wastes. The study reported a caloric value of 4764 cal/g for a 100% coffee skin briquette with 16.5 wt.% moisture, 12 wt.% ash content, a combustion rate of 0.019 g/s, and an ignition time of 196 seconds.

6. BRIQUETTE CHARACTERIZATION

Briquettes are characterized in terms of physical, mechanical, chemical, and combustion properties, depending on the measured parameters. It is also indicative of the effectiveness of the densification process and influences their ability to endure certain impacts because of handling, storage, and transportation.

6.1 Physical Properties

6.1.1 Change in volume

The briquette volume is determined after the briquette is removed from the mold and released for 10 min (Aransiola et al., 2019; Mandal et al., 2019). The percentage of change in briquette volume can be calculated using equation 1.

$$\eta v = \left(\frac{V_m - V_b}{V_m}\right) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq\ 1.$$

Where ηv is percentage of change in volume (%), Vm is the volume of the cylindrical mold (cm3) and Vb is the volume of briquette after compressing (cm3).

6.1.2 Dimensional stability

The briquette's dimension could change during storage due to stress relaxation, which might be determined using the Jiao et al. (2020) approach. The diameter and height of the briquette is measured immediately after it is taken from the mold and every day until its measurements stopped changing. The dimensional stability of the briquette can be calculated using:

$$DS = 100 - \left(\frac{V_t - V_0}{V_0} \times 100\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq\ 2.$$

Where DS is dimensional stability (%), Vt is the volume of the briquette after releasing (cm3) and V0 is the volume of the briquette after production (cm3).

6.1.3 Relaxed density

After allowing the briquettes to dry, their weight is always measured. Since the briquettes is cylindrical in shape, the volumes is calculated based on their height and diameter. Eq. (3) is used to calculate the relaxed density of briquettes using the mass and volume, as recommended by as recommended by Mandal et al. (2019) and Ndindeng et al. (2015).

$$\rho = \frac{M}{\pi H_{(r^2{}_o - r_i{}^2)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq.3$$

Where ρ is relaxed density (kg/m3), M is briquette mass (kg), π is mathematical constant, H is briquette height (m) and ro and ri were inner and outer radius of briquette (m).

6.1.4 Water resistance

The porosity of briquettes determines their ability to absorb water. Their porosity is assessed by measuring the amount of water absorbed in each sample, as described in Kpalo et al. (2020). After drying, a pre-weighted briquette is immersed in water at ambient temperature. Following that, its weight is measured again, and the relative weight change as well as the time necessary for dispersion is recorded (Samomssa et al., 2021). The water resistance can be calculated using Eq. (4) as suggested by Adu-Poku et al. (2022).

$$\text{WR} = 100 - \left[\frac{(W_{w-}W_s)}{W_s} \times 100\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq. 4$$

where WR is water resistance (%), Ws is dry weight of briquette (g) and Ww is wet weight of briquette after immersed in water.

6.1.5 Shatter resistance

The shatter resistance of the briquette reflects its durability, which is measured by the proportion of briquettes that remained unshattered (Kpalo et al., 2020; Wang et al., 2015). Briquette shatter resistance is evaluated by subjecting it to a free fall from a constant height (Tanui et al., 2018). The dried briquette sample is dropped onto a concrete floor five times from a constant height. The weight retained by the briquettes after breaking is measured, and the shatter resistance can be determined using Eq. (5) as proposed by Adu-Poku et al. (2022) and Ranaraja et al. (2022).

$$\text{SR} = 100 - \left[\frac{(W_{1-}W_2)}{W_1} \times 100\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Eq. 5$$

Where SR is shatter resistance (%) and W1 and W2 are weight of briquette before and after shattering (cm), respectively.

6.2 Chemical Properties

6.2.1 Proximate analysis

A proximate analysis is performed to assess the percentages of moisture content (MC) (liquid state), volatile matter (VM) (gaseous state), fixed carbon (FC) (solid state), ash content (AC) (inorganic waste material), and high heating value (HHV) in the raw material and optimal condition samples.

6.2.1.1 Moisture content

Moisture content (MC) is a crucial parameter in biomass briquetting, and it is defined as the ratio of the mass of water in a briquette sample before and after drying, expressed as a percentage. The moisture content significantly influences the combustion process because the heat produced during combustion will initially be used to evaporate the water present in the briquette (Suryaningsih et al., 2018). For pelleting pruning of olive residues, the moisture content (wb) is reported to be less than 10% (Carone et al., 2011). On the other hand, switchgrass typically has a moisture content of about 10% (Gilbert et al., 2009). Managing and controlling the moisture content within these ranges are essential to optimize the combustion efficiency and overall performance of biomass briquettes. Moisture content can be calculated using equation 6.

$$\%MC = \left(\frac{M_b - M_a}{M_b}\right) * 100\% ----------------- eq. 6$$

Where mb is the mass of briquette immediately after compression and ma is the mass of briquette after drying in still air.

6.2.1.2 Ash content (AC)

Ash content (AC) is defined as the mass of incombustible material remaining after burning a specific briquette sample, expressed as a percentage. The ash content is an important parameter to consider in the evaluation of briquettes because it indicates the proportion of non-combustible materials present in the biomass. According to the SNI No. 1/6235/2000 standard, the recommended limits for briquette properties are as follows: the moisture content and ash content should be less than 8%, and the volatile matter should be less than 15% (Idris et al., 2018). These guidelines help ensure that the briquettes possess desirable characteristics for efficient combustion and meet the necessary fuel standards. A higher value of ash content in the briquette implies a lower caloric value, as it represents the non-combustible fraction. Consequently, higher ash content indicates that more of the briquette's mass is composed of incombustible materials, making it harder for the briquette to combust efficiently. Managing the ash content is crucial in producing high-quality briquettes with optimal combustion performance. The equation below is used to calculate the ash content of a briquette.

$$\%AC = \left(100 - \frac{W_O - W}{W_{SO}}\right) * 100\% ------------------------ eq.7$$

represents substances that are lost when the sample is heated in a furnace for 7 minutes at 900°C. The volatile matter content is an important parameter in assessing the combustion behavior of bio-briquettes. As indicated by Suryaningsih et al. (2018) and Ifa et al. (2020), a higher volatile content in bio-briquettes makes them easier to combust. This is because the volatile matter contributes to the release of flammable gases during the combustion process, facilitating ignition and sustaining the combustion reaction. However, it is essential to manage the volatile matter content in bio-briquettes effectively. A high value of volatile matter can lead to the degradation of briquette quality by reducing the content of fixed carbon. This, in turn, can impact the calorific value produced during combustion and result in an increase in the amount of smoke generated (Idris et al., 2018). Therefore, achieving an optimal balance of volatile matter in bio-briquettes is crucial to ensure efficient and clean combustion. Equation 9 below was used to calculate volatile matter of a briquette.

$$\%\ lost\ weight = A = \left(\frac{W_O - W}{W_{SO}}\right) * 100\% ------------------- eq.8$$

$$VM = Lost\ weight - Moisture\ Content * 100\% --------------- eq.9$$

Where W0 is sample weight and initial cup (g), W is the weight of cup and ash after heating (g), and WSO is the initial sample weight (g).

6.2.1.3 Fixed carbon (FC)

Fixed carbon is defined as the percentage of bonded carbon contained in the briquettes. It is calculated as the remaining carbon after the reduction of 100% of the sample, accounting for the volatile matter, moisture content, and ash content. A higher level of fixed carbon in bio-briquettes results in an increase in their calorific value (Suryaningsih et al., 2018; Ifa et al., 2020). Fixed carbon is a crucial parameter in determining the energy content of bio-briquettes. As it represents the carbon that remains after the volatile matter has been driven off during combustion, a higher fixed carbon content indicates a greater amount of carbon available for combustion. The equation 6 bellow can be used to find fixed carbon content of a briquette.

$$\%FC = 100 - \left(AC\ (\%) - VM(\%)\right) ------------------ eq.10$$

6.2.1.4 Heating Value

Heating value (HV) or energy value, refers to the amount of heat released per unit mass of the briquette and is typically measured using a bomb calorimeter. This value indicates the energy content contained within the briquette. The calorific value is determined by measuring the heat produced through the complete combustion of a specified quantity of the briquette, expressed in calories per gram. Conducting a calorific value test is essential to assess the standard quality of the briquette's fuel power and determine its market value (Suryaningsih et al., 2018). The results of the test provide valuable information about the briquette's energy efficiency and usefulness as a fuel source. Calorific values can be calculated using the fixed carbon content and volatile matter of the briquettes, often following a specific method and equation as presented in the work of Adetogun et al. (2014). This calculation offers a reliable estimation of the briquette's heating value and allows for comparisons between different briquettes to identify the most suitable fuel source for various applications. Equation 11 is used to find the heating value of a briquette

$$HV = \frac{(FC\% + VM\%)kJ}{kg} ---------------------- eq.11$$

Where HV is the calorific value, FC is the percentage of fixed carbon content, and VM is the percentage of volatile matter.

Table 2 presents the list of bio-briquettes made from agricultural waste and their values obtained after proximate analysis. According to Suryaningsih et al. (2018), other briquette characterizations that are essential for packaging design and transportation handling include mass density and compressive strength.

6.2.2 Ultimate analysis

An ultimate analysis is performed to determine the percentages of hydrogen (H), carbon (C), oxygen (O), nitrogen (N), and sulfur (S) in the material (Chukwuneke et al., 2020; Tanui et al., 2018; Mandal et al., 2019).

The energy density can be calculated using the previously examined HHV result and Eqs. (10)– (12) As shown in the study by de Souza et al. (2022).

LHV = HHV − (0.23 × H) ………………………………………………………eq 10

(10) Where LHV is low heating value (MJ/kg).

NHV = (((LHV × 238.85) × (1 − (0.01 × MC)))− (6 × MC))/238.85 ………………eq. 11

(11) Where NHV is net heating value (MJ/kg).

ED = NHV × ρ (12) ……………………………………………………………. eq. 12

Where ED is energy density (MJ/m3)

6.3 Combustion Properties

6.3.1 Ignition time

The ignition time is the length of time it takes for a known mass of fuel to ignite, as measured using a technique established by Onukak et al. (2017). Sample of fuel briquettes should be placed on a wire mesh grid and immediately burn on a liquefied petroleum gas (LPG) stove. The briquettes will catch fire once the stove is ignited. The ignition time can be calculated using Eq. (13).

IT = t1 − t0 …………………………………………………eq 13

Where IT is ignition time (min), t1 is time the briquette ignited (min) and t0 is time the LPG gas stove is lighted (min).

6.3.2 Burning rate

Burning rate. The burning rate is the rate at which a specific mass of fuel burns in the air (Onukak et al., 2017). The samples should be placed on the wire mesh grid and ignit using the LPG gas stove. The weight of the burning briquettes should be recorded until they are completely burned, and a constant weight is maintained, as determined by an Onukak et al. (2017) developed process. The weight loss at a specified time can be calculated using Eq.14

$$Bs = \frac{Q_1 - Q_2}{t} \quad \text{eq. 14}$$

Where Bs is burning rate (g/min), Q1 is initial weight of briquette before burning (g), Q2 is final weight of briquette after burning (g) and t is total burning time (min).

7. CONCLUSION AND RECOMMENDATION

This study provides valuable insights into the potential of utilizing waste biomass for bio-briquette production, offering a sustainable and cleaner energy alternative to conventional fossil fuels. The findings underscore the importance of responsible waste management, resource conservation, and renewable energy solutions for combating climate change and promoting a greener future. The knowledge gained from this study can guide policymakers, researchers, and stakeholders in implementing bio-briquette production and fostering a transition to more sustainable and environmentally friendly energy sources.

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Figures

Plate 1: Examples of biomass that is good for briquettes production

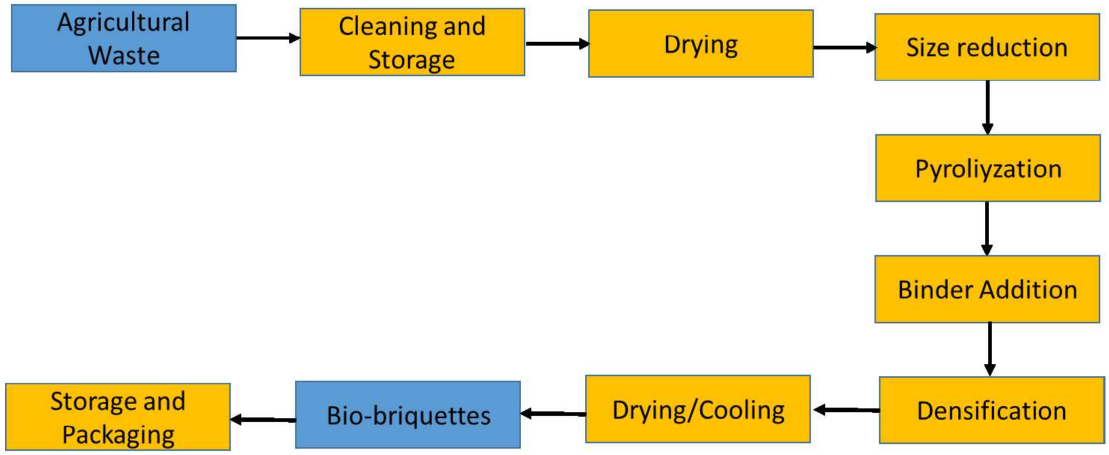

Figure 3: Flow chart process for pyrolyzed densification using binder.

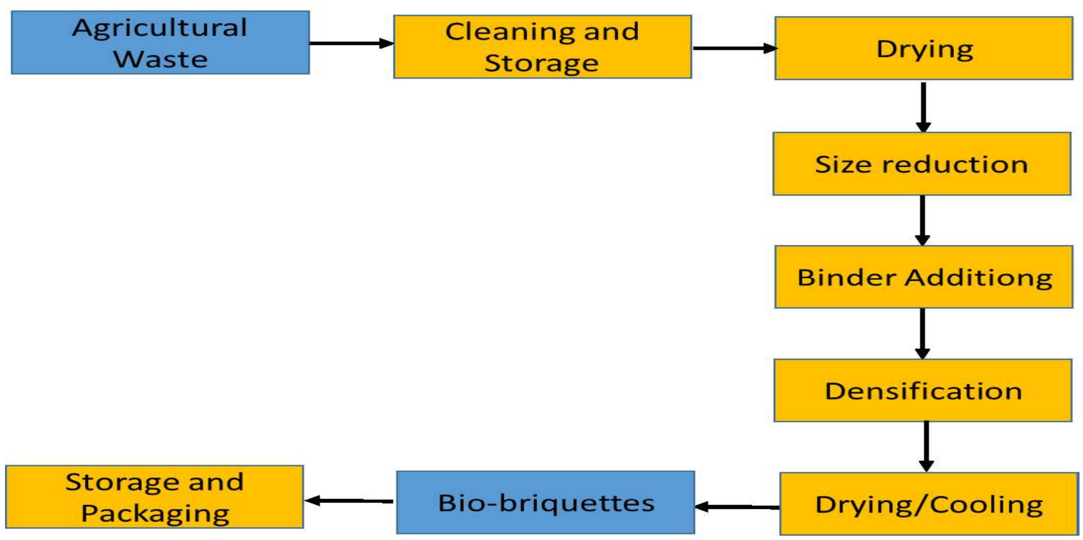

Figure 4: Flow chart process for direct densification with binders.

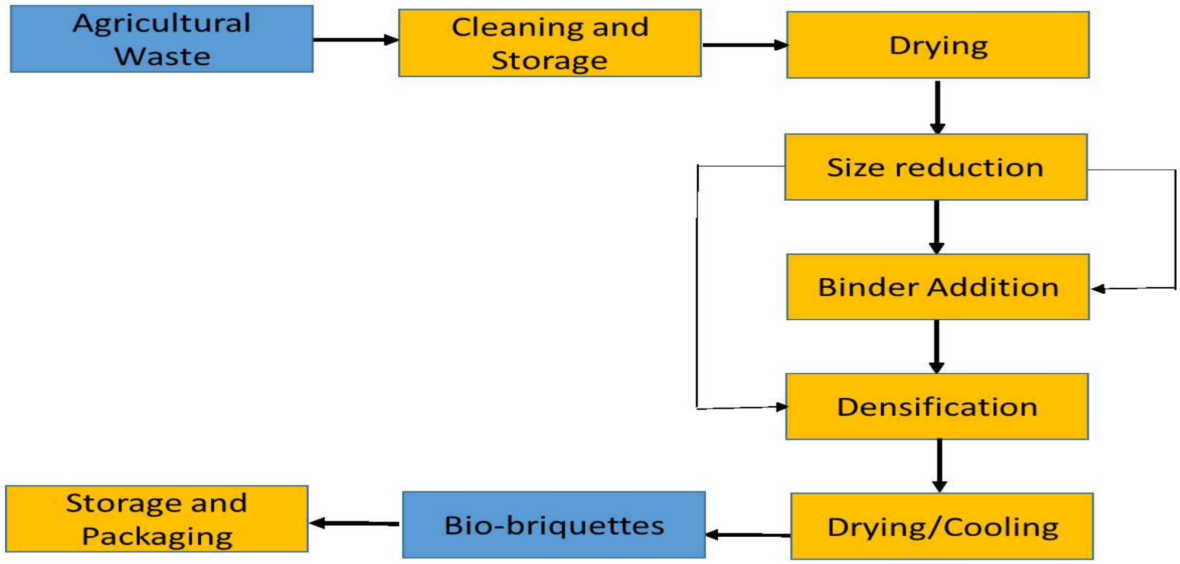

Figure 5: Flow chart for binderless briquetting

Tables

Table 1: Biomass Sourced from Agricultural Crops

Burnt biomass dry matter (Mt)					
Region	Year	Maize	Rice, paddy	Sugar cane	wheat
	2009	30.30	4.87	0.93	4.12
Africa	2019	40.71	9.41	1.04	3.90
North America	2009	33.31	0.69	0.23	11.94
	2019	34.40	0.55	0.24	9.88
South America	2009	19.60	2.87	6.47	3.35
	2019	28.15	2.24	7.54	3.75
Asia	2009	55.48	76.94	6.31	40.44
	2019	66.47	76.23	7.13	39.46
Europe	2009	13.93	0.37	-	24.47
	2019	18.35	0.34	-	24.95
Oceania	2009	0.09	0.01	0.29	5.43
	2019	0.08	0.01	0.31	4.18

(Source FAOSTAT, 2021)

Table 2: Proximate and heating values of bio-briquette from various agricultural materials

Material	Moisture (wt %)	Ash (wt %)	Volatile matter (wt %)	Fixed carbon (wt %)	Calorific value (Mj/kg)
Cashew nut waste	5.30	4.96	17.16	72.62	29.49
Banana peels,corn cobs, coal mixture	5.14	6.06	26.18	62.62	26.36
Bagasse & corn starch waste	6.86	8.59	48.50	42.92	10.30
Banana leave	7.17	10.70	75.3	14.00	17.70
Banana tree waste	11.0-19.3%	3.3-11.7%	75.08-94.7%	-	-
Mixture bagasse and coffee husk	4.40	12.00	24.00	64.00	11.13
Bagasse	4.10	36.4	27.20	36.40	18.38
Hazelnut shell	-	7.00	72.00	21.00	18.89
Durian peel	0.01	18.18	3.94	77.87	6274.29 kcal/kg

Source, (Sanchez et al., 2022)