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REVIEW

Biomass briquettes: Raw material, technologies and densification parameters, quality and future challenges

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Abstract

The implementation of renewable energy is a viable option to reduce the use of fossil fuels and polluting emissions. Biomass is an excellent renewable energy source and is cleaner than coal. It can be obtained from organic inputs such as wood and agricultural waste and, if used sustainably, can meet the energy needs of various sectors. Densification is a technology with the potential to convert lignocellulosic waste into clean and sustainable solid biofuels. Densification involves compacting loose biomass particles using a mechanical press to produce sustainable solid biofuels with low pollutant content that are not dependent on fossil fuels. The important parameters during the manufacturing process are pressure, temperature, residence time in the press and shape of the briquettes. The production of briquettes imparts certain important properties to the briquettes, such as mechanical strength, density, combustion time and calorific quality. These properties depend on the raw material, binder and pressing process and are of utmost importance during transportation, handling and combustion of briquettes. In accordance with the above, this paper analyzes and describes the properties of different agricultural residues used in the production of briquettes and their potential as a sustainable energy source, as well as the properties that must be evaluated to define the quality of the briquettes. One of the current and future challenges is to improve the processes for producing briquettes using residual biomass and, to the minimum extent possible, binders that favor their energy and mechanical properties.

Keywords: Biomass; briquettes; densification; binders; agricultural residues; solid biofuels.

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1. Introduction

To meet the growing demand for energy and at the same time mitigate problems such as greenhouse gas emissions, new sources of energy are needed (Breyer et al., 2017). The implementation of renewable energies in various sectors of society is a possibility to reduce energy demand and the emission of pollutants into the environment due to the use of fossil fuels (Quijera et al., 2011). One of the most well-known and long-used renewable energy sources is biomass. Biomass is a cleaner source than coal from mineral sources, which can be obtained from organic inputs such as wood, crops of different plants, and agricultural residues. If used sustainably, it can meet a large part of the energy needs of different sectors of society and industry.

Biomass is most often subjected to thermochemical processes and anaerobic digestions to obtain different biofuels. However, it can be used as an energy source directly through combustion. Nevertheless, *in natura* resources are not recommended as an energy source due to their precarious characteristics, such as low bulk density, high moisture content and low energy density. These characteristics result in high transportation, storage and handling costs (Felfli et al., 2011; Okwu & Samuel, 2018). The result is a solid fuel that is easy to handle and transport. To this end, biomass densification is an effective method for guaranteeing the desirable characteristics of solid biofuels, such as greater bulk density, energy density, hardness, and resistance. By subjecting biomass to the densification process, we can obtain briquettes and pellets, which are fuels that can be used directly through combustion (Sarkar et al., 2012; Okwu & Samuel, 2018).

Biofuels are subdivided into four generations, classified according to raw materials and processes. The first generation of biofuels is characterized using food crops, such as oilseeds and sugar cane, for the production of biodiesel and bioethanol. In contrast, the second generation focuses on biomass waste, which includes materials like stalks, leaves, and bark from both agro-forestry and municipal waste sectors. These biomass sources primarily consist of lignin, hemicellulose, and cellulose (Baeyens et al., 2015; El-Desouky et al., 2022). The third generation incorporates algae and microalgae, which contain a high concentration of total sugars, suitable for producing bioethanol and biodiesel (Baeyens et al., 2015). The fourth generation leverages bioengineering techniques to alter the cellular metabolism of algae and cyanobacteria, thereby enhancing biofuel (Lü et al., 2011). Additionally, the production of briquettes is typically linked to the second generation, as it encourages the utilization of residues from agricultural and forestry operations.

Unlike other energy sources, such as electricity, gas, and solar energy, firewood consumption is not systematically monitored and measured in an objective way (Romanach & Frederiks, 2021). The use of wood as a primary energy source causes the decline of forest areas, affecting ecosystems and the inhabitants of rural areas in daily habits such as cooking and the need for heating in some areas. The direct use of firewood as a primary energy source in some homes contributes to air pollution and human health (Rao et al., 2012). Briquettes have many advantages compared to the use of conventional firewood, such as higher calorific value, easy handling, cleaning, and compact size (Dinesha et al., 2019). This contributes to the reduction of storage space and less transportation, which reduces costs.

Briquetting is the process of increasing the density of biomass by compacting loose particles of forest or agricultural waste using a press and applying mechanical force. The advantages of briquettes include the creation of a strong bond between particles to form a solid biofuel, a reduction in moisture content, an increase in calorific value per unit of volume, a solid fuel of uniform size and quality, ease of transportation, reduced storage space and a contribution to reducing the problem of agricultural waste storage (Ossei-Bremang et al., 2024). Briquettes produced from agricultural residues are sustainable, produce low levels of pollutants compared to the use of conventional fuels, are not dependent on fossil fuels and have a high calorific value (Table 1).

The world agricultural output is expected to increase by 60 per cent from 2005/07 to 2050 (or 1.07 per cent per year) (Pardey et al., 2014). The abundant agricultural waste, if used for briquettes, can contribute to the energy demand for cooking and heating (Rao et al., 2012). For all the above reasons, the objective of this work is to evaluate and describe the different characteristics of the different types of waste that have been used in the preparation of briquettes. An exhaustive investigation has been carried out in different sources to analyze the potential of different agricultural wastes for energy consumption, as well as the manufacturing process and mechanical evaluations.Briquetting serves as a sustainable approach that offers an alternative energy source.

2. The physical properties of biomass and its use in the production of briquettes

Biomass is defined as all organic matter present in the biosphere, whether of plant or animal origin, and those materials that have been obtained through natural or artificial conversion (Mehedintu et al., 2018). It is a renewable and sustainable energy source to produce electricity, heat and other forms of energy (Shabani & Sowlati, 2013). Biofuels derived from biomass include firewood, wood residues, and agricultural and agro-industrial waste. A direct example of biomass used as a direct source of energy is cut and chopped firewood because it is usually only burned directly in stoves or ovens.

Table 1
Characteristics of different solid biofuels

Fuel type	Calorific value (MJ/kg)	Ash contents (g)	Emission of gases	References
Briquettes	17.5 - 20	0.5 - 8	Emission of ~22.9 g CO kg^{-1}	(Ferronato et al., 2022; Maitah et al., 2016)
Coal	17-18.5	30 - 50	Emission of aromatic compounds and smoke of ~24 g CO kg^{-1}	
Firewood	9.2 - 12.9	20 - 25	High smoke generation~ 32.6 g CO kg^{-1}	

Residues and waste from the agricultural industry make up a considerable proportion of global agricultural productivity. Although the amount of waste produced by the agricultural sector is significantly low compared to waste generated by other industries, the pollution potential of agricultural waste is high in the long term (FAO, 2023). In addition, agricultural waste resulting from agricultural activities often has no use, and converting this waste into briquettes is an option to mitigate two major problems such as the accumulation of waste in landfills and a renewable source of energy. Briquettes produced by biomass do not increase the carbon footprint, compared to firewood used for cooking, the amount of heat generated per unit mass is higher. The combustion properties of agricultural residues increase by 20% and only 1/9 of greenhouse gases are emitted, 1/5 of nitrogen oxides (NO subscript x closes brackets and 1/10 of sulfur dioxides opens brackets SO subscript 2 closes brackets) and 1/10 of sulfur dioxides (SO subscript 2 closes brackets) compared to coal (Yusuf Kpalo & Faiz Zainuddin, 2020). Biomass briquettes also bring social and economic benefits to farmers, more jobs in rural areas, dedicated support for local and regional businesses and the use of biomass briquettes in energy production (Solano et al., 2016).

Biomass, particularly that of plant origin, is lignocellulosic, as it is composed of lignin, cellulose and hemicellulose (Velvizhi et al., 2023). The lignocellulosic nature of biomass makes it rich in energy content. Studies have examined diverse types of biomass materials, some of them combined with non-biomass materials, used to produce briquettes, some of which are listed in Table 2.

Table 2
Characteristics of raw materials for briquettes

Agricultural wastes	Chemical composition (% wt)	Flow characteristic	Heating powers (MJ/kg)	Reference
Rice husk	Lignin: 9-20 Cellulose: 28-38 Hemicellulose: 4-16	Particle size: not registered Moisture content: 13%	16.6	(Lubwama et al., 2020)
Peanut shell	Lignin: 30.2 Cellulose: 35.7 Hemicellulose: 18.7	Particle size: not registered Moisture content: 5.79%	18.47	
Coffee husks	Lignin: 27.4 Holocellulose: 47.29	Particle size: 1.2-1.8 mm Moisture content: 10%	21 – 23.9	(Setter et al., 2021)
Corn cobs	Lignin: 15.3 Cellulose: 45 Hemicellulose: not registered	Particle size: <1.6 mm Moisture content: 20%	18	(Muazu & Stegemann, 2017)
Rice mask	Lignin: 19.2 Cellulose: 45 Hemicellulose:	Particle size: <2 mm Moisture content: 8%	16	
Sugar cane bagasse	Lignin: 23 Cellulose:43 Hemicellulose:27	Particle size: 4 mm-3 cm Moisture content: 10%	17.9 – 19.85	(Afra et al., 2021)
Coconut shell	Lignin: 19.3 Cellulose:35.9 Hemicellulose:18.5	Particle size: not registered Moisture content: 4.33%	29	(Bot et al., 2023)
Pine sawdust	Lignin: 27.5 Cellulose:37.7 Hemicellulose:11.6	Particle size: 3 mm Moisture content: 10.8%	Not registered	(Niño et al., 2020)
Sorghum panicle	Lignin: 15 Cellulose:40 Hemicellulose:20	Particle size: <2.36 mm Moisture content: 3.01%	Not registered	(Velusamy et al., 2022)
Coffee bean waste	Lignin: 20 Cellulose:30 Hemicellulose:25	Particle size: not registered Moisture content: 8%	23.5	(Seco et al., 2020)
Tobacco stalks	Lignin: 25 Cellulose:50 Hemicellulose:15	Particle size: 0.5-1 mm Moisture content: 10	16	(Malnar et al., 2023)
Cassava rhizome residues	Lignin: 25 Cellulose:50 Hemicellulose:15	Particle size: 1.19 mm Moisture content: 11.8%	17.12	(Granado et al., 2021)
Pal stem	Lignin: 15 Cellulose:30 Hemicellulose:20	Particle size: not registered Moisture content: 9.1%	18.12	(Helwani et al., 2020)

Among the important parameters for raw material selection are flow characteristics and calorific value. The flow characteristic is the capacity of a material that can facilitate the handling of the raw material in the briquette manufacturing process. Therefore, small granular particles are preferred, some projects have worked with particle sizes in the range of 1.25 to 7 mm (Saptoadi, 2008), and the moisture tolerance level for briquette raw material is between 8% and 12%, which may depend on the nature of the raw material (Dinesha et al., 2019; Haq et al., 2021). These two parameters affect the competitiveness of briquettes in the market, as they are related to thermal and mechanical properties. Also, it is useful to understand the specific combination of raw materials to be selected to make different mixtures and increase the calorific value. In this regard, Table 2 shows the different agricultural residues that have been used to make briquettes. A briquette can be made from the same materials or mixtures of biomass of different materials. The mixture of different agro-industrial waste makes it possible to combine the physical and chemical characteristics of the raw materials, which improves the quality of the briquettes. For example, Muazu & Stegemann (2017) worked with a mixture of rice husk, corn stover and sugarcane bagasse, the use of lower rice husk and bagasse content (i.e. higher corn cob content) in the biomass mixture had a positive effect on the briquettes, because the corn cob particles were smaller and this contributed to the densification in the mixture, although a high amount of moisture was found in the sugarcane bagasse. In addition, of the different residues with which the briquettes are produced Binders are also used, which maintain the shape of the briquettes and increase their mechanical properties. The binder materials also influence the density and combustion characteristics of the briquettes. Among the properties that materials must have to be considered as binders, they must be economical (Olugbade et al., 2019), free of contamination, do not affect combustion and have properties that increase the bonding between the particles of the briquettes.

3. Parameters and technologies for densification

The densification process allows obtaining briquettes from biomass and the stages are shown in Figure 1. Densification is a technology with the potential to valorize lignocellulosic waste into solid, clean and sustainable biofuels for applications where thermal energy is required, whether domestic, commercial or industrial (Eling et al., 2024).

Biomass entering the briquette production process is normally dried, ground, and screened. Briquettes vary greatly in different shapes, sizes, materials, types of binders and the technologies applied for production. Most briquettes are cylindrical in shape, usually with a diameter of 25 to 100 mm and a length of 10 to 400 mm, sometimes with a hollow in the middle to increase combustion efficiency (Vivek et al., 2019). Other briquette shapes are rectangular, square and polygonal.

3.1 Densification parameters

The production of briquettes is the result of the application of various parameters, which have important characteristics such as mechanical durability, density, burning time and calorific quality. The important parameters during the manufacturing process are pressure, temperature, retention time in the press and the shape of the briquettes (Granado et al., 2021b; Li et al., 2023; Ossei-Bremang et al., 2024). Therefore, the influence of densification process variables (Figure 2) on briquette production has been studied by several authors (Table 3).

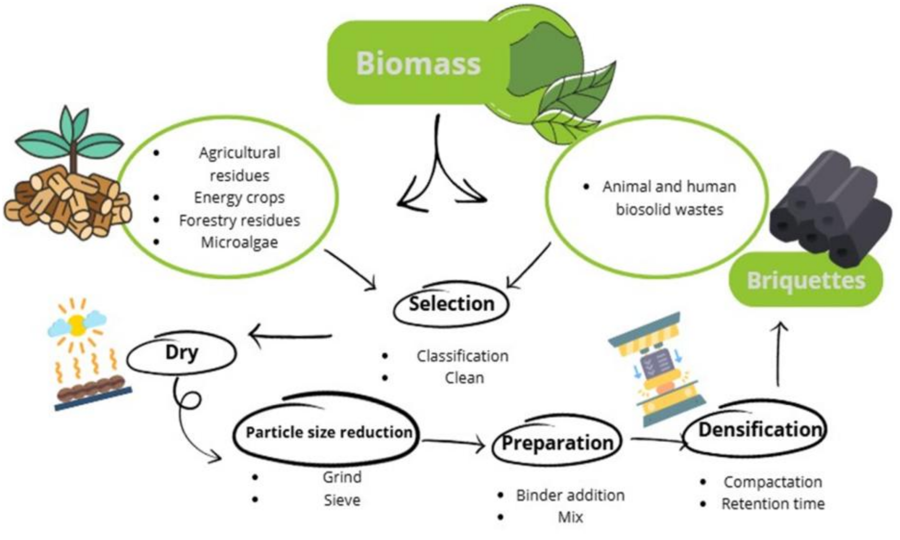

Figure 1. Briquetting process for biomass residues.

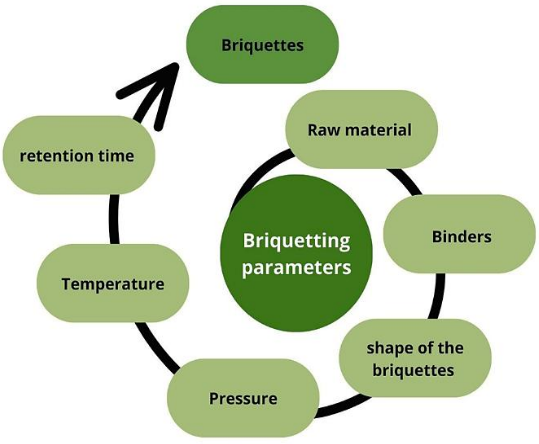

Figure 2. Parameters for briquette production.

3.1.1 Selecting and preparing raw materials

The process of densifying biomass into briquettes usually begins with the selection and cleaning of the raw material. This process, also known as screening, is carried out to remove unwanted materials and to ensure that all the raw material is the right size (Bajwa et al., 2018). After selecting the raw material, it is dried, as this increases its energy properties, but not to excess, as a reduced amount of moisture helps to bind the particles together. If the moisture content is above 12% it will need to undergo a drying process to remove as much moisture as possible (Haq et al., 2021).

3.1.2 Binders for briquettes

Binders are used to improve the bond between biomass particles during densification, although the actual mechanism of the bonding process is complex and not yet fully understood (Anukam et al., 2021). The choice of binder among the various types depends largely on several factors, including desired binding strength, low emissions, effect on briquette burning performance, environmental friendliness, sustainability, and economic availability (Kumar et al., 2021).

The binders can be incorporated during the mixing of the raw material, while in the case of carbonization, they should be added after carbonization. Some types of biomass, especially those densified at low pressures, require the addition of some type of binder (Bajwa et al., 2018). Adding binders to biomass is a practice that improves the thermal and mechanical properties of briquettes. The amount of binder required depends on the properties of the raw material and the binder used (Petricoski et al., 2020). The binders used in the densification process can be classified into three diverse types: inorganic binders, organic binders and compound binders (Kpalo et al., 2020). Table 4 shows some binders according to the classification. Nowadays, several theories have been developed to explain particle binding in biomass densification, including attractive forces between biomass particles, adhesive forces, cohesion and capillary pressure.

Although binders are used to improve the mechanical properties of the briquettes, they are sometimes not necessary, since the raw material has a high lignin and starch content, which acts as a natural binder during the pressing process, according to Mendoza Martinez et al. (2019), produced and characterized briquettes from pine and coffee bush residues, since pine residues have a high lignin and silica content, so it was not necessary to add any additional binder, since lignin acts as a natural binder. In addition, the resin content in pine residues increases the calorific value.

Table 3
Preparation, binders and densification conditions

Agricultural wastes	Binder	densification conditions (MPa)	Reference
Rice husk	Cassava starch, corn starch, and gelatin	19.39	(Lubwama et al., 2020)
Peanut shell	Cassava starch	≤7	
Coffee husks	Cassava starch and wheat starch	15	(Setter et al., 2021)
Corn cobs	Starch, biosolids and microalgae	31.19	(Muazu & Stegemann, 2017)
Rice mask	Nanolignocellulosics, nanocellulose and lignin	19.2	
Sugar cane bagasse	Cassava starch	6	(Afra et al., 2021)
Coconut shell	Does not use	6	(Bot et al., 2023)
Pine sawdust	Cassava starch	97	(Niño et al., 2020)
Sorghum panicle	Xanthan gum	10	(Velusamy et al., 2022)
Coffee bean waste	Does not use	8	(Seco et al., 2020)
Tobacco stalks	Lignin power	150	(Malnar et al., 2023)
Cassava rhizome residues	Cassava starch, corn starch, and gelatin	102	(Granado et al., 2021)
Pal stem			(Helwani et al., 2020)

* P:pressure.

Table 4
Types of binders and their characteristics

Types of binders	Examples of binders	Advantages	Disadvantages	Related works (References)
Organic	Microalgae, xanthan gum, guar gum, water hyacinth, gum arabic, corn straw, starches	Good mechanical and energetic properties, wide availability and low cost	Low ignition temperature and emission of pollutants	(Espuelas et al., 2020; Marangon et al., 2021; Miao et al., 2023; Midhun et al., 2023; Rezania et al., 2016)
Inorganic	Clay, bentonite, calcium hydroxide, iron oxide, bituminous binders	Strong adhesion properties, non-contaminating, desulfurizing	Low combustion efficiency, low calorific value, high ash content	(Celestino et al., 2023; Chukwuneke et al., 2021; Ikelle et al., 2014; Mitan et al., 2015)
Compounds	Lignin and calcium hydroxide, starch with calcium hydroxide, starch with sodium hydroxide	Good mechanical and thermal properties	High ash content and expensive	(Kong et al., 2013; Li et al., 2021; Nazari et al., 2022; Yilma et al., 2023)

3.1.3 Briquette compaction pressure

The quality of the briquettes produced is mainly influenced by the pressures used to compress the briquette's raw material. The application of pressures produces plastic and elastic deformations which fill the voids that the briquettes may have causing an increase in their density, as demonstrated by Navalta et al. (2020), they concluded that an increase in compression pressure facilitates the compaction of the briquettes and improves the resistance of the residue, in that sense, Zhang et al. (2019) mentioned that an increase in the pressure and temperature conditions would lead to an increase in the density, durability and impact resistance of corn bran briquettes.

Khlifi et al. (2020) manufactured briquettes from olive mill residues where three pressure values (100, 125 and 150 MPa) were considered, where it was observed that the optimum pressure applied significantly increases the unit density and compressive strength. Likewise, the work of Yusuf Kpalo & Faiz Zainuddin (2020) produced briquettes using a manually operated 20-ton hydraulic piston press at a compaction pressure ≤7 MPa. The results showed a rupture index of 98.28% to 99.08%, a compressive strength of 18.47 to 21.75 MPa, while calorific values ranged from 16.54 to 16.91 MJ/kg. The manufacture of briquettes using pressures and binders improves the mechanical properties of the briquettes. The manufacture of briquettes without binders at low pressure can lead to insufficient contact between the particles that make up the briquettes, thus affecting the compressive strength due to the large spaces between the particles (Olugbade & Ojo, 2021). Therefore, the presence of high pressures can contribute to improving the mechanical properties of the briquettes, since it increases the contact forces between the particles, such as capillary force and Van der Waal's attractive force, which leads to a significant increase in the compressive strength of the briquettes (Kaliyan & Morey, 2010; Sun et al., 2014).

3.1.4 Compression temperature

The temperature during the briquetting process is also an important parameter. Many researchers indicate that a high temperature is desirable, since in the case of low humidity the biomass allows the particles to bond more, harden more and obtain a higher density (Nurek et al., 2019). This was also mentioned by Kaliyan & Vance Morey (2009), who produced briquettes from plant materials at 65-100 °C, characterized by high durability and density, in the form of pads, observed how temperatures were distributed in the press through the thermographic chamber and how this affected the mechanical properties of the briquettes, having a temperature of 49 °C over most of the briquette.

3.1.5 Retention time

Retention time is one of the considerations that should also not be underestimated in briquette production, as it has a considerable impact on properties (Nganko et al., 2024). Since it refers to the time in which the raw material is subjected to constant pressure in the densification process, as demonstrated by Pari et al. (2023), who worked with a mixture of coal and pine resin, used a hydraulic press for 3 min. Where they obtained calorific values of 5,338 to 6,120 kcal/kg and began to combust at a speed of 0.40 s. In some works, retention times are very brief, e.g. 5 s at 150 MPa as in Afra et al. (2021). Yang et al. (2021) Studied different pressure levels (28 – 48 MPa) and retention times (0 – 90 s) for the introduction of the feedstock into a press.

3.1.6 Briquette shapes

Yang et al. (2021) proved that the shape of briquettes affects their compaction process, producing cylindrical, box and hollow cylinders with and without holes (Figure 3), all subjected to the same pressures (Table 4).

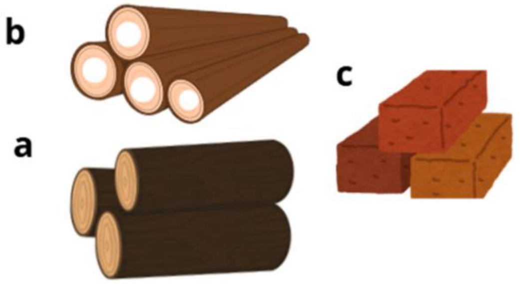

Figure 3. Briquette shapes. a) cylindrical briquette; b) cylindrical briquette with a central hole; c) box.

Florentino-Madiedo et al. (2018) densified the feedstock through a press at 100 bars. The briquettes were manufactured with 40 mm diameter. Omoniyi & Igbo (2016) manufactured cylindrical briquettes with an opening in the middle measuring 70 mm in height by 50 mm in diameter. Holes in the briquettes increase combustion efficiency by letting air in so that all the material can burn completely (Chen et al., 2022).

3.2 Technologies for biomass densification

The densification or briquetting process is a material compaction process used to produce fuels with high density, low moisture content and increased energy content (Ibitoye et al., 2021). It is an efficient method for using agricultural waste and generating clean energy, which promotes socioeconomic development (Ikubanni et al., 2019). The density after compaction can indicate the energy content of the briquettes. Materials with high moisture content and large particle size contribute to a decrease in the density and calorific value of the briquettes, therefore, subjecting the particles to the pressing process at a certain temperature increases the density and calorific value of the particles. On the other hand, low pressure compaction uses binders to agglomerate the materials. Binders also increase the strength of the briquettes and on many occasions materials that increase the calorific value are used (Yusuf Kpalo & Faiz Zainuddin, 2020). After mixing the biomass and the binders, a press is used to produce the briquettes, of which there are currently different types, which can be classified as: piston press, screw press, hydraulic press and roller press. Despite the variety of materials that make up the briquettes, most research has used hydraulic presses (manual, automated, bench and experimental) (Marreiro et al., 2021).

3.2.1 Piston press

The piston press is one of the most used and simplest devices for producing briquettes, and generally circular shapes are produced in this type of device. Ayodeji Akogun & Waheed (2022) used a piston press (Figure 4) to make briquettes from corn leaf, cassava peel and sawdust, in the case of this press it has the characteristic that the cylindrical molds can be interchanged to make briquettes of different dimensions, also mentions that this type of machines can produce 576 briquettes in 8 hours. Rahaman & Salam (2017) prepared produced rice and sawdust briquettes using a manual briquetter which used cylindrical molds that were less than 5 mm in diameter and operated at a pressure of 27.6 MPa.

3.2.2 Screw press

A screw press consists of a screw extruder and a die as shown in Figure 4. In this press the raw material is fed into the raw material hopper. The screw extruder is conical in shape and has a minimum diameter in the die area (Dinesha et al., 2019). The raw material selected for briquetting must be free of foreign particles such as metal parts or stones and the maximum production capacity of the presses is 90 kg/h at a temperature of 300 °C.

3.2.3 Hydraulic press

Hydraulic presses can be manual or electric. In the case of hydraulic presses, electrical energy is converted into mechanical energy and the main advantage of using this device is that it can work with raw materials with a high moisture content (Dinesha et al., 2019). The disadvantage of this type of equipment is the slow production of products.

Omoniyi & Igbo (2016) evaluated the physical-mechanical properties of rice husk briquettes using banana peels and gum Arabic as binders in a hydraulic press with a dwell time of 5 minutes, under a die pressure of 2.5 MPa.

4. Quality parameters of briquettes

After the briquette production process, it is imperative to delineate the packaging, storage, and transportation of the briquettes, as failure to do so can result in degradation due to the handling involved in these processes (Gilvari et al., 2019). This results in a decrease in the energetic properties. The mechanical and energetic characteristics define the quality of the briquettes, and these depend on the raw material, the binder and the densification process. These properties of briquettes are due to particle size, chemical and physical characteristics (Kpalo et al., 2020).

The energetic or combustion properties of a material are determined by a variety of parameters, including the calorific value, ease of ignition, and ash content. In the case of mechanical properties that contribute to the quality of briquettes, they are evaluated by means of compressive strength, durability, density, and impact resistance. These parameters simulate transport, handling, and storage conditions (Kaliyan & Vance Morey, 2009). In general, there are different methods to evaluate the energetic and mechanical properties of the briquettes, so the evaluations define the quality of the briquettes, some of the standard methods or techniques that are performed on the briquettes are described below (Table 5).

4.1 Proximate analysis of biomass briquettes

Generally, fuels that are directly sourced from biomass are analyzed to report the relative properties of volatile matter, moisture content, fixed carbon and ash content (Afra et al., 2021). The ash and volatile matter content can be obtained according to the following standards ASTM E1755-01 (2007) y ASTM E872-82 (2006), respectively. Ash determination provides the percentage produced after combustion since a high ash content could affect the combustion properties and calorific value of the briquettes (Sotannde et al., 2010; Velusamy et al., 2021).

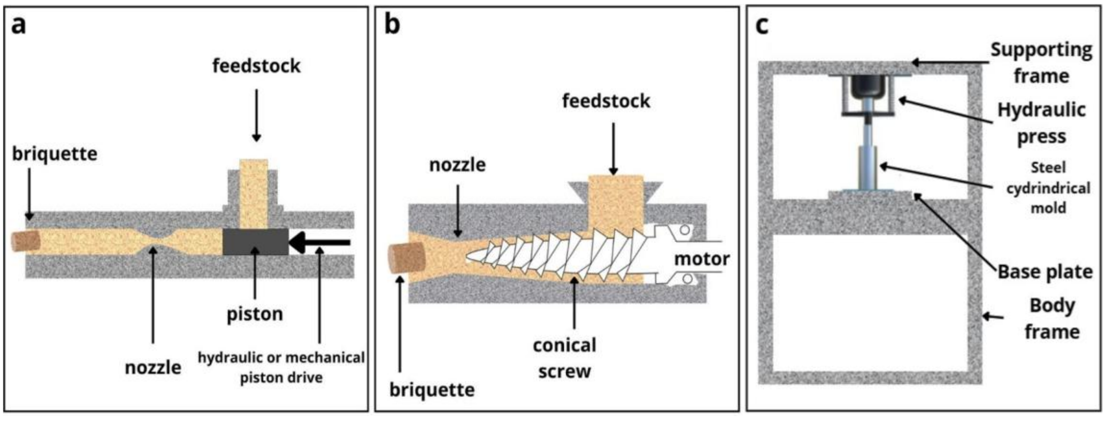

Figure 4. Equipment to produce briquettes. a) Mechanical piston press; b) screw extruder; c) hydraulic press.

Table 5
Physicochemical and thermal characteristics of briquettes

Raw materials	Chemical characteristics	Physical characteristics	Heat capacity	Autor
Charred corn on the cob	Starch, carbohydrates (44.8% - 69.6%), proteins (4.5% - 9.87%), fats (2.17% - 4.43%), fiber (2.10% - 26.77%), consisting of cellulose, hemicellulose and pectin and ash (1.10% - 2.95%)	Dimensions of 150 and 850 µm, melting point of 27.8 °C, 8% - 12% moisture	16584 J/g, las tusas un valor de 16573 J/g y las hojas un valor de 16432 J/g	(Choi et al., 2022)
Rice husk, coffee husk and peanut shell	Cellulose (30% -4 0%), Hemicellulose (20% - 30%), Lignin (15% - 25%), Silica (SiO_2) (15-20%),	particle size of 150 µm and 233 µm, 10% - 15% moisture	14.215 kJ/kg to 31.204 kJ/kg	(Givi et al., 2010)
Peanut shells, sugar cane bagasse, coffee husks and rice hulls	Cellulose (35% - 45%), Hemicellulose (23% - 30%), Lignin (27% - 33%)	particle size of 180 µm and 330 µm, 8% to 10% moisture	17.5 - 18.5 MJ/kg	(Wang et al., 2023)
Rice hulls, corn cobs and sugar cane bagasse	Cellulose (35% - 50%), Hemicellulose (20% - 30%), Lignin (20% - 25%)	particle size of 130 µm and 190 µm, 9% to 13% moisture	18.5 - 22.11MJ/kg	(Phaenark et al., 2023)
Banana peel, sugar cane bagasse, coconut shell, and rattan residues	Cellulose (30% - 40%), Hemicellulose (20% - 30%), Lignin (15% - 25%), Starch (16.8% - 21%)	particle size of 100 µm and 140 µm, 8.3% to 10% moisture	16.2 - 19,8 MJ/kg	(Bot et al., 2023)
Rice husk and pine sawdust	Cellulose (40% - 50%), Hemicellulose (20% - 30%), Lignin (25% - 35%)	Dimensions of 140 and 650 µm, melting point of 35.7 °C, 9% - 14% moisture	12.8 - 13.5 MJ/kg	(Niño et al., 2020)
Pine sawdust, onion peel and tamarind peel	Cellulose (44% - 50%), Hemicellulose (18% - 25%), Lignin (20% - 31%)	Dimensions of 122 and 350 µm, melting, 9% - 14% moisture	14.8 - 16.01 MJ/kg	(Velusamy et al., 2022)

Moisture content can be determined using the standard protocol given by the International Organization for Standardization (ISO) ISO 18134-2:2017, which is a method for determining the total moisture content of a test sample of solid biofuels, likewise, we also find Antwi-Boasiako & Acheampong (2016) used the standard ASTM D4442-16 (2016) to determine moisture content, which is one of the properties that could influence mechanical strength, durability and thermal efficiency (Kpalo et al., 2020; Onukak et al., 2017). Fixed carbon is generally determined by the difference in the sum of the above values (Pari et al., 2023).

4.2 Energy and combustion properties

The calorific value can be determined by employing a variety of methods and protocols. One such method is ASTM E711-23e1 (2023), which involves the use of a calorimetric bomb. Alternatively, Ferrera-Lorenzo et al. (2014) with the following equation: $\text{HHV (MJ/kg)} = (3.55 \cdot \text{C}^2 - 232.2 \cdot \text{C} - 2230 \cdot \text{H} + 51.2 \cdot \text{C} + 131 \cdot \text{N} + 20600) \times 10^{-3}$, where HHV is the high calorific value of the briquettes, C is the percentage of carbon, H is the percentage of hydrogen and N is the percentage of elemental nitrogen in the biomass briquettes. The method applied by Sotannde et al. (2010) where they calculated the calorific value of the briquettes using the following formula of Gouthal: $\text{H}_\text{v}(MJ/kg) = 2.326 \cdot (147.6\text{C} + 144\text{V})$, where Hv is the calorific value, C is the percentage of fixed carbon and V is the percentage of volatile matter. The calorific value reflects the energy produced when briquettes are burned. Combustion efficiency is assessed through atmospheric combustion tests, where the briquette's mass is measured every three minutes until it drops below 10% of its initial weight. Subsequently, the remaining ash from the burned briquettes is subjected to heating in a laboratory muffle furnace at 600 °C for four hours to determine the total ash content and ensure complete combustion (Muazu & Stegemann, 2017).

4.3 Compressive strength

Compressive strength is defined as the maximum crushing load that a briquette can withstand before cracking or breaking (Pari et al., 2023). Therefore, the model is employed to simulate the maximum compression to which briquettes can withstand during transportation, handling and storage.

Various types of equipment can assess the compressive strength of briquettes, all operating on a similar fundamental principle. In this process, the sample is positioned between two horizontal plates, where compression is exerted at a steady rate until the material fractures or breaks (Granado et al., 2021). However, the pressure applied to the briquettes varies in the literature, making it hard to compare their strength. This is one of the preferred evaluations within the literature to determine the quality of briquettes, some of the standards used to determine the compressive strength is the ASTM D2166-85 (2008), the process is based on subjecting the briquette in a press with a load capacity of 50 kN and a crosshead speed of 1 mm/min, the load to which it is uniformly subjected, until the briquettes crack (Mitchual et al., 2014), in comparison with Afra et al. (2021) where the briquettes were positioned horizontally between two plates, but the applied speed was 0.305 mm/min until the briquettes broke.

4.4 Impact resistance (Rupture index)

To assess this property, the initial mass of the briquette is weighed and recorded, and the sample is then subjected to a free fall from a constant height of 2 m, as specified in the standard ASTM D440-86 (2002). Impact resistance is the percentage ratio of the number of times a briquette is dropped from a height of 2 m until it breaks, to the average number of resulting pieces into which the briquettes break (Afra et al., 2021). Sunnu et al. (2023) assessed the impact strength of briquettes made from agricultural waste biomass. The briquettes were dropped from a height of 2 meters onto a concrete surface five times. After the five drops, the resulting fractured pieces were gathered and weighed immediately after the drops. Only those fragments that accounted for 5% or more of the original weight were included in the calculation of the impact strength, using the following equation: $IR = \frac{N}{n} \times 100$, where IR is the impact resistance, *N* is the number of drops and *n* the number of pieces of briquettes that weighed 5% or more of the initial weight. The resistance of briquettes to impact is evaluated by assessing their durability against breakage when they are dropped from a predetermined height onto a surface made of a specific material. The degree of weight loss is expressed as an indicator of the briquette's capacity to endure such impacts (Rajaseenivasan et al., 2016). This property is important for understanding the behavior of briquettes during logistics handling and transportation of briquettes.

4.5 Durability

The durability of the briquettes is important because it indicates the amount of dust and larger parts that can be generated during the handling of agricultural waste briquettes. Different equipment is widely used in the literature to determine the durability of briquettes, mostly equipment with a rotating drum (Hoyos Álvarez et al., 2019; Zhang & Guo, 2014). The evaluation is performed by casting a briquette with known mass into the module or rotating drum of the evaluating equipment. After a set time and speed, the durability is calculated as the loss of mass released during the evaluation divided by the initial mass of the briquette evaluated. Hoyos Álvarez et al. (2019) determined the durability by subjecting the briquettes to blows against the walls of a rotating chamber rotating at a speed of 21 RPM for 5 minutes.

5. Current and future challenges

Currently, the consumption of fossil fuels is one of the main causes of global warming and pollution. Oil reserves are not renewable nor are they available worldwide; therefore, the substitution of renewable energies is dependence on crude oil (Bhatt & Bal, 2019). The area of transportation, the generation of electrical energy and the use of fuels for the generation of heat lead to economic, political and environmental problems that could be solved by looking for new sources of renewable energy, such as biomass (Ramalingam et al., 2024). In this context, these environmental and economic consequences led to the development of renewable energy alternatives (biofuels, hydrogen, wind, solar and bioenergy), considering sustainability and technical-economic viability. Renewable energy is expected to increase due to preferential access, recent capacity growth and the start of projects (Pishvaee et al., 2020).

The energy sector must consider bioenergy: renewable energy stored in an organic chemical state. Biomass is a promising source of renewable energy and bio-based products due to its natural origin, carbon stability, cost-effectiveness, non-toxicity and abundant supply (Han et al., 2023). Agriculture is a key area for increasing the potential of bioenergy in the future. There is a great opportunity for the growth of diverse crops in the world, which will allow for an increase in the production not only of food but also energy crops and agricultural waste. Biomass waste is produced in huge quantities worldwide, with the largest annual producers being rice straw (731.3 million tonnes), wheat straw (354.34 million tonnes), sugar cane bagasse (180.73 million tonnes) and maize stover (128.02 million tonnes). Biomass has enormous potential, every year, around 950 million tonnes of biomass are generated, with the capacity to produce approximately 300 million tonnes of biofuel, equivalent to oil. This means that biomass waste could cover up to 65% of total oil consumption (Kalak et al. 2023). However, issues such as high-water content or low calorific value limit the amount of energy that can be harnessed (Hansted et al., 2024).

The direct use of biomass waste, without the need for many processes, is densification, increasing the density of the biomass and reducing volumes through a process of pressing solid biomass, generating pellets and briquettes. The technical feasibility of briquetting depends on the raw material and the pressing process (Yilma et al., 2023). Therefore, the current aim is to produce briquettes from wet biomass waste with water as a natural binder, in contrast to conventional methods that require forced drying and/or the addition of binders (Hansted et al., 2024).

6. Conclusions

In the present review, the following are mentioned the types of binders in different briquettes of biomass origin, technologies and procedures adopted in the manufacture of briquettes, as well as the quality properties to be considered for the briquettes. Among the parameters that stand out are densification, pressure, compression temperature, retention time and the different shapes of the briquettes. The different presses used in the densification process are also mentioned, such as the piston press, screw press and hydraulic press. Of these, the piston press is the most widely used due to its ease of operation and construction. Similarly, a series of important parameters were examined during the densification process, including pressure, which indicates that there is no specific pressure range to which agricultural waste should be subjected to the briquetting process. This review was based on different research papers which showed that densified agro-industrial waste in the form of briquettes increases its energy and mechanical properties. Therefore, regions with too much agricultural waste could use this technique to make use of waste from the agro-industry. In this regard, the increasing generation of solid waste and the high energy demand represent global challenges. Therefore, the conversion of waste into alternative fuels, through techniques such as briquetting, offers a solution to reduce the environmental footprint of the waste management sector and improve combustion efficiency.

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Authors' contributions

H.J. Orantes-Flores: Investigation, Writing-original draft, Visualization and editing. Y. Sánchez-Roque: Supervision and Writing-review and editing. P. López-de-Paz: Supervision, Investigation and Writing-review and editing. Y.C. Pérez-Luna: Investigation and Conceptualization. M.A. Canseco-Pérez: Writing-review & Investigation. A.G. Zenteno-Carballo: Visualization and Investigation.

Conflict of interest

The authors declare that they have no known financial or personal conflicts that could influence this article in the form of a review. The authors assume all responsibility for this publication.

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