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Review Article

Biomass Carbonization, Briquetting and Briquette Characterization: A Review

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Abstract: Briquetting is a contemporary means of converting waste biomass into a high calorific value solid fuel through densification of biomass-binder mixture. The process of briquetting is carried out in different ways depending on the type of biomass, binder or desired properties of the briquettes, the economic value and heating efficiency of the biomass as a fuel. This review paper aims at demonstrating the research achievements attained so far in the use of various forms and sources of biomass, the different binders and binder formulations, biomass carbonization, briquetting techniques and the characterization methods used to study the qualities of briquets. The future of biomass recycling to solve world energy crisis is a topical issue. Conversion of biomass into fuel briquettes can be a sustainable endeavour if research directs its focus on availability and renewable nature of raw materials given the seasonal nature of some types of biomass and binders.

Keywords: biomass; binder; briquette; carbonization; characterization

Biyokütle Karbonizasyonu, Briketleme ve Briket Karakterizasyonu: Bir İnceleme

Öz: Briketleme, biyokütle-bağlayıcı karışımının yoğunlaştırılması yoluyla atık biyokütleyi yüksek kalorifik değere sahip katı yakıta dönüştürmenin güncel bir yoludur. Briketleme işlemi, biyokütlenin, bağlayıcının veya briketlerin istenen özelliklerinin türüne, biyokütlenin yakıt olarak ekonomik değerine ve ısıtma verimliliğine bağlı olarak farklı şekillerde gerçekleştirilir. Bu derleme makale, çeşitli biyokütle formlarının ve kaynaklarının kullanımında, farklı bağlayıcılarda ve bağlayıcı formülasyonlarında, biyokütle karbonizasyonunda, briketleme tekniklerinde ve briketlerin niteliklerini incelemek için kullanılan karakterizasyon yöntemlerinde bugüne kadar elde edilen araştırma başarılarını göstermeyi amaçlamaktadır. Dünya enerji krizini çözmek için biyokütle geri dönüşümünün geleceği güncel bir konudur. Biyokütlenin yakıt briketlerine dönüştürülmesi, bazı biyokütle ve bağlayıcı türlerinin mevsimsel doğası göz önüne alındığında, araştırmanın odak noktasını ham maddelerin bulunabilirliği ve yenilenebilir doğasına yöneltmesi durumunda sürdürülebilir bir çaba olabilir.

Anahtar Kelimeler: biyokütle; bağlayıcı; briket; karbonizasyon; karakterizasyon

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1. Introduction

Biomass, especially waste by-products originating from timber industry are generated at a high rate, especially in countries where such industries are economically important like Zimbabwe. Recently, more and more attention has focused on utilizing saw dust potential from timber industries as resources for fuel production owing to both composition and abundance, achievement of sustainable energy for heating applications, reduction of environmental impact, creation of bio-economies, reduction of over reliance on fossil fuels, improvement of quality of rural and urban life as well as production of several biofuels (Pellera et al. 2021; Obi et al. 2022). On the other hand, the using wood as a fuel either directly or for making charcoal has exhausted national forest resource as exploitation far surpasses reforestation and growth rate. There necessitates diversity on energy resources by incorporating sawdust as domestic fuel and a lot of work has been done in that regard (Obi et al. 2022; Rotich, 1998).

Direct combustion of sawdust yields little energy as sawdust tends to hold high moisture in its loose natural state, nonuniform and poor feeding into gasifiers and boilers and has low bulk density leading to poor combustion efficiency (Obi et al. 2022; Olugbade et al. 2019). A further approach will be to densify the sawdust into briquettes to improve its handling, transport, and combustion characteristics and provides a favourable economic option for saw-millers to dispose of the environmentally hazardous. Many studies have been reported in this regard where several binders have been tested in the production of briquettes from different biomass; rice husk/cassava peel gel, rice husk/banana peel, maize cob/cassava peel gel, maize cob/banana peel, groundnut shell/cassava peel gel, groundnut shell/banana peel, sugarcane bagasse/cassava peel gel, sugarcane bagasse/banana peel with encouraging bulk densities calorific values and other properties (Idah, & Mopah, 2013). Nevertheless, burning of sawdust briquettes does not eliminate air pollution, has low heating value, high ash and mineral content as well as inadequately improved combustion efficiency briquettes hence the need for an alternative approach (Ghani et al. 2014; Rotich, 1998). One such approach is carbonization prior briquetting and limited studies are available on this (Ghani et al. 2014).

Most studies have mainly focused on direct briquetting of biomass, characterization and evaluation for relative density, shatter index, ignition time, burning rate, yield and proximate analysis, ultimate analysis, specific surface area and bulk density as so on. Combustion, liquefaction, gasification and pyrolysis are the thermochemical technologies available for converting sawdust into fuel products with pyrolysis being preferred for large scale energy conversion of biomass into solid fuel (Ghani et al. 2014). This carbonization technology depends on pyrolysis of feedstock to produce bio-char which is then bound into a solid fuel using a binding agent and subsequently briquetted by casting and pressing. Carbonization of biomass, followed by briquetting of the charcoal with a binder would be the most attractive alternative for energy utilization of sawdust to improve its calorific value and combustion properties (Rotich, 1998). Justifiably, during the utilization carbonization there would be low emissions of the oxides of the combustible elements, biomass can also be densified into pellets, logs or briquettes to improve its handling, transport, and combustion characteristics as a domestic fuel. Despite some studies on carbonization and briquette production and utilization, there is ample scope for further study and attention.

2. Sources of Biomass for Carbonization

Biomass refers to carbon based complex polymers derived from animal and plant remains. It is also composed of a mixture of organic molecules containing hydrogen, oxygen, and also small quantities of other atoms (Suryaningsih et al. 2017). The constituents of biomass are carbohydrates, lignin, starch, proteins and lipids and their compositions vary depending upon the geographical condition and source (Thomas et al. 2019). Typical sources of biomass include agricultural and industrial residues, animal wastes, wood wastes, energy crops, municipal solid waste, bagasse, sawdust, waste paper, waste from food processing, bio-solids, aquatic plants and algae (Ighalo et al. 2021).

In general, biomass as a source of fuel is densified by briquetting in order to increase the energy content per unit volume. The biomass may be carbonized before briquetting or be briquetted without carbonization. Yank et al. (2015) used rice husk and bran to produce briquettes, without carbonizing the biomass. Thulu et al. (2016) produced briquettes from a blend of raw banana peels and sawdust as binder. Setter et al. (2020) produced briquettes from sugarcane bagasse and kraft lignin, with the lignin improving the properties of the briquettes. A proximate analysis documented by Promdee et al. (2017) showed that the fixed carbon content of rice husk is 18.88 % and that of bagasse is 5.86 %, thus this biomass has the potential to be carbonized.

A lot of research work has been done on production of activated carbon from biomass. Prior to producing activated carbon, the biomass is carbonized. Activated carbon has been synthesised from coconut shell (Promdee et al. 2017), Jatropha curcas fruit pericarp and seed coat (Okeola et al. 2012). Waste tea was utilized by Gurten et al. (2012) in the production of activated carbon. Mahat, & Shamsudin (2019) produced carbon quantum dots from oil palm empty fruit bunches.

Charcoal briquettes were produced from residues of banana peels, sugar cane bagasse, coconut husks and rattan waste by Bot et al. The resulting briquettes had satisfactory physicochemical properties (Bot et al. 2021). In other developing countries, various types of waste have been used in order to develop biomass briquettes such as wheat straw, rice straw and husk, waste paper and a mixture of coconut husk and maize cob. Other materials can be used like banana leaves, rice straw and rice ban, coffee residues and eucalyptus leaves (Bot et al. 2021). Lubwama, & Yiga (2018) developed briquettes from carbonized rice husk and coffee husk using cassava starch and clay as binders. Briquettes produced from rice husk and coffee husk by Lubwama, & Yiga (2018) showed a higher fixed carbon content and lower volatile matter than those produced from banana peels, sugar cane bagasse, coconut husk and rattan waste by Bot et al. (2021). These findings show that carbon content of briquettes vary depending on the type of biomass used and this in turn affects the properties of briquettes.

Wheat straw, maize straw and rice straw was carbonized before briquetting by (Guo et al. 2020) with part of their study being on pollutant emission reduction during combustion of the charcoal briquettes. Suryaningsih et al. (2017) did a comparison of charcoal briquettes made from coconut husk, sawdust from acacia tree, rice husk and coffee husk using tapioca starch as binder. The observed calorific for carbonized sawdust obtained in their research is 4 247 cal/g, which approximately 18 MJ/kg. Mopoung, & Udeye (2016) produced charcoal briquettes from banana peels and banana bunch using clay as a binder. The banana peel charcoal briquette exhibited a higher calorific value than that obtained by Bot et al. (2021) maybe due to differences in briquetting pressure, which affects the energy density of the fuel. Wu et al. (2018) investigated the properties of briquettes made from cotton stalk and wood sawdust. In this study, the biomass was pretreated by dry torrefaction and hydrothermal process and then briquetted prior to carbonization. The calorific value of the charcoal briquette from sawdust that underwent the hydrothermal pretreatment process of approximately 30 MJ/kg (Wu et al. 2018) is significantly higher than that obtained by Suryaningsih et al. (2017) apparently due to the thermal pretreatment process. Akowuah et al. (2012) did a physico-chemical analysis of sawdust charcoal briquettes produced in Kumasi, Ghana. They concluded that the briquettes met the recommended briquette characteristics.

3. Carbonization Techniques

The terms “slow pyrolysis” and “carbonization” are often used interchangeably, however slow pyrolysis can be considered a broader term, which covers both carbonization (i.e., pyrolysis of biomass into highly carbonaceous, charcoal-like material) as well as torrefaction (i.e., a low temperature pyrolysis process that serves as a pretreatment process) (Basu, 2013). Similarly, “char” refers to any solid product obtained from slow pyrolysis, whereas “charcoal” refers to the char obtained from carbonization and with intended use as a fuel. Carbonization is the oldest form of pyrolysis known to humankind for the production of charcoal from woody biomass (Antal, & Grønli, 2003).

The characteristic feature by which carbonization differs from other, dry thermochemical conversion techniques is the heating time being significantly longer than the pyrolysis reaction time (Basu, 2013). It is often carried out in an oxygen-limited rather than an oxygen-free environment. The limited amount of oxygen serves to partially combust the biomass (fuel), thus providing the required heat for the pyrolysis reactions to take place (Ronsse et al., 2013). In addition, certain carbonization processes, such as the flash carbonization process as described by Antal et al. (2003) are carried out at elevated pressures (up to 1 MPa). Process equipment for carbonization ranges from simplistic kilns (which are still used where manual labor is cheap) toward complex and highly automated processes such as continuously operating retorts.

Hydrothermal carbonization (HTC) is considered an attractive and constantly expanding eco-friendly methodology for thermochemical processing of different types of biomass in energy, carbonaceous materials, structured hybrids, and other chemical products and method for converting lignocellulosic biomass into different value-added products (Fang et al. 2018; Kumar et al. 2018).

The hydrothermal carbonization (HTC) is a thermochemical conversion process that occurs in hot water (subcritical) and produces gases, liquids, and solids fractions. Among the many biomass conversion technologies, the advantage of hydrothermal carbonization is that wet biomass with a water content of 70-90 % by weight can be converted without prior drying (Kruse, & Dahmen, 2018). The main product is hydrochar (solid fraction) with great applications in the agricultural, medicinal, environmental, energy, etc. (Fang et al. 2018; Heidari et al. 2018; Kambo, & Dutta, 2015). However, liquid (water-soluble) and gaseous (mainly CO_2) by-products are also produced (Heidari et al. 2018; Kambo, & Dutta, 2015; Liu et al. 2018). The method has been proving versatile to obtain various products from different types of biomass, using lower temperatures and reactional conditions lighter compared to other thermal conversion processes (Gallifuoco et al. 2017), thus being considered an eco-friendly methodology. Although described with a sustainable methodology, hydrothermal carbonization needs to overcome some challenges to fit clean production processes.

One of the main problems associated with hydrothermal carbonization concerns the excessive use of water during the process. Considering that one of the greatest challenges facing humanity today is the shortage of drinking water, due to the degradation of aquatic environments and the constant irregular discharges of contaminants from various sources (Anumol et al. 2016; Sophia, & Lima, 2018), the process faces a double challenge to adapt to the processes of clean production. Initially, it is necessary to create alternatives for reducing excessive water expenditure. It is important to give an appropriate destination to the aqueous fraction originated after hydrothermal treatment. An alternative that has been presented to reduce the mentioned problems concerns the recirculation of process water (Chen et al. 2018; Kambo et al. 2018).

The variables involved in (HTC) include temperature which is one of the main variables in (HTC) which significantly influences the biomass conversion process from the degradation of the structural components. This process occurs due to the breaking of the chemical bonds of the biomass structural components, which occurs by the joint action of hydrothermal reactions as a consequence of the temperature (Zhang et al. 2019). The higher the temperature, the higher the carbonization and the more intense will be the dehydration and decarboxylation reactions. This occurs in a relatively slow reaction process. Current publications report responses in processes occurring in a time interval between 30 min and 12 hr (Chen et al. 2017), and residence times of 1 and 2 hr are the most used. In addition, to yield, the textural features such as surface area and porous structure of the produced hydrochars are also exposed to the significant effects of residence time. This deficiency is due in large part to the low specific surface areas observed in the hydrochar because of the weak porous structure established. In this respect, the specific surface areas observed are generally attributed to the external surface area. Another parameter which is less discussed in the HTC literature are the catalysts. The use of catalysts has the drive of accelerating reaction rates, modifying or adapting the reaction path and acting on the biomass decomposition. Studies show that the use of catalysts reduces the activation energy in the hydrolysis of biomass, and at the same time, favors the production of high-oxygenated functional groups, even in biomass with high lignin content, low temperatures and lower reaction periods.

3.1. Factors Affecting Carbonization

Charcoal density and biomass density, or the ratio of dry mass to saturated volume, have a positive correlation (Assis et al. 2016). Charcoal's tensile modulus, gravimetric yield, and resistance to parallel compression of charcoal fibers all increase with density (Moutinho, 2013). Density changes between hardwood and softwood, for instance, are highly dependent on the species engaged in carbonization (Assis et al. 2016). Temperature significantly increases density loss. According to the species, the average density loss is 40

%, with variances ranging from 33 % to 50 % (Chrzazvez et al. 2014). According to laboratory experiments, the humidity of charcoal's moisture content has a significant impact on the particles produced in drum testing (Rousset et al. 2011).

The particle size of the pieces for carbonization is also related to the friability of charcoal. Larger diameters will be more negatively affected by carbonization process because the carbonization front will have to shift across the piece as it moves toward the center (Assis et al. 2016). In wood, the main components are cellulose, hemicellulose and lignin. In addition to the solid portion, charcoal, condensable and non-condensable gases are produced during carbonization. The way these precursors interact affects the solid material's properties (Assis et al. 2016). Consequently, the quantity and arrangement of each component have a direct impact on the mechanical characteristics of wood and the quality of the charcoal that is produced after carbonization. For instance, lignin is technically more stable and is therefore the primary component that influences the creation of charcoal. Charcoal formation and mechanical properties are influenced by the quantity and configuration of its anatomical components, biomass proportions, the ratio of early to late biomass in the rings and the variations throughout the radius (Chrzazvez et al. 2014).

Klar (1925) emphasized that charcoal preserves the shape and structure of the biomass it is made from to the point that its look can be utilized to determine where it comes from. According to Chrzazvez et al. (2014), the porosity of charcoal is directly related to the carbonization temperature, the density of the biomass it came from, and the rate of carbonization. The findings of research conducted by de Oliveira et al. (1982) demonstrated how the carbonization temperature affected the charcoal's compression strength. In an eight-year-old Eucalyptus grandis, the scientists found that when the temperature rose from 300 to 900 °C, the charcoal's resistance to compression increased.

The product weight yields (dry wood base) from various wood pyrolysis modes are significantly impacted by the heating rate (Assis et al. 2016). The formation of liquids is favored by fast and intermediate pyrolysis, which happens in a matter of seconds or less. Carbonization, gasification, combustion, and torrefaction can all be seen in the event of slow pyrolysis (10–60 min to days) (Bridgwater, 2012). Lower heating rates may smooth the drying process and the carbonization gas output, minimizing flaws and cracks in the carbonized samples (de Oliveira et al. 1982). There is a condensation of volatiles in the solid matrix when the carbonization process is carried out in reactors under high pressure (Assis et al. 2016). A more stable structure known as secondary charcoal is created when highly reactive compounds undergo secondary reactions, increasing the fixed carbon content and gravimetric solids yield (Manya et al. 2014). According to Assis et al. (2016), high pressures enhance heat transference inside the reactor, resulting in more homogeneous charcoal and a shorter heating time.

4. Binders for Briquette Processing

Binders are extensively used in processing coal and biomass fines into solid fuel briquettes although binderless briquettes with an inferior quality to those having binders have also been previously produced (Taulbee et al. 2009; Manyuchi et al. 2018; Olugbade et al. 2019). The main role of the binders in briquetting is to ensure that solid particles constituting the briquette remain strongly bound to each other during processing, transportation and use of the briquettes. This bonding ensures a consistent briquette density and shape as well as reducing variability on other important solid fuel characteristics along the supply chain for customer satisfaction (Borowski et al. 2017). In cases where the biomass undergoing briquetting contains adequate natural binders as part of its chemical composition, it will not be necessary to add more binders during the briquette processing since an optimal binder concentration applies for best briquette performance. Higher or lower than optimal binder concentration in the briquette affects the economics and briquette mechanical performance as well as the briquette heating properties (Zanella et al. 2017). There are many different materials that have been successfully evaluated as binders for biomass briquette processing (Rejdak et al. 2020). Properties vary across these binders in terms of binding effectiveness, quantity required and environmental friendliness. Some binders are more expensive than others. The choice of a binder for each specific briquetting application is therefore dependent on many factors that may be dictated by the material being briquetted, the briquette end use, the binder properties, etc (Taulbee et al. 2009). It is therefore necessary to run laboratory or pilot plant tests as part of binder evaluations for each specific application.

4.1. Binders Classification

Binders are classified into organic, inorganic and compound binders. Organic binders contain mainly carbon and hydrogen atoms while inorganic binders contain substantial amounts of inorganic elements in their chemical structure. The sub-classifications for both organic and inorganic binders are depicted in Figure 1 where examples for each binder type are also displayed. Organic binders are more popular than inorganic ones because of their strong bonding capabilities but they also present some disadvantages such as high emissions generation. The detailed list of advantages and disadvantages of using any binder type in briquetting are spelt out in Figure 1. Most of these extreme disadvantages specific to inorganic or organic binders are addressed by blending different ratios of inorganic and organic binders to produce what are termed compounded/blended binders.

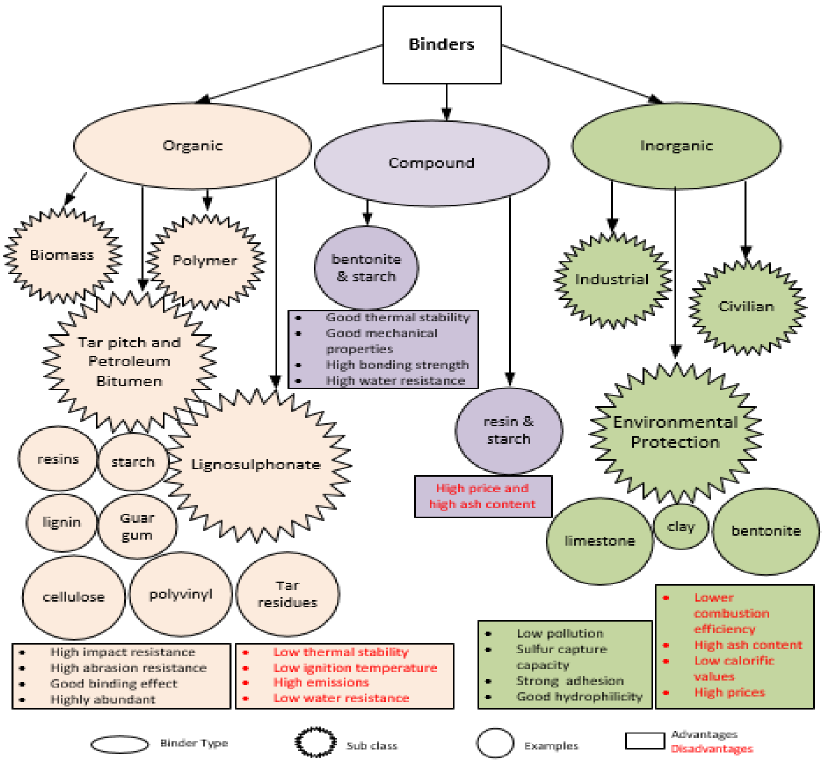

Figure 1. Binder types and examples including their advantages and disadvantages.

4.2. Binder Selection Factors

The key considerations in choosing a binder for briquetting and the significance of the factor are reported in Table 1. Some factors may be more important than others depending on the end use of the briquette. As previously stated in this review, desired binder properties can be formulated from blending two or more binders. This strategy can also be used to address unfavourable binder characteristics.

Table 1. Factors affecting the choice of binders used in biomass briquetting.

Binder Factor	Significance of the factor in briquetting production	References
Desired bonding strength	A binder offering strong bonding tends to have better mechanical properties hence generate less fines and is therefore desirable than a binder with weak bonding properties.	(Naude 2015)
Effect on emissions generation	If briquettes are to be used indoors, undesirable odours or unhealthy fumes introduced into briquettes by using certain binders especially those originating from fossil sources should be avoided through binder selection or chemical additions.	(Olugbade et al. 2019)
Effect on moisture	Some binders alter the moisture retaining capacity of briquettes, a characteristic that affects mechanical properties hence storability of briquettes.	(Aransiola et al. 2019)
Effect on combustion performance	Certain binders increase or decrease the calorific value of the briquette. Further binder effects can be introduced on the burn rate of the briquette.	(Olugbade et al. 2019)
Effect on environmental friendliness	Environmental protection types of inorganic binders are more favorable in stringent environmental conditions. These have sulphur retaining capacity. Despite price and bonding benefits from organic binders that may be discouraging on pollution grounds.	(Zhang et al. 2018)
Sustainability	The carbon footprint, economic and social impacts of sourcing a binder contribute towards the briquette's sustainability ranking hence the binder choices especially in societies where sustainability issues are highly valued.	(Salah and El-Haggar 2007)
Economics and availability	The binder price which adds to the briquette costs affect binder choices for business competitiveness.	(Adeleke et al. 2019)

4.3. The Future of Binders in Briquetting Process

More research work is required towards the formulation of a wider spectrum and advanced performing compound binders. These formulations must be based on locally available resources. If such research efforts address most of the binder selection factors, then these formulations will form a basis to guide local strategies for briquetting binder choices in future. If a reputable database of biomasses compatible with certain compound binders could be developed with the support of empirical evidence, it will act as a driver for promoting briquetting technology as a cleaner fuel processing route for the globally abundant biomass. There are still several on-going debates on binding mechanisms and this area is still open for more research.

5. Briquetting Techniques

Briquetting is a densification technique involving the use of high pressure to compact loose biomass so as to increase the density of biomass residues. Briquetting techniques may vary depending on whether a binder has been used or not, the compaction methods used and also whether the biomass is carbonized prior to briquetting or after briquetting. Briquetting process can be done with or without the use of binders (Ajimotokan et al. 2019; Yang et al. 2016). Briquetting without binder can be of economic value since it lowers the cost of processing of briquettes but may require high compaction pressure for biomass densification (Yang et al. 2016; Papin et al. 2015). Low to moderate densification pressures are necessary during binder-based briquetting because higher pressures beyond 5.0 MPa may result in the collapse of cell walls of the biomass (Olorunnisola, 2004).

Binders give the briquettes some plastic deformation and act as cement between biomass particles (Papin et al. 2015).The purpose of densification or compaction of material biomass is to reduce the bulk so that transportation becomes easier and cheaper, increase energy density by squeezing out moisture during compaction, obtain a homogeneous product with the same physical properties, ensure uniformity in terms of energy quantity per unit mass of feedstock, create a highly cohesive fuel material from loose particulate material that is otherwise difficult to process and also to increase particles' shutter resistance during transportation, handling and storage (Olorunnisola, 2004).

Sotannde et al. (2010) carried out batch experiments on production sawdust briquetting. In each batch, 100 g of dried sawdust was mixed thoroughly with either cassava starch or gum arabic as binders to obtain a uniform mixture. The sawdust-binder mixture was hand loaded into the PVC pipe that served as a mold and covered at both ends with the wooden disk before compacting at a pressure of 10.70 kg·cm-2 using a press. The mixture was kept under pressure of the press for 5 minutes (Olorunnisola, 2004) to consolidate the shape and size of the briquettes by perhaps preventing spring back effect (Ajimotokan, 2019). Sawdust was briquetted without carbonization perhaps as a way of reducing the cost of production although the briquettes will have a lot of smoke and ashy during combustion, contributing to pollution. Uncarbonized briquetting may require a thorough cost benefit analysis since the products can contribute to pollution during combustion and the high compaction pressure required can make the process expensive and hence unsustainable.

Emerhi (2011) also briquetted uncarbonized sawdust using a hand pressing machine. The sawdust was first sun dried to reduce the moisture content to just about 12 %. Different proportions of binding agents were added to the mixtures before feeding them into a hand press machine where high pressure was applied to form the briquettes. The pressing method is almost similar to the use of screw press machine reported by Akowuah et al. (2012) and Aina et al. (2009) in production of quality briquettes with no other additives or binder.

Lela et al. (2015) also reported on the use of a special experimental rig for uncarbonized briquette production which consisted of a mold, punch and pressing plate. The bores in the mold were 38.6 mm in diameter and a height of 110 mm. Cardboard/sawdust mixture was used as the biomass. The mixture was loaded into the bores and compressed in the rig using a minimum compressing force of about 100 kN to obtain briquettes with satisfactory strength or mechanical properties (Lela et al. 2015). The benefit of both binder and biomass used is that they are both factory wastes which become part of clean up system and a renewable energy source.

Biomass can be carbonized first before briquetting as was reported by Ofori, & Akoto (2020) in their work on carbonized cocoa pod husks. The biomass was ground and sieved with a mesh size of <2 mm. 400 g of carbonized, sieved cocoa pod husks was thoroughly mixed with starch gel made from cassava in the ratio of 4 kg to 1 L to form a paste. The paste was then loaded into a metallic extrusion briquetting press where it was compacted into briquettes. Sieving was done perhaps to achieve smaller particle size which can effectively pack together during compaction (Yaman et al. 2001).

Stolarski et al. (2013) reported on the production of briquettes from agricultural and forest biomass using a specially designed briquetting machine. Separate biomass of each type, as well as their mixtures of different proportions were briquetted using a Polish piston-briquetting machine BT86M (WAMAG, Walbrzych). The main components of the device were a horizontal crank-and-piston briquetting press, a briquetting unit consisting of a briquetting bush, a pre-forming bush, a piston and a two-part clamping bush with a pneumatically adjustable clamping pressure component. The device had also a material feeding-compacting worm unit and a briquette conveyor, 5 m long, on which the briquette thermal and strength stabilization took place. The device also had a storage and dispensing container, a cyclone for automated pneumatic transport of material and a control cabinet (Aina et al. 2009). The machine was fitted with three electric motors to make the process automatic (Stolarski et al. 2013). The machine is a multi-component and complex one which can be ideal for bulky and large-scale commercial production of carbonized and uncarbonized briquettes in an automated way so as to increase consistence in the quality and properties of the briquettes.

Lignite fines as a biomass were reported by Tosun (2007). The biomass was mixed with each magnesia and gypsum as binders to produce different types of briquettes. The mixture of lignite, water and binder was poured into cylindrical iron molds and kept in the chamber at ambient temperature for 2 days to allow setting. No compaction was reported because these binders have a tendency of solidifying in water as a way of binding the particles. The uniqueness of the technique is on the use of inorganic substances to bind biomass and the ability of the briquettes to dry into a hard combustible solid without compaction. Test on compression strength and water resistance were measured for both types of briquettes. It was found that the compression strength of magnesia bonded briquettes reached 800 N at 20 % magnesia content when compared to gypsum bonded lignite briquettes which had a compression strength of 300 N at 10 % gypsum content (Tosun, 2007). This method of briquetting cannot meet commercial standards due to the long setting time which delays the production line.

5.1. Briquetting Machines

Briquetting machines come in various shapes, sizes and applying different mechanisms of compaction. They can be broadly classified into three categories namely screw presses, piston presses and roller presses.

5.1.1. Screw presses

Material to be briquetted is continuously fed to a screw which forces the material to a cylindrical die. The briquette is formed as the material is compacted in the die and then exits at the other end of the die. Screw presses can be applied for high pressure compaction as well as for low pressure compaction. For high pressure compaction, heat is added to the die to facilitate lignin flow, with lignin acting as the binder. For low pressure compaction, no heat is added to the die and the material is often mixed with an external binder prior to feeding to the screw conveyer (Oladeji, 2015).

5.1.2. Piston presses

Piston presses are operated in a discontinuous, stroke mode, where material is added in a cylinder and then compressed by a reciprocating piston into a slightly tapering die. Frictional forces heat the material as it is being compressed in the die, facilitating the flow of lignin which binds the material. The briquettes produced exit at the other end of the die. Piston presses are classified according to the mechanism used to drive the piston. Mechanical piston presses use an electric motor geared down through a belt coupling whilst hydraulic piston presses transmit energy from the electric motor using a high-pressure hydraulic system (Marreiro et al. 2021; Oladeji, 2015).

5.1.3. Roller presses

Material is fed continuously through a gap between two rotating cylindrical rollers. The rollers rotate horizontally, in opposite directions and on parallel axes. As the material is forced through the gap, it is compressed and simultaneously agglomerated to form briquettes that come out at the opposite side (Dinesha et al. 2018; Kpalo et al. 2020). Table 2 shows the advantages and disadvantages of each briquetting machine type.

Table 2. Advantages and disadvantages of briquetting machines.

Type of machine	Advantages	Disadvantages	References
Screw press	- The briquette making is continuous - The briquettes from screw presses are often denser and stronger than those produced by piston presses. - Briquettes produced are usually homogeneous. - Screw presses usually process material with very low moisture content, between 4 and 8 %. - They require low capital costs	- Wear of contact parts are high - They are associated with higher maintenance costs than piston presses	(Oladeji, 2015) (Kpalo et al. 2020) (Kapelyushin, 2023)
Piston press	- Piston presses can process material with a higher moisture content, usually ranging from 10 to 15 % - The wear of contact parts is low - The power consumption rates are lower than those associated with screw presses	- High level of maintenance is required - Briquettes produced are usually non-homogeneous - The briquette making process is not continuous.	(Kpalo et al. 2020) (Marreiro et al. 2021) (Oladeji, 2015)
Roller press	- Briquette making process is continuous - Roller presses can process material with a higher moisture content, usually ranging from 10 to 15 % - The wear of contact parts is low.	- The briquettes produced are usually non-homogeneous	(Dinesha et al. 2018) (Kpalo et al. 2020)

5.2. Current Briquetting Techniques Versus Energy Demands

The world population and industrial technology are fast growing, increasing the volume of waste and the demand for energy. The conversion of organic waste into fuel briquettes can augment the current energy infrastructures as well as offering a means of waste management. Robust automated briquetting techniques have to be developed to increase output so as to meet the ever-increasing energy demand as well as to prevent accumulation of waste. This will go a long way in creating significant economic value to waste material and conserving forests which are being exploited for firewood. Currently there is a very big energy deficit which calls for tremendous research in the possible ways of enhancing briquetting productivity from different forms of biomass. The future of biomass densification as a sustainable energy solution depends on the universal research approach in dealing with diversified forms of waste and the successes in large scale production.

6. Characterization of Briquettes

Different characterization methods can be carried out on briquette samples to get an insight of their properties. The properties of the briquettes determine the performance qualities of the briquettes. The purpose of characterization is to obtain proximate and ultimate qualities or information on the briquettes. Ultimate analysis provides elemental composition of the briquettes while proximate analysis gives other general properties of a fuel like ashy content, moisture content, volatile matter content etc. Thermogravimetric analysis (TGA), Fourier Transform Infrared Spectroscopy (FTIR), Scanning electron microscopy (SEM) and X-Ray diffraction (XRD) are of critical importance in understanding the structural, chemical and thermal performance of the briquette.

6.1. Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) helps to understand the combustion behavior of the briquette by revealing the thermal decomposition stages of the samples. In the first stage, mass loss is due to dehydration, which is equivalent to the removal of moisture content. Occasionally, it is accompanied by the loss of extremely minute quantities of volatile substances. It results in a mass loss of 5.7 % and is initiated at 30 °C and ends at 150 °C. The next stage is regarded as the primary stage of reaction during combustion. It involves burning of volatile materials produced when cellulose and hemicellulose break down. A temperature range of 150 to 345 °C is suitable for this thermal degradation, which accounts for 48.79 % of the mass loss. The third stage, which requires temperatures between 345 and 510 °C accounts for a mass loss of 33.88 %, is brought on by the char that remained after the samples were devolatilized (Liu et al. 2021). Typical rice husk briquettes exhibited a mass loss associated with moisture that is valued at 9.25 % leaf, 10.27 % pseudostem and 7.94 % rice husk. Briquettes ignited at temperature 180 °C. The briquettes' peak temperature during their burning profile was established as 280 °C for banana leaf, as 276 °C for banana pseudostem, and as 315 °C for rice husk (de Oliveira Maia et al. 2018). Nyakuma et al. (2014) inferred that the decomposition of Empty Fruit Bunch briquettes happens in four stages: drying (A), heating (B), devolatilization (C), and char aggregation (D).

6.2. Fourier Transform Infra-red Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) analyzes the chemical composition of binders or carbonization products. Briquettes from bagasse charcoal showed a number of distinct peaks at particular wavelengths, including the CO groups at 1050–1300 cm-1, the C = C alkenes groups at 1610–1680 cm-1, and the C-H alkane group at 2850–2970 cm-1. The wavelength at which the CO_2 C = O group is presently active is 2991.59 cm-1 (Veeresh, & Narayana, 2012). Because they can form hydrogen interactions, oxygen-containing functional groups, like the carboxyl group (1740–1650 cm−1), have a significant impact on strength (Sun et al. 2014). Bands forming in the 3700 and 2300 cm−1 regions, could be related to CO_2 and H_2O, respectively (de Oliveira et al. 2017).

6.3. Scanning electron microscope (SEM)

Scanning electron microscopy (SEM) allows observation of the surface morphology of the briquette and the distribution of binders among the particles. Charcoal briquettes demonstrated a consistent morphology and distribution along with the ongoing presence of pores (de Oliveira et al. 2017). Particles covered in a layer of natural binders, as evidenced by the SEM images of the briquettes and under light microscopy, these coatings looked to be glassy or white sugar-like coatings on the particles, and significant accumulation of these binding components are seen where the particles joined (Kaliyan, & Morey, 2010).

6.4. X-ray Diffraction (XRD)

X-Ray Diffraction (XRD) allows the identification of the mineral structures that constitute the ash content. The XRD spectrum analysis results demonstrate that the sample forms a soft peak in the 20 ^{0} - 30 ^{0} spectra, suggesting that it is amorphous (Rahman et al., 2021). Peak increases in intensity until 1000 at a frequency of 20 µm, after which it somewhat decreases as ash is formed by partial dissolution. According to Raju et al. (2014), the minerals found in cocopeat briquette are called fizelyite ($Ag_5 Pb_{14} Sb_2 S_{48}$) and anorthite ($Ca Al_2 Si_2 O_8$). The peak intensifies until 2600 at a resolution of 4 cm-1, at which point it somewhat diminishes as ash from partial dissolution forms (Raju et al. 2014).

6.5. Proximate Analysis And Heating Values for Different Briquettes

Table 3 is a brief summary of research studies on proximate analysis and high heating values of briquettes. The volatile matter content of briquettes, which is correlated with the energy released during combustion, is a crucial factor in briquette combustion. Fuels with higher volatility will burn more quickly because they are more reactive and readily flammable (Fernandes et al. 2013) and will volatilize and burn as gas in combustion chambers due to the high volatile matter content.

Table 3. Research studies on proximate analysis and high heating values of briquettes.

Type of Briquette	Volatile Matter (%)	Ash Content (%)	Moisture Content (%)	HHV (MJ/kg)	References
Corn straw briquette	69.65	8.84	10.20	16.79	(Liu et al. 2021)
Sawdust	54.59	10.30	15.71	-	(Raju et al. 2014)
Badam leaves	47.30	15.80	18.20	-	(Raju et al. 2014)
Cocopeat	53.55	9.80	18.65	-	(Raju et al. 2014)
Rice husk	34.38	30.05	7.90	18.57	(Deshannavar et al. 2018)
Rice husk	68.20	16.10	12.67	15.17	(Feng et al. 2006)
Dry leaves	74.50	25.50	10.30	10.24	(Kaur et al. 2017)
Palm kernel shell	76.50	2.70	3.50	-	(Sunnu et al. 2023)
Corn cob	73.80	3.90	4.10	-	(Sunnu et al. 2023)
Sawdust	70.60	3.20	5.90	-	(Sunnu et al. 2023)
Rice husk	67.10	6.80	5.50	-	(Sunnu et al. 2023)
Bagasse	28.90	10.99	5.10	10.44	(PallaviHV et al. 2013)
Coffee husk	23.00	13.10	3.50	11.39	(PallaviHV et al. 2013)
Rice straw	70.00	10.00	8.00	16.33	(Jittabut, 2015)
Sugarcane leaves	68.00	10.00	7.00	16.43	(Jittabut, 2015)
Rice straw	68.59	18.68	-	13.57	(Talukdar et al. 2014)
Waste wood charcoal	19.83	15.83	2.67	30.52	(Shiferaw et al. 2017)
Charcoal briquettes	16.67	8.33	8.33	19.24	(Hasan et al. 2017)

With a moisture content of 10 %, briquettes are suitable for burning (Liu et al. 2021) and a high-quality and stable briquette should have a moisture content of 5 % to 10 % (Oyelaran 2015; Pallavi et al. 2013). Ash content represents the proportion of impurities that will not burn both during and following combustion. Briquettes of low ash content are appropriate for thermal use and fuel's calorific value typically decreases as its ash content increases. High heating value of at least 15 KJ/kg is adequate to generate the heat needed for small-scale industrial applications and domestic cooking.

7. Conclusions

Various researches on briquette formation from biomass seem to share the same conclusion that biomass is a sustainable economic value addition process as well as a viable means of waste management. Different types of biomass have been researched on using different binders, biomass-binder ratios and densification methods producing briquettes of different performance qualities. Carbonized biomass briquettes have high carbon content, heating efficiency, low ash content and volatile matter but they are associated with high costs of production when compared to the uncarbonized type. High energy pressing during compaction or densification remains key to briquette formation because it ensures easy handling and transport as well as high calorific values for the briquettes. Biomass-binder ratios differ from one biomass to another due to compatibility issues. Instead of allowing organic solid waste to pile up around industrial sites causing environmental and health hazards, the waste seems to have found a value chain mechanism which can augment the available energy supplies for industries and homes. More research needs to be done to come up with briquette formulations which are cost effective in their production but with very high calorific values to run thermal power stations for the increasing demand of electricity. The future of coal as a source of power in thermal power stations is bleak because of its non-renewable and polluting nature. Biomass briquettes are the future source of hope for thermal energy. However, if the process of converting biomass into fuel briquettes is to become a sustainable energy source for the future, it's more imperative to focus on localized processes which exploit the available forms of waste or raw material within homes and industries so as to prevent accumulation of waste. Researchers should also focus on viability studies such as cost-benefit analysis as well as making briquette formation process automated for mass production in order to meet the ever-increasing demand of energy as well as preventing piling up of organic waste in homes, municipalities and industries.

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