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Review

A Review of Technical and Economic Aspects of Biomass Briquetting

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Abstract: Growing global demand and utilization of fossil fuels has elevated wealth creation, increased adverse impacts of climate change from greenhouse gases (GHGs) emissions, and endangered public health. In most developing countries, biomass wastes, which include but are not limited to agricultural residues, are produced in large quantities annually. They are either inefficiently used or disposed of indiscriminately, which threatens the environment. It is possible to convert these wastes, through densification, into high-density and energy-efficient briquettes. Densification of biomass into briquettes presents a renewable energy option as an alternative to fossil fuels. This paper reviews biomass briquetting with reference to biomass resources, feedstock pre-processing, briquetting process parameters, briquetting technology, and briquettes quality evaluation parameters. The review also includes the economic aspect of briquetting relating to costs and feasibility.

Keywords: biomass; briquette; densification; technology; production costs; economic feasibility

1. Introduction

The demand for energy has been on the increase mostly attributed to the growth in human population as well as a significant rise in the commercial and industrial activities witnessed across the globe. Fossil fuels such as petroleum products, coal, natural gas, etc., are the most important energy sources, which supply about 80% of the global primary energy requirement [1]. The depletion of fossil fuel, which is non-renewable, has been a global issue; nevertheless, it is the growing utilization that is currently presenting a new and major challenge. According to Tursi [2], the increasing usage of fossil fuels for industrial and post-industrial development has attracted growth in wealth, but so also higher levels of pollution and the consequent degeneration of public health. In 2018, the global carbon dioxide (CO_2) emissions from fuel combustion reached 32.8 billion tonnes [3]. The rise of carbon dioxide concentrations will continue unless emissions are drastically reduced. A recent report noted that the earth is set to warm up to 3.2 °C by 2100 unless efforts to cut emission are tripled [4]. The desire for the average rise in temperature to be sustained well below 2 °C requires a total decarbonization of energy generation away from fossil fuels [5]. Interestingly, fossil fuels are not the only constituents of environmental degradation. Inefficient use and disposal of biomass as well as inadequate proper cooking technologies also persist. Anenberg et al. [6] reported that 3 billion people rely on fuelwood, coal, charcoal, or animal waste for cooking and heating. Most of these people are predominantly found in developing countries. They get exposed to high indoor concentrations of health-damaging pollutants including particulate matter and carbon monoxide due to incomplete combustion [7,8]. Furthermore, one-third of the global population lives without access to healthy, clean, and sustainable cooking fuel or technologies [5].

Of all energy sources, biomass is the third largest energy resource in the world [9]. It is also the most dominant source of cooking and heating energy for three-quarters of all people in developing countries, and accounts for about 14% of the total global energy use [10–12]. In most of these countries, more than 80% contributes to national energy consumption [13,14]. In Ethiopia for instance, traditional biomass burning supplies more than 92% of its energy consumption [15], over 64% in Ghana [16], 70% in Kenya [17], 78% in Nigeria [18], 60% in Bangladesh [19], and 7% to electricity in Brazil [20,21]. The threats posed by the continuous consumption of fossil fuels and inefficient use and disposal of biomass can be curbed by effective utilization of biomass waste when converted to briquettes through densification [22]. Studies showed that the combustion properties were increased by 20% after the biomass was molded into solid briquettes and the emissions of greenhouse gas, NOx, and SO_2 were only one-ninth, one-fifth, and one-tenth that of coal [23]. Briquettes are used domestically and industrially for heat and power generation. The use of renewable energy from biomass is one of the few proven, cost-effective, and available technologies that can decrease CO_2 emissions [24].

Thermochemical conversion technologies that utilizes briquettes include combustion, gasification, and pyrolysis. However, combustion is the most developed and widely applied process used for such utilization because of its low costs and high reliability [25]. Additionally, co-combustion of biomass with fossil fuel is considered as one of the attractive short-term options for biomass utilization in the power generation industry. As shown by Andrić et al. [26], the addition of about 20% biomass to the mass of the combustion mixture in a biomass co-combustion power plant can reduce CO2 emissions by 11%–25%. Christoforou and Fokaides [25] noted that the co-combustion mix of less than 50% of coal is achievable but that is dependent on the co-combustion technology, the type of combustion boiler, and the plant configuration. A summary and comparison of the main observation and conclusions from several studies that reported the use of these conversion technologies can be found elsewhere [27].

The production and use of biomass briquettes are considered environmentally sustainable if the practice meets certain environmental sustainability indicators, which are classified in broad categories related to land use, air and water quality, soil and biodiversity conservation, and carbon stock preservation [25]. Ultimately, access to modern, sustainable, and eco-friendly energy enhances opportunities to have better healthcare, education, financial possibilities, and even longer life [28]. This paper is specifically aimed at reviewing biomass briquetting technology as a sustainable means of bioenergy production, with reference to biomass resources, briquetting processes, technology assessment, and its economic implication.

2. Biomass Resources

The ISO 16559 [29] defines biomass as any material of biological origin excluding those that have been embedded in geological formations undergoing a process of mineralization. It is a renewable and sustainable source of energy for producing electricity, heat, and other forms of power [30,31]. Biomass, particularly of plant origin, is lignocellulosic in nature as it is comprised of lignin, cellulose, and hemicellulose [2,32] including a few organic components like lipids and extractives [33]. The lignocellulosic nature makes biomass rich in energy content. The combustion characteristics and energy potentials of different biomass materials have been reported [34–36].

According to Bajwa et al. [37], biomass resources can be grouped in terms of properties ('woody' and 'non-woody' biomasses) or sourcing (agricultural residue and harvested natural materials). The ISO 17225-1: [38] classified biomass feedstock resources into four specific groups, namely woody, herbaceous, fruit, and aquatic biomass. Other classification includes animal and human waste and biomass mixtures [2]. In developing countries, large amounts of biomass residues are generated annually as by-products of the commercial forestry, agricultural, and industrial sectors [39,40]. In 2008, about 134 million tons (Mt) of rice husks were produced globally from 671 million tons (Mt) of rice production and approximately 135 million tons (Mt) of corn cobs from 797 million tons (Mt) of corn production [41]. Similarly, for the year 2010-2011, agricultural and forest biomass feedstock was found to be 242 million tons (Mt) and it is estimated to increase to 281 million tons (Mt) in 2030–31 due to the growing production of the agricultural crops [42]. The supply of biomass from various sources around the globe is approximately 220 billion tons per year [43].

These resources are used as fuel, directly or indirectly, avoiding needless burning, burying, or storage [44–46], but can also cause extensive environmental pollution when used inefficiently [20,47]. In comparison to other renewable energy options, several studies noted that biomass is abundant in supply from various sources and its energy has the key advantages of being nearly carbon neutral [48–50]. The carbon neutrality of biomass resources is dependent on the net CO_2 equivalent greenhouse gases (GHGs) emitted across the entire life cycle processes considered [51], which also involves the emissions generated during the manufacturing and transport phases. The CO_2 released through its burning, utilization, and exploitation processes does not cause an increase in atmospheric CO_2, but instead leads to a faster transfer of CO_2 into the atmosphere that is reused by plants to produce biomass again [2]. This environmentally friendly attribute of biomass makes it an ideal renewable and sustainable source for briquette production. Studies have explored several types of biomass materials with some in combination with non-biomass materials used in briquetting (Table 1).

Table 1. Types of biomass and non-biomass materials used for briquetting.

Material	Waste Composition	Binder Used	Reference
Agricultural residue	• Rice husks, corn cobs and sugarcane bagasse. • Rice straw.	• Starch, biosolids, microalgae. • Cotton stalk.	• [52]. • [53]
Woody biomass	• Wood and bark • Shredded cones	• None. • None.	• [54]. • [55]
Fruit waste	• Mango seed. • Orange bagasse. • Durian, coconut, coffee, cacao, banana and rambutan. • Cashew press cake.	• Starch, Clay soil, Red soil' • Corn starch. • None. • Cassava starch.	• [56]. • [57]. • [58] • [59]
Tannery solid waste	• Hair, flesh, chrome shavings and buffing dust. • Buffing dust, chrome shavings, fleshing and hair	• Cassava starch. • Cassava starch.	• [60]. • [61]
Human waste	• Fecal matter	• Starch, molasses, lime	• [62]
Textile industry solid waste	• Biosludge, cotton residue. • Cotton waste	• None. • None.	• [63]. • [64]
Paper and cardboard	• Office and commercial printing paper, newsprints, and cardboard • Cardboards, magazines, newspapers, office paper, books. • Cardboards.	• None. • None. • None.	• [65] • [66] • [67].
Vegetable market waste	• Cauliflower/cabbage leaves, coriander stalk and leaves, field beans and green pea pods	• None.	• [68]
Furniture waste	• Wood and upholstery foam	• None.	• [69]
Garden waste	• *Mesua ferrea* leaves,	• Wastepaper	• [70]
Oil palm waste	• Palm kernel shell, palm fiber • Empty fruit bunch. • Palm kernel shell. • Rubber seed kernel and palm oil shell.	• Wastepaper. • Starch, asphalt. • Starch. • Starch.	• [71]. • [72]. • [73]. • [74].
Biomass and plastic waste	• Sachet water bags, polythene bags, saw dust, maize husk, coal. • Sawdust, date palm trunk, wire, printed circuit boards, automotive shredder residues.	• Starch, limestone, laterite • None.	• [75]. • [76]
Biomass and coal	• Sawdust and coal. • Coal fines, sawdust. • Woodchips, olive stone, anthracites, and coal	• Cassava starch • Molasses. • Starch, resin	• [77]. • [78] • [24]
Black liquor	• Straw pulp black liquor	• Starch.	• [79]
Aquatic biomass	• Giant reed (*Arundo donax L.*) and reed (*Phragmites australis*) • Water hyacinth. • Water hyacinth.	• Loess, lime • Phytoplankton scum. • Molasses	• [80] • [81]. • [82]

3. Biomass Feedstock Pre-processing

3.1. Cleaning

The densification of biomass materials into briquettes usually starts with sorting and cleaning of the feedstock. This procedure is also called sieving, which is done to remove all unwanted materials ensuring that all the feedstock is of the required size [83]. As reported in [37], screening equipment such as sieves and magnetic conveyors are used to remove impurities such as soil, dirt, metal, and plastic strings, etc., to achieve the maximum cleanliness of the feedstocks. These unwanted materials are generated during the collection and storage of residues. Washing the materials with water or mild solvents is another means of cleaning out impurities generated through alkali oxide, chemicals, and fertilizer application in agricultural farms. Said et al. [84] observed that washing can improve the combustion properties of biomass

3.2. Drying

Feedstock drying is essential particularly if the feed is wet, however some materials like coffee husk, groundnut shells, and rice husk usually may not require drying. Drying of feedstock increases its efficiency but should not be excessively dried. Allowing a small amount of moisture helps in binding the biomass particles. According to Solano et al. [85], drying can be done naturally by exposing the feedstock to favorable environmental conditions to reduce its moisture contents without supplying any heat externally. Another way is forced drying by industrial process that reduces the moisture content of biomass fuel down to a specified range (5% to 15%) suitable to start densification. For biomass that has to be forced dried, Grover and Mishra [86] noted the use of direct driers in which hot air or flue gases are intimately mixed with material and indirect ones where heat is transferred to materials through a metallic surface. In the indirect driers, material is not mixed with the hot air. Purohit and Chaturvedi [87] noted that the drying process is the most energy-intensive process and accounts for about 70% of the total energy used in the biomass densification process.

3.3. Size Reduction

Size reduction is a very important process prior to biomass briquetting. Studies have noted that it partially breaks down the lignin content of biomass and increases the total surface area leading to greater inter-particle bonding [88,89]. Size reduction in biomass also increases the bulk density, which improves the flow of biomass during densification [90]. There are several size reduction methods, which include chopping, chipping, hammer milling, crushing, shredding, and grinding. Size-reduced biomass was classified as chopped (50–250 mm), chipped (8–50 mm), or grinded (<8 mm) [85]. Another means of reducing the size of biomass before densification is through the use of sieve either by oscillatory screen method [91] or by vibratory screen method [92]. The status of the biomass feedstock determines which method or combined methods that needs to be adopted. Tumuluru and Heikkila [93] reported a two-stage grinding process of woody and herbaceous biomass materials. The first stage entails the grinder breaking the biomass bundles into a larger size material enhancing its movement in the conveyors, while the second stage involves a further grinding to a smaller size to make the biomass suitable for biochemical and thermochemical conversion processes. Common equipment used to reduce the size of biomass for briquette densification include hammer mill, knife mill, linear knife grids, and disk attrition. However, hammer mills are considered the most suitable [86], whereas the cutting mill is the next most preferred [94]

3.4. Binder Addition

Binders can be added during mixing of the feedstock or after carbonization of the feedstock before densification. Some biomass material will not agglomerate except with the addition of binder especially if a low-pressure compaction technique is employed. Binder addition to biomass feedstock is a co-processing practice, which aids in densification or increase the mechanical or thermal properties of the product [37]. Binder addition helps to reduce wear on production equipment. It forms a bridge to enhance strong inter-particle bonding with biomass components [90]. The amount of binder to be added depends on the binding properties of the raw material and the binding agent [95]. There are three types of binders used for briquette production, namely inorganic binders, organic binders, and compound binders [96].

Common examples of inorganic binders include clay, lime, cement, plaster, and sodium silicate. On the other hand, the organic binders are sub-grouped into biomass binder (e.g., cassava paste, wastepaper pulp, molasses, cow dung, and starch), tar, pitch and petroleum bitumen binder, lignosulphonate binder, and polymer binder [97–99]. A combination of the two or more binders from both the organic and inorganic binders forms the compound binder. Different types of briquette may require different binder, but the strength, thermal stability, combustion performance, and cost of briquette is influenced by the quality of binder [100]. There are some advantages that one type of binder may have over the other because of its material components. Briquettes made with inorganic binders have higher compressive strength, compaction ratio, and hydrophobic nature compared to those made with an organic binder. However, such briquettes display an increase in ash content, burn out temperature, and reduced calorific value [72,97,101,102]. For effective fuel production, the binder must be plastic and elastic as its use is known to improve density, durability, and resistance to shearing [103].

4. Biomass Densification and Particle Bonding Mechanism

Biomass densification represents a set of technologies for the conversion of biomass into a fuel. It essentially involves the compaction under pressure of loose material to reduce its volume and to agglomerate the material so that the product remains in the compressed state [104]. The densification process is critical for producing a feed-stock material suitable as a commodity product. Densification enables several advantages, including (i) improved handling and conveyance efficiencies throughout the supply system and biorefinery infeed, (ii) controlled particle size distribution for improved feedstock uniformity and density, (iii) fractionated structural components for improved compositional quality, and (iv) conformance to pre-determined conversion technology and supply system specifications. [9].

There are several densification technologies used in producing a uniform feedstock commodity for bioenergy applications, however pelleting and briquetting are the two most widely used [105]. Briquetting is an agglomeration method for upgrading solid biomass and producing end products with standardized properties and characteristics. It is a process of changing low-bulk-density biomass into high-density and energy-concentrated fuel [44,106] and carried out to improve the density, burn time, and calorific value (per unit volume) of raw biomass thereby improving the handling and transportability of biomass [107,108]. It uses relatively small amounts of energy to increase the mass and energy density, thus reducing the cost of transportation to the point of use [37].

Densification of biomass under high pressure brings about mechanical interlocking and increased adhesion between the particles, forming intermolecular bonds in the contact area [86]. This is achieved by forcing the particles together by applying mechanical force to create inter-particle bonding, which makes well-defined shapes and sizes such as briquettes [109]. The quality of densified biomass depends on strength and durability of the particle bonds, which are influenced by a number of process variables, like die diameter, die temperature, pressure, binders, and pre-heating of the biomass mix. [9]. The mechanism of particle bonding as reported in Manickam et al. [110] can be subdivided into five major categories including (i) forces of attraction between solid particles, (ii) interfacial forces and capillary pressure in movable liquid surfaces, (iii) adhesion and cohesion forces at not freely movable binder bridges, (iv) solid bridges, and (v) mechanical interlocking.

During the densification of corn stover and switchgrass, Kaliyan and Morey [109] used scanning electron microscopes (SEMs) to understand the formation of solid-type bridges. Results from the SEM images showed that the bonding between particles was created mainly through solid bridges. The solid bridges between particles were made by natural binders in the biomass expressed during the densification process. Ultraviolet auto-fluorescence images of briquettes and pellets further confirmed that the solid bridges were made mainly by natural binders such as lignin and protein. It was found that activating the natural binders using moisture and temperature in the range of glass transition is important to make durable inter-particle bonding. Tumuluru et al. [9] suggested that more studies at a micro level using techniques like SEM and transmission electron microscope (TEM) will be useful in understanding intra-particle cavities, material properties, and process variable interactions on the quality attributes of densified biomass

5. Briquette Quality and Determining Parameters

The quality of briquettes is dependent on the raw materials and the briquetting process. The desired qualities for briquettes as fuel include good combustion, stability and durability in storage and in handling (including transportation), and safety to the environment when combusted [111]. Combustion and environmental safety are dependent mostly on the nature of the raw material. This nature includes the structure (e.g., size, fibrous, non-fibrous, etc.), chemical (e.g., lignin-cellulose content), physical (e.g., material particle size, density, and moisture content), and purity (e.g., trace of element (sulfur), etc.). Combustion is measured by parameters such as calorific value, ease of ignition, and ash content, while environmental concern is measured by the toxic emissions during combustion.

The briquetting process, on the other hand, determines the durability and stability of briquettes. Compressive strength, abrasion resistance, impact resistance, moisture absorption, and density are basically the parameters that determines durability and stability. They are considered as the most important quality parameters of densified biomass [112]. The quality of briquettes is characterized in terms of physical, mechanical, chemical, and thermal 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. Table 2 presents parameters and tests standards used to measure briquette quality.

Table 2. Summary of some briquette quality parameters, guiding values, test standards, and equipment.

Parameter	Guiding Value	Test Standards	Purpose/Significance	Measurement Equipment
Moisture content	≤12% *, ≤15% **. [113], [114]	ASTM D2444 [115] ISO 18134-2 [116]	• To evaluate possible changes in the physical conditions of briquettes during storage and transport. ➢ Could influence mechanical strength [117] durability [69] and thermal efficiency [60].	Thermogravimetric analyzer, drying oven with temperature range of 105 ± 2 °C, Digital weighing scale
Density	≥0.9 gcm^{-3} *, ≥1.0 gcm^{-3} ** [113] ≥0.6 gcm^{-3} *, ≥0.9 gcm^{-3} ** [114]	ASTM D2395 [118] ISO 18847 [119]	• To determine the mass of particles per unit volume of a sample briquette ➢ Influences transportation cost and energy density [120]	Digital weighing scale, Digital or manual Caliper
Water resistance	95%. [121]	ASTM D870-15 [122]	• To determine the rate at which briquettes can withstand degeneration in humidity or water exposure. ➢ The ability of briquette to resist moisture penetration when exposed which could affect combustion and durability in storage	Digital weighing scale, Digital or manual Caliper
Shatter index	≥90%. [123]	ASTM D440-86 [124] ISO 616 [125]	• To gauge the strength of briquettes for the purposes of handling, transportation, and storage ➢ It indicates briquette's ability to produce fewer fines during handling. [126] and high durability to gravitational deterioration [117]	Digital weighing scale, Meter rule, Steel plate, Sieve
Compressive strength	1.0 MPa. [127]	ASTM D2166-85 [128]	• To determine the maximum crushing loads a briquette can withstand before cracking or breaking. ➢ Make briquettes safe to store, transported without breaking [75].	Universal Testing Machine
Durability	95%. [121]	ISO 17831-2 [129]	• To determine the rate at which briquettes can withstand degeneration when handled and transported. ➢ The test simulates mechanical or pneumatic handling [90] which shows briquettes ability to resist abrasion.	Durability tester
Calorific value	≥14.9 MJ/kg *, ≥15.5 MJ/kg **. [113] ≥14.5 MJ/kg *, ≥14.5 MJ/kg ** [114]	ASTM D5865-13 [130] ISO 18125 [131]	• To determine the amount of thermal energy in the combustion of one kilogram of briquette. ➢ This indicates the energy recovery potential of biomass during thermos-chemical conversion [90]	Bomb calorimeter
Ash content	≤1.0% *, ≤3.0% ** [113].≤6.0% *, ≤10.0% ** [114]	ASTM D3174-12 [132] ISO 18122 [133]	• To determine the percentage ash content briquette may produce after combustion. ➢ Ash content in the briquette causes increase in the combustion remnant in form of ash which lowers the heating effect of the briquette [134] and may cause slagging [86]	Furnace with a temperature range of 550 ± 10 °C

Table 2. *Cont.*

Parameter	Guiding Value	Test Standards	Purpose/Significance	Measurement Equipment
Volatile matter	Not specified	ASTM D3175-18 [135] ISO 18123 [136]	• To simulate the practical aspect of combustion of the biomass in the boiler. ➢ It enhances sporadic burning and an indication of ignition rate in briquettes [134]	Furnace with a temperature range of 900 ± 10 °C
Carbon (C)Hydrogen (H)Nitrogen (N)	48–50% [137] 6.2% [137]. ≤0.3% *, ≤1.0% ** [113].≤1.5% *, ≤2.0% ** [114].	ASTM 3176-15 [138] ISO 16948 [139]	• To determine combustion properties of briquettes and undesirable amount of emission i.e., NO_X. ➢ These elements suggestive of the fuel properties of briquettes. They influence combustion.	Element analyzer
Sulphur (S)	≤0.04% *, ≤0.05% ** [113]. ≤0.20% *, ≤0.30% ** [114].	ASTM D3176-15 [138] ISO 16994 [140]	• To determine the amount of undesirable emissions, i.e., SO_X. ➢ Sulfur is oxidized and converted to SO_2 gas during combustion in furnaces. Sulfur pollutants are harmful to the environment.	Atomic emission spectrometer

* Minimum value, ** Maximum value.

6. Briquette Production Process

The production process of briquettes essentially involves the acquisition of the biomass feedstock, processing it, and eventual densification (Figure 1). Densification is done by applying pressure, heat, and binding agent on the residues to produce the briquettes [141]. The output of the densification process is briquette (Figure 2), which is referred to as a compressed block of organic waste material [83] used for domestic and industrial purposes in both rural and urban areas [141]. Briquettes are made of different qualities and dimensions depending on the raw materials, mold, and technologies applied during production [83,95]. Briquettes vary a lot in size and form, but usually they are of a cylindrical shape with a diameter of between 25 and 100 mm and lengths ranging from 10 to 400 mm [142]. Square, rectangular, and polygonal briquettes also exist. Densified biomass such as briquettes have several advantages, which includes, but are not limited to, increased energy density, ease of handling, transport and storage, improved combustibility, lower particle emission, low volatility, and uniform size, density, and quality [143–145].

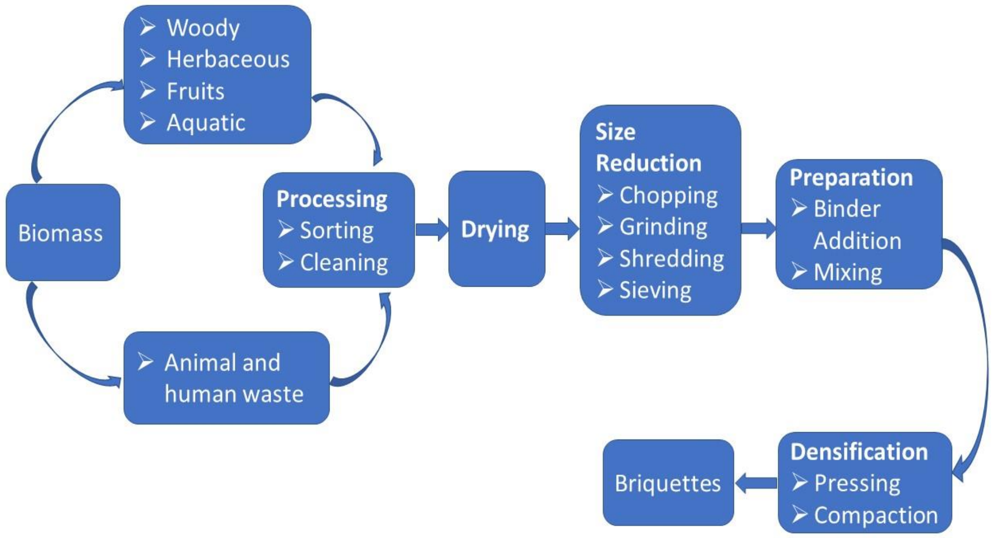

Figure 1. Briquette production process.

Figure 2. Sample of briquettes produced using a manually operated piston press.

7. Briquetting Process Parameters

Compression conditions (pressure, temperature, time) and feedstock properties (particle size and shape, moisture content, feedstock composition) are some of the major determinants of briquette's quality. Understand these parameters enhances smooth operation during briquetting.

7.1. Compression Condition

7.1.1. Compaction pressure

Biomass can be densified under a high compaction pressure or a low compaction pressure. Generally, the feedstock type, moisture content, and particle size and shape determine the amount of pressure to be applied. Densification under low compaction pressure requires a binding agent to enable interparticle bonding. High-pressure densification utilizes the natural binding components such as starch, protein, lignin, and pectin, which are squeezed out of the particles of the biomass materials, to facilitate inter-particle bonding. According to Dinesha et al. [42], the outcome of pressure application is plastic and elastic deformations and filling of voids, forming higher density briquettes. Compaction pressure influences density, compressive strength, and durability of briquettes. Kpalo et al. [70] varied pressure from 5.1 to 15.3 MPa to produce briquettes made from wastepaper and *Mesua ferrea* mixtures at different ratios. The study reported that pressure at 15.3 MPa produced the highest densities for each ratio of briquettes, while the pressure at 5.1 MPa produced the lowest densities. Additionally, in measuring the shear strength of biomass briquettes, Chin and Siddiqui [146] raised the densification pressure from 1 to 10 MPa and found that the shear strength of briquettes increased from 27.5 to 95.7 N (sawdust), 1.2 to 4.6 N (rice husk), 1.3 to 6.7 N (peanut shell), 10 to 73.3 N (coconut fiber), and 10 to 36.2 N (palm fiber). Kaliyan and Morey [144] noted that high pressure helps the densification of biomass and suggests a range of 100–150 MPa, or higher. However, studies have shown that low compaction pressure can produce low-cost briquettes that are durable [73,147,148].

7.1.2. Temperature

Temperature affects both biomass feedstock and the die of the briquetting machine before and during the briquetting process. It aids in the release of components such as lignin, cellulose, and hemicellulose where the lignin act as binders. Yank et al. [147] noted that high temperature and pressure are widely agreed to enhance binding mechanisms but require important energy input. Grover and Mishra [86] advised that the preheating temperature should not exceed 300 °C to prevent biomass materials decomposition while that of the die in a screw press extruder should be kept at about 280–290 °C. Okot et al. [149] investigated maize cobs briquettes densified at varying temperatures of 20–80 °C. The study concluded that densification at temperature of 80 °C could produce briquettes with high density and durability/mechanical strength required to meet quality certification standards. As part of the process parameters in briquetting of pine needles, Mandal et al. [150] used a temperature range of 60–150 °C. Results from the study showed that a temperature of 150°C was found to be optimum to produce briquette. Optimum temperature value within the range of 65–100 °C for feedstock preheating was proposed by Kaliyan and Morey [144] but added that temperatures higher than 100 °C and up to 300 °C can be used if desired. According to Grover and Mishra [86], die temperature exceeding what is required will decrease the friction between feedstock and die wall enabling densification at lower pressure to produce low-quality briquettes. Conversely, low temperature will result in higher pressure and power consumption. It also leads to lower production rate, but higher-quality briquettes.

7.2. Feedstock Properties

7.2.1. Moisture Content

Moisture content of biomass feedstock is an important parameter that determines the overall quality of biomass briquette. During briquetting, moisture content of biomass facilitates starch gelatinization, protein denaturation, and fiber solubilization processes [89]. It acts as a lubricant, reducing friction between the residue particles [42]. Additionally, it serves as binder and forms a solid bridge between particles via van der Waal's forces [73,151]. Under room temperature, moisture contents from 12% to 20% (w.b.) may help the densification process but may not be possible beyond 20% (w.b.). [144].

In assessing the influence of moisture on the final properties of briquettes made from platan tree chips, Brožek [152] used four moisture levels, namely 5.7%, 7.7%, 15.7%, and 23.9%. Results showed that the best properties were reached at briquettes made from chips of moisture 7.7%. The study concluded that at higher or lower moisture, the briquettes rupture force and density were sharply failing. Similarly, the initial moisture content of spruce sawdust measured immediately before densification reported in Matúš et al. [153] were 7.4%; 9.1%; 10.3%; 11.7%; 12.6%; 14.5%; 16.5%; 19.6%; and 22.0% w.b. The study discovered that 12.6% was the best value of initial moisture content, which produced the best briquette based on the physical and mechanical properties.

It is important to obtain a balance for moisture content prior to densification in order to ensure briquette quality. For instance, low moisture content will hinder proper agglomeration of the particles of the feedstock. High moisture content, on the other hand, would incur more cost of energy for drying, which could influence the cost of the final product. Optimum moisture content varies with the type of feedstock [89,95]; so far, a value in the range of 8%–12% is considered as generalized optimum densification value [144]. The right amount of moisture develops self-bonding properties in lignocellulosic substances at elevated temperatures and pressures prevalent in briquetting machines [83].

7.2.2. Particle Size, Shape, and Distribution

Particle size and shape are of great importance for the densification of biomass materials. It influences the quality of briquettes [154–156], the production cost [144,157], and the briquetting process [158]. According to [86], biomass feedstock of 6–8 mm size with 10%–20% powdery component (<4 mesh) is generally agreed to gives the best results. However, opinion is still divided as to what constitutes an optimum particle size. Some studies opined that finer grind of feedstock material (<2 mm) gives a larger surface area for bonding, which results in the production of briquette with higher density, strength, and durability [117,144,159,160]. In contrast, others noted that larger sized particles proved best for durability and other quality parameters [105,161,162].

In determining optimal particle size of pine and spruce bark, Brunerová and Brožek [163] concluded that the study's results values did not support opinion that smaller particle sizes are more suitable for briquette production. The study also noted that the choice of optimal particle size partly depends on feedstock material but unarguably not defined yet in general. The distribution of particle sizes is often most important with a mixture of fine and coarse particles. Grover and Mishra [86] and Yumak et al. [164] noted that mixing various particle sizes improves the packing dynamics and also contributes to strength and stability of briquettes.

7.2.3. Feedstock Composition

As earlier mentioned, biomass mainly consist of cellulose, hemicelluloses, and lignin including extractives like fats, resins, and ash. A comprehension of this chemical composition can be useful in knowing feedstock compaction behavior during briquette densification. This paper is restricted to the lignocellulosic content only

Cellulose, a linear polymer, is a complex carbohydrate (or polysaccharide) with a high molecular weight and a maximum of 10,000 monomeric units of D-glucose, linked by β-1,4-glycosidic bonds. Cellulose is an abundant source of carbon in biomass [165]. Carbon enables combustion of briquettes and a higher carbon content is commonly related to a higher calorific value [166]. Hemicellulose consists of heterogeneous branched polysaccharides and is strongly linked to the surface of cellulose microfibrils. It is amorphous in nature and has adhesive properties, with a high tendency to toughen when it is dehydrated [2]. Lignin, contained in plant cell wall, denotes a complex amorphous aromatic polymer with a three-dimensional network, composed of phenylpropane units linked together. In the feed material, lignin serves as an in-situ binder enabling the binding process at high temperatures when it softens [144], making it possible to produce more durable briquettes [55]. Additionally, it yields more energy when burned than cellulose [9].

8. Briquetting Technology and Types of Machinery

The briquetting technology is new in African nations, but advanced in Asia, America, and Europe [167]. Certain advantages of using biomass have led to the development of such advanced technologies for energy and fuels conversion [168]. According to Wilaipon [169], the technology can, based on compaction, be divided into high-pressure compaction and low-pressure compaction. Eriksson and Prior [104] classified compaction pressures as low (5 MPa), intermediate (5–100 MPa), and high (100 MPa and above). High-pressure compaction technology uses a heating device while the other uses a binder. However, based on equipment used, Ahmed et al. [141] categorized the technology into piston press technology and screw press technology. There are several types of briquetting machines available for densification and compaction of biomass. Their mode of operation varies from one principle to another. Several studies have identified these machines to include the screw press extruder, roller press, piston press (which can either be mechanical or hydraulic), and manual press [9,47,83,170,171]. Table 3 shows a comparison of these machines based on certain parameters while their utilization in briquette production from the literature is presented in Table 4.

Table 3. Comparison of different briquette presses.

	Screw Press	**Roller Press**	**Piston Press (Hydraulic/Mechanical)**
Optimum moisture content of raw material (%)	4–8	10–15	10–15
Particle size required (mm)	2.6	Less than 4	6–12
Shape	Cylindrical	Generally, elliptical (depends on the shape of the die)	Cylindrical
Dimensions (mm)	Length: 1940 Width: 750 Height: 1310 (similar dies produce smaller extruded logs)	Almond shaped briquettes dimension: 31.75 (length) × 20.32 (width) × 11.16 (depth). (depends on the shape of the die	32 (dial) × 25 (thick)
Wear of contact parts	High	Low	Low
Output from machine	Continuous	Continuous	In strokes
Specific energy consumption (KWh/ton)	36.8–150	29.91–83.1	37.4–77
Throughput (ton/h)	0.5–1	5–10	2.5
Unit density (g/cm^3)	1–1.4	No information	Less than 0.1
Bulk density (g/cm^3)	0.5–0.6	0.48–0.53	0.4–0.5
Combustion performance of briquettes	Very good	Moderate	Moderate
Maintenance	Low	High	High
Homogeneity of densified biomasss	Homogenous	Not homogenous	Not homogenous

Source: Adapted and modified from [9].

8.1. Screw Press Extruder

A screw press consists of screw extruder and a die (Figure 3). Three types of screw presses are recognized, and they include conical screw presses; cylindrical screw presses with heated dies;

and those without externally heated dies. In the screw extruder, the biomass is continuously fed into a screw, which forces the material into a heated cylindrical die to the point where lignin flow occurred [104]. The technology is based on the pressure of a special screw that pushes raw material within a chamber that becomes progressively narrower [85]. The pressure is built up along the screw rather than in a single zone as in the piston machines. Binder is hardly required in a screw press densification; however, it could be necessary if the required temperature (200–250 °C) to dissolve lignin is not achieved, or when biomass has been carbonized, which destroys lignin content. The screw press may enjoy lower capital costs, but higher maintenance cost than the piston presses due to substantial wear on the screws, which must be reconstructed regularly. Its specific energy demand is also higher. Screw extruders were initially built and used for briquetting sawdust; however, field data verify that the machine also work well when briquetting rice husks, apart from the high wear problems [104]. Screw press briquettes have a concentric hole, which gives better combustion characteristics due to a larger specific area. They are also homogeneous with a high combustion rate and do not disintegrate easily. Briquette densities from these machines usually range between 1000 to 1400 kg/m^3 [86].

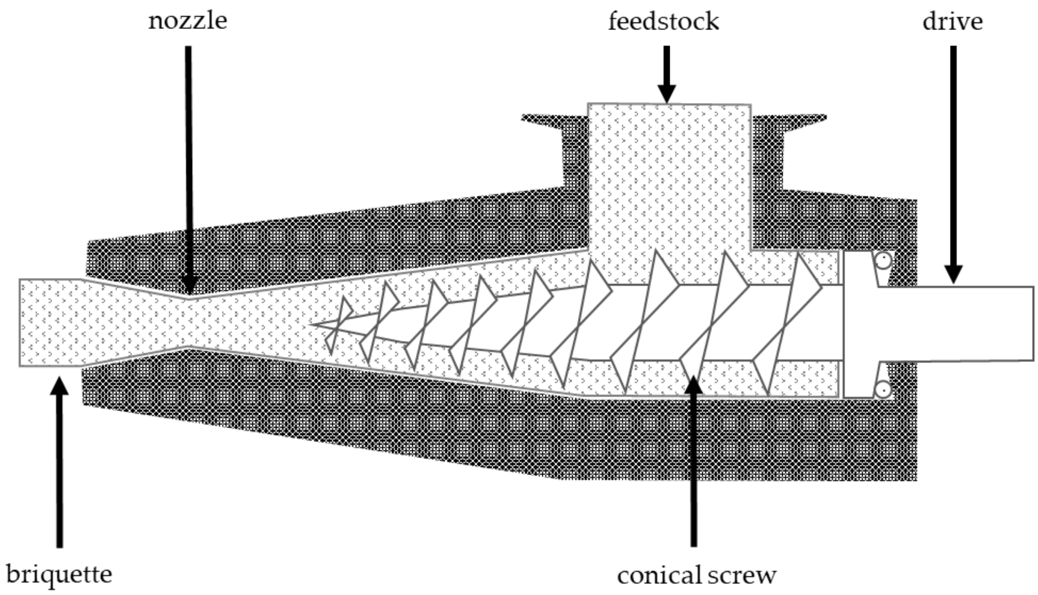

Figure 3. Screw press (Adapted from [25]).

8.2. Mechanical Piston Press

The mechanical piston press consists of a ram (piston) and a die and it is driven by an electric motor (Figure 4). Biomass feedstock is punched into a die by a reciprocating ram with a very high compaction pressure to obtain a briquette. According to Tumuluru et al. [9], this machine develops a compression force of approximately 196.1 MPa and is typically used for large-scale production, ranging 200–2500 kg/h. The achieved briquette densities are generally in the range between 1000 and 1200 kg/m^3 [85]. The capacity of a mechanical piston press is defined by the volume of material that can be fed in front of the piston before each stroke and the number of strokes per unit of time. Capacity by weight is then dependent on the density of the material before compression. The moisture limit of feedstock in most cases is 15%; nonetheless, the ideal operating region is 8%–12%. A lower limit of 5% is acceptable as anything less will cause friction and thus increase energy demand [104]. Materials that can be densified include agricultural waste, coal dust, saw dust and shavings, tree bark, etc. In comparison to the screw press, it has long life of wearing parts and a low power consumption rate. It also requires a higher level of maintenance and the briquettes produced are of lower quality. Additionally, it generally gives a better return on investment (ROI) than the hydraulic piston press [9].

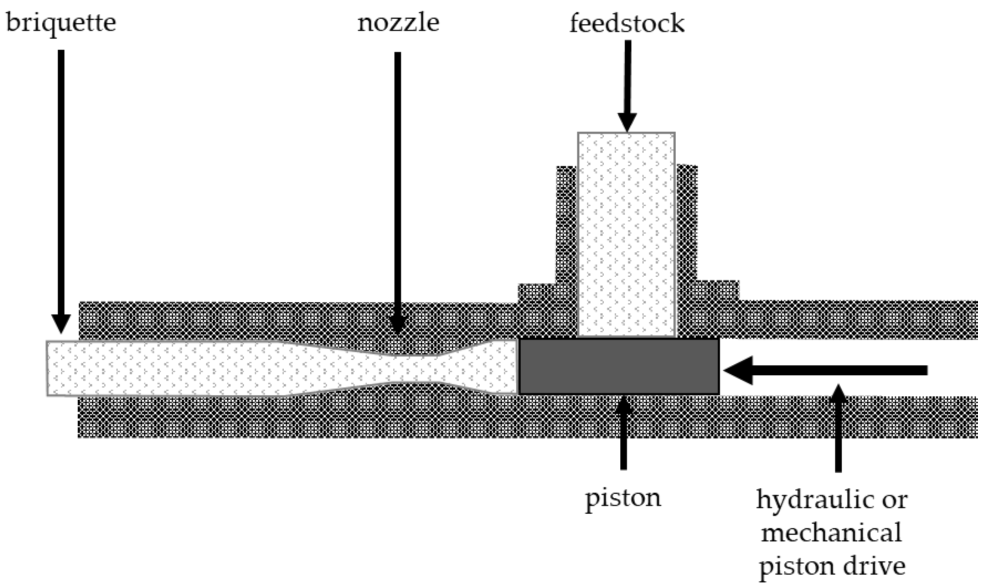

Figure 4. Piston press (Adapted from [25]).

8.3. Hydraulic Piston Press

The hydraulic piston press operates like the mechanical piston press. However, the energy to the piston is exerted by a cylinder operated by a hydraulic system. Eriksson and Prior [104] noted that the briquetting pressures with hydraulic presses are considerably low and this is because of limitations in pressure in the hydraulic system, which is normally limited to 30 MPa. The piston head can exert a higher pressure when it is of a smaller diameter than the hydraulic cylinder, but the gearing up of pressure in commercial applications is modest. The typical production capacities of these machines are in the range of 50–400 kg/h and can tolerate higher moisture contents than the usually accepted 15% for mechanical piston presses. It usually produces briquettes with a bulk density lower than 1000 kg/m^3 because pressure is limited [9]. In general, briquettes produced have a uniform shape and size, typically using 40 × 40-mm cylinders [105], and the quality of the product here is much higher compared to mechanical presses. Additionally, a hydraulic press can sometimes be an alternative to a mechanical press, and typical materials suitable for this machine are paper, cardboard, manure, etc. [104].

8.4. Roller Press

Roller presses are considered the global standard technology to produce pillow-shaped briquettes using diverse types of biomass. The roller press works on the principle of pressure and agglomeration (Figure 5). It consists of dual cylindrical rollers of the same diameter, rotating horizontally in opposite directions on parallel axes [172]. The two rollers are arranged in such a way that a small gap exists between them and the distance from each other depends on factors such as the biomass type, the particle size, the moisture content, and the addition of binders. During operation, the raw material is fed into the press and forced through the gap between the rollers on one side. It is then pressed into a die forming the densified product, which comes out on the opposite side. The smooth production of briquettes using this technology requires high-quality rollers with smooth surfaces on which the briquettes are shaped. The type of roller or die used determines the shape of the densified biomass [172] and typical bulk densities range from 450 to 550 kg/m^3 [173].

8.5. Manual Press

Different types of manual presses exist for the densification of biomass materials. Some come in the form of piston or screw presses but are operated with bare hands and hardly uses electricity.

According to Maninder et al. [47], manual presses are designed for the purpose of briquette making or adapted from existing implements used for other purposes. Manual clay brick making press is a good example with which briquettes can be made from both carbonized and non-carbonized biomass feedstock. Another common example of manual press is the WU-Presser (Figure 6) developed by the Washington University, USA [174]. The press is made from both metal and wood with the latter being the most common. These machines operate with very minimal pressure and binder addition to feedstock is required. Manual presses are characterized by low capital costs, low operating costs, and low levels of skill required to operate the technology. However, they have a low production capacity of about 5 kg/h or 50 kg in a 10-hour day [142].

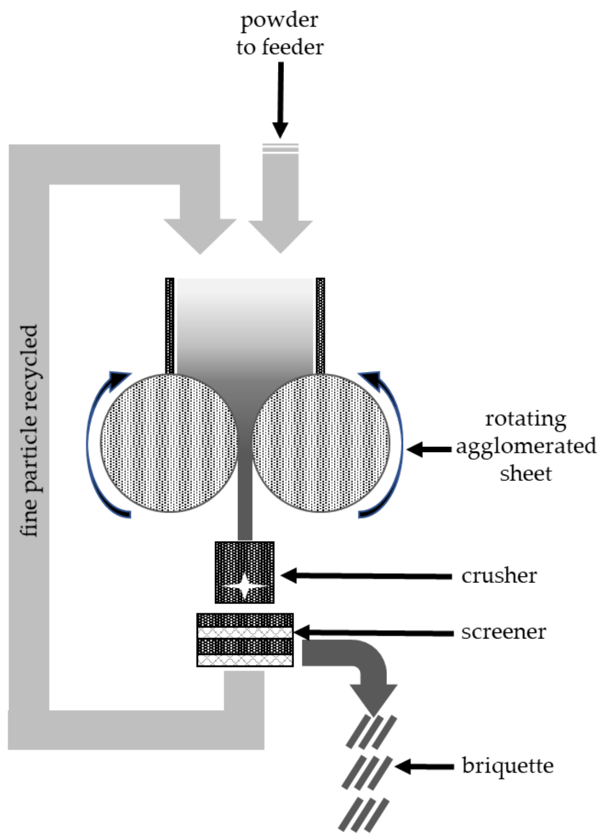

Figure 5. Roller press (Adapted from [9]).

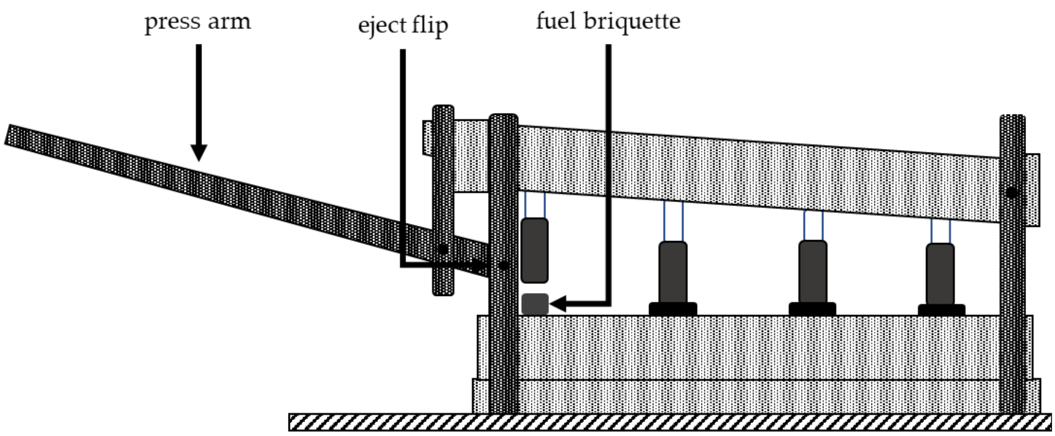

Figure 6. Manual press (WU Presser) (Adapted from [174]).

Table 4. Briquette presses and their study outcome.

Briquette Press	Reference	Output Capacity	Briquettes' Shape and Dimension	Raw Material Used	Study Outcome
Screw extruder	• [175]	• 120 kg/h	Hexagonal. 100 mm length.	• Cassava rhizome waste	• The briquettes had higher density (0.69 to 0.91 g/cm^3), compressive strength (8.51 to 14.94 kg/cm^2), Impact resistance index (153.7 to 416.7) and calorific value (21,670 to 24,367 KJ/kg).
	• [74]	• 200 kg/h	Hexagonal. 50 mm length, 20 mm inner diameter	• Rubber seed kernel (RSK), Palm oil shell (POS)	• The maximum compressive load of the POS briquette was 101.11 N and the calorific value was 16.05 MJ/kg whereas the RSK briquette was 141 N for compressive load and 16.03 MJ/kg for calorific value.
Mechanical piston press	• [68].	• 500 kg/h.	Cylindrical. 50 mm diameter.	• Vegetable market waste (VMW)	• The bulk densities for VMW briquettes increased substantially to 509 to 747 kg/m^3 from initial bulk densities of 44.2 to 60 kg/m^3 of dried and loose vegetable market waste. The calorific values of different VMW briquettes were in the range of 10.26 to 16.60 MJ/kg.
	• [53]	• 1200 kg/h	Cylindrical. 70 mm	• Rice straw	• Briquettes were produced with high-density (1030.38–1159.22 kg/m^3), durability ranging from 71.9 to 92.3%, maximum calorific value of 15.61 MJ/kg, and minimum ash content (16.34%).
Hydraulic piston press	• [69]	• Not available	Cylindrical. 50 mm diameter.	• Furniture wood waste, Foam.	• Briquettes produced from combining furniture wood waste and foam generated more heat and energy. Durability of briquette with 20% of polyurethane foam was like a common briquette of furniture wood waste.
	• [78]	• Not available	Rectangular. 30 mm length, 25 mm width, 15 mm height	• Saw dust, Coal fines	• The addition of saw dust as well as molasses as a binder resulted in a briquette with a calorific value of 26 MJ/kg, fixed carbon of 76% and high compressive strength of 0.25 kN/cm^2 which is not easily shattered
Roller press	• [173]	• Not available	Almond shaped. Maximum size of 31.3 mm length, 23.3 mm width, 17.9 mm depth.	• Corn stover, Switch grass	• Briquettes produced with the roll press briquetting machine had bulk densities (351 to 527 kg/m^3), durability (39% to 90%), and crushing strengths (28 to 277 N)
	• [123]	• Not available	Pillow shaped. 60 mm width, 50 mm height, 30 mm depth.	• Charcoal powder	• The machine produced briquettes whose physical properties were satisfactory, regardless of the type of binder and showed adequacy for use in barbecues.

9. Applications of Briquettes

Briquettes are used for domestic and industrial purposes in both rural and urban areas. They serve as a development intervention to replace firewood, charcoal, or other solid fuels because current scarcities and rising prices of fuel has made consumers to look for affordable alternatives [83]. The various uses of briquettes are presented in Table 5

Table 5. Potential applications of briquettes.

No	Industry	Possible Application
1	Domestic use	Cooking, water heating, and space heating
2	Commercial and institutional catering	Cooking, water heating, grilling
3	Hospitality	Cooking, water heating, space heating (outdoor dining areas)
4	Industrial Boilers	Generation of heat and steam
5	Food processing	Distilleries, bakeries, canteens, restaurants, drying
6	Textiles	Dyeing, bleaching
7	Crop processing	Tobacco curing, tea drying, oil milling
8	Ceramic production	Brick kilns, tile making, pot firing, etc.
9	Gasification	Fuel for gasifiers to produce electricity
10	Charcoal production	Initiating pyrolysis to make charcoal production more efficient
11	Poultry	Incubation and heating of chicks

Source: [44].

10. Economic Implication of Briquetting Technology

Economics of briquetting is very site specific and depends on the local conditions of regions with different outcomes. Therefore, this review restricts itself to the basic economic aspect of briquetting considered in general but applied to suit local conditions. Production of biomass briquettes requires technology, which can be high energy-powered or low energy-powered. Raw materials for the briquetting process are a major determinant of the equipment and machinery used [22] as well as briquette's varied quality and production costs [176]. A critical element to consider when proposing the setting up of a briquetting plant is the cost. The following section briefly explains costs in general and reviews a few scenarios.

10.1. Costs of Briquette Production

The briquetting production cost, which can be denoted as the total cost, is dependent on several other costs. Tripathi et al. [22] outlined these other costs to include capital cost, installation cost, operation cost, and repair and maintenance cost.

The costs of processing equipment, briquetting machine and accessories, land, and building where necessary, are basically what constitutes the capital cost of a biomass briquetting system. The costs associated with mounting such equipment and machinery on site refer to the installation cost. The cost of labor, raw material, electricity, oil and lubricant for machinery, transportation, and other related inputs that enhance the smooth running of the briquetting plant essentially forms the operation cost. Finally, the repair and maintenance cost are basically comprised of expenditure made on the appropriate maintenance of the briquetting plant and machinery on a daily, weekly, monthly, or as deemed necessary basis. This involves repair or outright replacement of damaged parts, oil cleaning, and tightening of loose screws. Several studies have reported the application of these costs to arrive at the total production cost of briquettes.

Żarski [177] reported that total cost of producing 1 ton of briquette from cereal and oil-rape straw amounted to $62.43, with cost of raw materials, depreciation, and cost of electricity taking the largest share. Similarly, the total cost of producing 1 ton of fuel briquettes from sawdust was $84.45, which is more than 35% higher than in the case of production of briquettes from straw. In analyzing the cost of smokeless charcoal briquette produced from agricultural and forest residues, Tippayawong et al. [178] reported $0.42 as the total cost of a kilogram of the briquette. The cost of the raw char accounted for around 70% of the total cost, however an estimated 22.4% was also reported as profit. These studies agree with [22,176] that the purchasing price of biomass account for the largest proportion in briquettes price. Additionally, Gill et al. [53] reported that the total cost of making briquettes from chopped rice straw only was $0.041 per kilogram and $0.00281 per mega joule of energy, while that of briquettes from chopped rice straw with 10% and 20% cotton stalks was $0.050 and $0.051 per kilogram, respectively, and $0.0033 per mega joule of energy. The study concluded that it is economically viable to produce briquettes from chopped rice straw with and without cotton stalk as a binder. Srivastava et al. [68] produced and evaluated briquettes using four types of vegetable market wastes (VMW) without the use of external binder. Results showed that the total cost of briquettes, including the cost of raw material, ranged from $24.68 to $28.90 per ton. The study noted that the cost is comparable to the cost of wood available at market rate and thus concluded that the briquetting of VMW may be a viable option for obtaining useful energy instead of being allowed to rot creating environmental problems

Eriksson and Prior [104] noted that the economic feasibility of briquetting technology anywhere will be significantly subject to the relationship between these unit costs and the price of the alternative fuels. It is therefore important to analyze these costs because biofuels would only be a viable alternative if their costs are less than those of fossil fuels [179]. Biomass briquettes can complement firewood, coal, and kerosene for cooking purposes when produced at low price and made easily available to consumers leading to lower demand of such fuels [42].

10.2. Feasibility Analysis

The economic feasibility of any technology including briquetting can be determined through economic analysis of same. It is also dependent on four factors, namely the type of equipment used, the type of biomass, skills of human resource, and investment capital [180]. The economic analysis is performed by deploying certain basic economic indicators of net present value (NPV), internal rate of return (IRR), payback period (PBP), and benefit cost ratio (BCR) (Table 6).

Table 6. Economic indicators for the feasibility of projects.

Economic Indicator	Definition	Equation
Net Present Value (NPV)	The present value of the benefit minus the present value of the cost	$NPV = \sum_{t=\dot{O}}^{n} (C_b - C_c)_t (1+\mathrm{i})^{-t}$
Payback Period (PBP)	The number of years that it will take, from day one of a project, before the investment cost is fully recovered	$\sum_{t=\dot{1}}^{Pt} (c_b - c_c)_t (1+\mathrm{i})^{-t} = 0$
Internal Rate of Return (IRR)	The cut-off discount rate that makes the NPV equal to zero	$\sum_{t=\dot{O}}^{n} (c_b - c_c)_t (1+\mathrm{i}rr)^{-t} = 0$
Benefit-Cost Ratio (BCR)	The ratio of the equivalent worth of benefits to the equivalent worth of costs.	$B/C = \frac{\sum_{t=1}^{n} C_b (1+\mathrm{i})^{-t}}{\sum_{t=1}^{n} C_C (1+\mathrm{i})^{-t}}$

Source: [181]. Where $\boldsymbol{C_b}$ is the cash benefit of the investment, $\boldsymbol{C_c}$ is the cash cost of the investment, $\boldsymbol{(C_b - C_c)_t}$ is the net cash flow in the year (t), $\boldsymbol{n}$ is the calculation period, which is equal to the project lifecycle, and $\boldsymbol{i}$ is the cut-off discount rate.

10.2.1. Past Studies on Economic Analysis in Brief

Net Present Value is used to determine the profitability of a project. A positive NPV means the project can be accepted [181], but should be rejected when negative, and can make the investor indifferent when it is zero [182]. In their work, Sengar et al. [183] found that $25,831.88, $30,117.20, and $8434.78 represented the NPV of cashew shell, grass, and rice husk briquettes, respectively. Similarly, an NPV of $17.2 million was realized from a study carried out by Hakizimana and Kim [184]. The values obtained confirmed the commercialization of peat briquettes. Other notable briquetting projects with high NPV include $9.81 million [185] and $1.40 million [186]. The NPVs of the cases mentioned are all positive. It can therefore be deduced that briquetting projects are profitable and so feasible.

Pay Back Period is calculated while accounting for the time-value of money and used also to measure the level of risk. Sengar et al. [183] reported that cashew shell and grass briquettes took 0.68 and 0.63 years, respectively, as the project's payback period. However, the same project took 2.5 year for rice husk briquettes, which is slightly above the two-year period reported by Hamid et al. [74] for the production of rubber seed kernel (RSK) and palm oil shell (POS) briquettes. In other studies, the payback period for durian peel and rice straw briquettes was 1.3 years [187] while peat briquettes production was between five and six years [184]. The payback period of a project is usually compared with its economic life. The lesser the number of years to recover the investment, the better for the project

Internal Rate of Return is the maximum interest that could be paid for the resources used if a project is to recover all cost expended and still break even [183]. In conducting an economic assessment of a briquetting project with an expected 15 years economic life, Hu et al. [186] reported an IRR of 36% and a payback period of 4.4 years. Onchieku [180] also reported 68%, 76%, and 100% on different scenarios when carrying out a cost-benefit analysis of charcoal briquette production over two years. The discount factor in this case was 15%. According to Walekhwa et al. [182], an investment is said to be profitable when the value of IRR is higher than the discount rate.

Benefit Cost Ratio is the ratio of the equivalent worth of benefits to the equivalent worth of costs. A project can be accepted if the BCR is equal or greater than 1 [181]. The economic analysis in [175] found that briquettes produced from cassava rhizome charcoal with either molasses or starch gel binder in proportion of 7:3 were found best with highest BCR of 2.01 and 2.15, respectively. BCR for cashew shell, grass, and rice husk briquettes were 2.8, 2.93, and 1.51, respectively [183]. The values for BCR obtained in these studies indicates acceptability. To conclude that a project like briquetting plant or technology is feasible and profitable, all economic indicators used for economic analysis are expected to be positive

10.2.2. Sensitivity Analysis

A Sensitivity analysis is used to include uncertainty in a project's economic assessment to generalize the results for diverse situations where input factors and costs are different [188]. In a recent study by Sahoo et al. [189], a sensitivity analysis was conducted to determine the impact of key input parameter on the minimum selling price (MSP) of woodchips briquettes (WCB), torrefied-woodchips briquettes (TWCB), and biochar. The MSPs per oven-dry metric ton (ODMT) of WCB, TWCB, and biochar were $162, $274, and $1044, respectively. The study varied ±20% change in input parameters for the financial model and results showed variation in the relationship between changes in the models' input variables and their impact on MSP. Moisture content was found to be the most sensitive input for WCB, and its MSP was decreased by 10% or increased by 12.5% by using woodchips at 29% or 43% moisture. Furthermore, about 4%–8% change in the MSP was obtained by a 20% variation in the capital cost.

In another study by Feng et al. [185], findings revealed that NPV was sensitive to change in the price of briquette and cost of raw materials. For instance, percentage change from −10% to +10% in the price of briquettes resulted in the fluctuation of the NPV from $4.93 million to $14.70 million. It also revealed that a 10% increase in the cost of raw material reduces the NPV and vice versa. The study concluded that the risk of lower NPV from briquette price reduction is less compared to the increase in the cost of raw material. Similarly, a varied percentage change from −20% to +20% in the price of briquette and cost of cornstalk influenced the economic performance of a biomass briquette fuel system [186]. The percentage change in briquette price caused the NPV, IRR, and PBP to range from −$0.40 million to $3.06 million, from −2% to 60%, and 2.8 to 25 years, respectively, while the change in cost of corn stalk led the economic indices to range from $0.68 million to $2.02 million, from 24% to 47%, and 3.5 to 6.5 years, respectively. The sensitivity analysis is geared towards determining how diverse values of an independent variable will impact a dependent variable given a set of assumptions and ultimately to determine the profitability of the proposed project.

11. Challenges and Prospects

As earlier stated, the briquetting technology is new in African nations, but advanced in Asia, America, and Europe. In such advanced nations, successes have been recorded in the production and utilization of briquettes, but the same cannot be said in most developing countries including Africa. The expansion of densification of biomass basically depends on three factors, which include residue availability, adequate technologies, and the market for briquettes [190].

For countries in the developing world, residue availability does not present a problem, however the optimization of the chemical and mechanical treatments needed for most of the innumerable feedstocks remains a challenge. With reference to the rural communities where power is hardly enough, an appropriate means of pre-processing will be the type that will require minimum energy input. Most technologies that produce high-quality briquettes, as reviewed, are expensive and requiring high energy input. Production of briquettes on a large scale will require significant capital investment. This presents an obstacle to further expand biomass densification. To attract more investment in areas that lacks adequate financial capacity and high energy input, efforts should be geared towards the development of more user-friendly and cost and energy effective technologies at various scales. Finally, the market for briquette and their extensive utilization as substitutes to conventional biomass (fuelwood) and fossil fuel exists. However, to bring its full potential to bear, the challenges presented above should be addressed.

12. Summary and Conclusion

The world today is experiencing a rise in population growth and this also comes with increasing energy demand. Records have shown that there is a lot of pressure on fossil fuel, which is diminishing at a fast rate and whose growing utilization has consequential effects leading to climate change. To forestall future energy crisis and mitigate climate change, it has become imperative to source for alternative energy supply. Biomass presents an opportunity to reduce our dependence on fossil fuels. The challenge with biomass is that it is usually low in bulk and energy density, which poses a problem of handling, transportation, and storage. This problem is however curbed by briquetting, which also improves the biomass density, burn time, and the calorific value. This paper reviewed studies on technical and economic aspects of biomass briquetting. The review revealed that type of biomass material (feedstock), pre-processing, briquetting process parameter, and technology determine the quality of briquettes. Briquetting can be done with a low-pressure or high-pressure technique. However, the technology utilizing high compaction pressure and temperature is significant in producing more durable and high energy density briquettes. Currently, the machines available for briquetting include the screw press extruder, roller press, and the piston press (mechanical or hydraulic). Additionally, successful briquetting requires financing and it is necessary to evaluate its economic viability since the products are meant to serve as alternatives to existing fuels. This evaluation is achieved by analyzing the various costs involved including economic indicators such as NPV, PBP, IRR, and BCR. In the end, it is in the overall interest of both producer and the end users for the cost of briquettes to be cheaper and more efficient than the cost of the fuels they are likely to substitute. Biomass briquettes can be used in both rural and urban areas for domestic heating applications. They can also be utilized in industrial applications for heating and energy production such as gasification. Since high-pressure technology and supporting conditions are not easily available in many local communities especially in the developing countries, more efforts should be directed towards improving the quality of fuel briquettes produced at lower pressures and temperature. Appropriate briquetting machine capable of producing such quality briquettes and at low costs suitable for local communities needs to be developed.

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Abbreviations

°C	Degree centigrade
%	Percentage
≤	Less-than or equal to
≥	Greater-than or equal to
BCR	Benefit Cost Ratio
CO_2	Carbon dioxide
g/cm^3	Gram per centimetre cube
GHG	Greenhouse gases
IRR	Internal Rate of Return
ISO	International Organization of Standards
Kg/cm^2	Kilogram per centimetre squared
Kg/h	Kilogram per hour
Kg/m^3	Kilogram per meter cube
KJ/kg	Kilojoules per kilogram
KWh/ton	Kilowatt hour per tonne
MJ/kg	Megajoules per kilogram
MPa	Megapascal
mm	Millimetre
MSP	Minimum selling price
N	Netwon
NPV	Net Present Value (NPV)
NOx	Nitrogen oxide
ODMT	Oven-dry metric ton
PBP	Payback Period
POS	Palm oil shell
ROI	Return on investment
RSK	Rubber seed kernel
SEM	Scanning electron microscope
SO_2	Sulfur dioxide
SOx	Sulfur oxide
TEM	Transmission electron microscope
ton/h	Tonne per hour
TWCB	Torrefied-woodchips briquettes
USA	United States of America
VMW	Vegetable market waste
w.b	Wet basis
WCB	Woodchips briquettes
WU	Washington University
$	Dollars (USA)

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