Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-023-04387-3

REVIEW ARTICLE

# A comprehensive review on the technical aspects of biomass briquetting

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Received: 11 February 2023 / Revised: 10 May 2023 / Accepted: 22 May 2023

**Abstract**

Biomass briquetting is gradually emerging as a means of sustainable energy production. The interest in briquetting has been occasioned by the continuous rise in the cost of energy coupled with the need to harness efficient and affordable alternatives. Briquettes are produced through various means, ranging from a simple low-pressured technique to a high-pressured technique. This, including the large-scale availability of biomass materials in many regions of the world, has made the process practicable and affordable. The technology has gained acceptance across the scientific community as it is a means of attaining a circular and green economy especially as it helps to curtail deforestation. Briquetting has advanced and now incorporates the blending of biomass with animal and municipal wastes such as dung, microalgae, plastics, sludge, and food waste. This paper reviewed recent literature spanning over a decade on the technical aspects of biomass briquetting to establish the current state of research. It contains a brief on renewable energy with a focus on biomass energy, as well as the impact of solid fuels on households and the environment. It reviewed briquettes and briquetting technology by highlighting key processes and quality parameters. The paper also reports the economic aspects of various briquetting technology to assess their viability and also reports the combustion process to evaluate the extent of toxic gas emissions and their impact on coal-based power plants. To this end, an overview of recent studies was made followed by a highlight of recent advancements in briquetting technology.

**Keywords** Energy · Solid fuel · Co-densification · Biomass blending · Briquette

## 1 Introduction

Energy security is a prerequisite to sustainable and socio-economic development [1–3]. Over the years, there has been a significant change in the global energy landscape [4], especially as fossil fuel reserves are gradually depleting due to the rise in population and overdependence [5]. Through this, energy demand has significantly outweighed the available energy resources and has compelled people to seek alternative sources [6, 7]. In most parts of developing countries where agricultural wastes are in abundance, people have resorted to directly combusting raw biomass as fuels to meet up with their energy needs. While this has served as an alternative form of energy, it has reportedly caused a lot of health disorders through the emission of household air pollution (HAP), especially Particulate Matter ($PM_{25}$) [8]. Currently, about 2.8 billion people globally are exposed to HAP through the use of loosed biomass and other solid fuels in meeting their domestic energy requirements [9]. This is intense in Africa as over 82% of the population uses solid fuels, with only 11% making use of

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clean fuels [10]. In addition to the health effect of raw biomass, biomass generally has a low density which makes it difficult for handling, transport, and storage for bio-refining or other future applications [11]. With this, the quantity of biomass keeps increasing but is poorly managed. Thus, it is considered waste and allowed to decompose in situ or be indiscriminately burned, thereby contributing to greenhouse gas emissions and other environmental pollution [12]. Despite having enormous biomass resources in many regions of the world, people still cut down trees for charcoal production or fuelwood extraction. This has contributed greatly to deforestation and climate change. Based on this, it becomes pertinent to adopt efficient valorization techniques such as briquetting to treat the growing waste and provide a cleaner source of energy better than the conventional burning of loosed biomass, coal, charcoal, and fuelwood [13]. Briquetting improves the energy content, density, shape, and size uniformity of biomass material, thereby making it efficient and easy for use, transportation, and storage.

In line with the aforementioned, the use of lignocellulosic biomass as an alternative energy source is gaining popularity and becoming a more promising option. Although, biomass can be processed into a solid, liquid, and gaseous form of energy using various approaches (physical, chemical, thermochemical, or biochemical), transforming it into densified fuels such as briquettes and pellets is considered one of the most easiest and promising methods [14, 15]. This is because lignocellulosic biomass is composed of complex molecular structures in the form of lignin, cellulose, hemicellulose, and other extractives which makes it a bit complex to be chemically, thermochemically, or biochemically transformed into energy [16]. Hence, densifying into briquettes is considered more effective [16]. Apart from being a renewable energy source that has the potential of curtailing deforestation, briquettes are cost-effective, thus, saving household energy costs [17].

It is worth noting that adopting briquetting technology has the potential of improving national and domestic income and minimizing household expenditure through the provision of employment opportunities to youths and the elderly who will venture into the production and sale of briquettes [18]. Furthermore, the time expended on fuelwood collection, especially in rural and peri-urban parts of the world which has kept a lot of children especially young girls out of school will be drastically reduced. In the review of [19], densified pellets and briquettes reportedly have the potential to completely curtail the demand and use of natural gas and also reduce the demand for Liquefied Petroleum Gas (LPG) by 73% in both residential and industrial scale with an estimated mitigation potential of 17.3 Mt CO2-eq/yr. Going further, biomass briquette has the potential to replace fossils and curtail environmental pollution [14], because it is a naturally occurring and renewable source of energy [20]. The technology has recently been hailed as one of the most potential solutions to deforestation, energy scarcity, and climate change [21].

The use of densified biomass as energy has increased significantly in recent years. [22] reported that from 2000 to 2015, it increases from 2 to 37 million tons as a result of the increase in global energy demand. Overall, according to the literature, briquetting research is higher in countries like China, Brazil, the USA, Poland, and India [5, 23]. The use of briquettes as an energy source has gained global recognition as it is used in many parts of the world. However, Sub-Saharan Africa, despite being rich in biomass is still having low adoption and use of briquettes possibly due to a lack of technology for mass production. On average, it cost about USD50,000 to set up a standard briquetting factory of 15 t per month capacity [12]. In China, there has been rapid growth in the production of densified fuels since 2010, with a six-fold increase from 3 million tons in 2010 to 18 million tons in 2018 [24]. While the technology keeps growing, there are setbacks in terms of the availability of national standards to ensure the quality of the briquettes in many parts of the world [12]. This has been one of the challenges limiting the progress of the briquettes industry.

The reviewed articles were sourced from Scopus, Google Scholar, and Science Direct databases to ensure a collection of purely indexed articles. Keywords such as biomass briquetting, briquette production, and densification of biomass feedstocks were used in searching the articles using a filter date of 2010 to 2022. Though there was a lot of literature, it was ensured that only articles dealing with experimental and review studies on briquette production were considered. Hence, the literature was screened based on titles and abstracts, and about 300 articles were downloaded. The review methodology was based on exhaustive literature analysis keeping in view briquette production from biomass materials. The observed gaps from the reviewed articles have been highlighted accordingly, followed by recommended pathways for future investigation.

Several studies have broadly reviewed different aspects of briquetting, including briquette binders and quality parameters [23], technical and economic aspects [6], production, marketing and use [18], binders and briquetting mechanism [25], and empirical studies on biomass briquette production [26]. However, the following gaps have been observed from the body of literature: Most of the reported studies are within the medium to the high-pressure range, with very limited studies on low-pressure briquetting. In addition, information on cold press binder-less briquetting is nearly unavailable [5]. This is largely perceived as impossible despite having a lot of potential biomass materials that need to be evaluated. In the same vein, there is a need to evaluate more biomass materials as binders. This is important as most of the conventional binders are starch-based and inorganic which are expensive.

As the technology is advocated to be a potential replacement of fossil and conventional solid fuels, none of the reported or reviewed literature tried correlating the production process with those of charcoal and fuelwood to know in quantity and energy value, the more efficient and sustainable option, and also the extent to which deforestation could be curtailed if adopted. Several studies focus more on feedstock types, proportion, and mix with less focus on the appropriate binding material and binder ratio. In the same vein, only a few studies considered optimizing the process and quality parameters. By not optimizing the experimental and production phase, the technology may be perceived as uneconomical and inefficient to practice.

While the technology is believed to be a climate change mitigation strategy, studies have not empirically linked briquetting to climate change. Thus, there is no adequate information on the overall life-cycle assessment of the process, especially at low to medium-pressure levels [27]. This will not only give insight into the environmental and climate impact but would assess the time and energy requirement as compared to the conventional traditional fuels (fuelwood and charcoal) [27]. According to the report of [5], briquetting research is more prominent in countries like China, Russia, America, etc. This shows that it is still lacking in developing countries, especially in Africa [28]. Hence, there is a need to broaden research in this area as developing countries produce a lot of agricultural waste and are still largely dependent on fossils and solid fuels (fuelwood and charcoal).

In addition to the detailed gaps extracted from the broad literature of briquetting technology, which would serve as a guide for future studies, another novelty of this review is that it brings together the recent advancements in briquetting technology such as the blending of biomass with non-biomass materials like plastics, coal and sludge, and also the use of microalgae as a potential binder. Thus, this paper aims at bringing together the recent advances in briquetting technology with a focus on key processes and quality parameters while focusing on literature spanning over the last decade to establish the current state of knowledge. The major benefits of biomass briquetting are highlighted in Fig. 1.

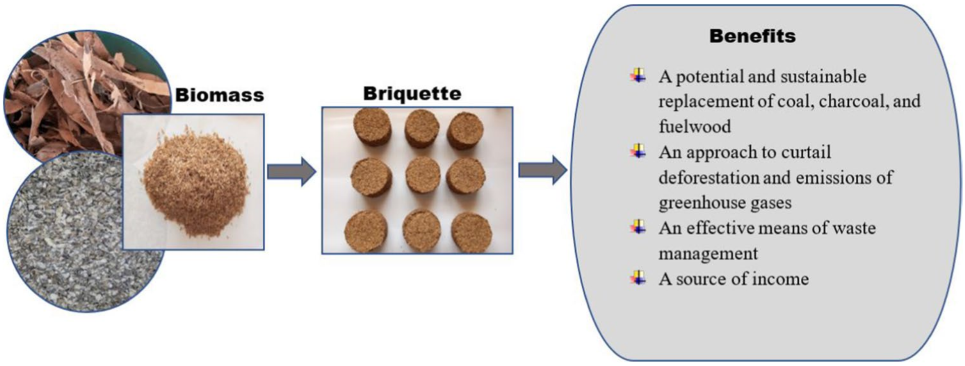
## 2 Solid fuels (fuelwood and charcoal)

The global increase in population coupled with the increased cost of energy has compelled many households, especially in the rural and peri-urban parts of developing countries to use solid fuels, especially fuelwood and charcoal [29–31]. This, among other factors, has negatively impacted the global climate [32], especially as forest covers which are major carbon sinks are depleting rapidly.

Currently, about 3 billion people globally use different forms of solid fuels in meeting their primary energy needs [33]. Out of these, about 2.6 billion people mostly belonging to poor and rural backgrounds (90%) rely solely on fuelwood and charcoal [34]. Through this, approximately 1 Gt of $CO_2$ equivalent is generated annually from the combustion of fuelwood for cooking [35]. Overall, cooking contributes about 5% of global greenhouse gas emissions [36], with 1.9–2.3% of the global $CO_2$ emissions coming from the use of fuelwood in traditional cookstoves [35]. This has resulted in a significant rise in household air pollution which is a critical problem in developing countries [37]. The stated emissions that emanate from indoor cooking through the use of open fires or traditional cookstoves and fuels are majorly in the form of black carbon and particulate matter resulting in millions of premature deaths and health disorders per annum [29, 38].

Going further, a series of detrimental impacts have been recorded in the use of solid fuels. Hence, the continuous or intense use of charcoal and fuelwood is considered unsafe and unsustainable [39], especially as it contributes enormously to deforestation and the health of its users. [40], added that prompt interventions and policies are pertinent in curtailing the use of solid fuels and household-based emissions towards improving the health and well-being of people. Thus, with the stated negative impacts, densified biomass (briquettes) is perceived as the best and most sustainable alternative to fuelwood and charcoal with improved socio-economic and environmental benefits [22, 27].

**Fig. 1** Benefits of biomass briquetting



To meet up with the targeted United Nations (UN) Sustainable Development Goal (SDG) 7 which focuses on the provision of clean, sustainable, and affordable energy for all [41], adequate intervention and outreach to rural and peri-urban households is pertinent. This could be in the form of the provision of clean cookstoves and fuels such as biomass briquettes as well as enlightening end users on the importance of switching from their conventional method to the use of processed biomass fuels [29, 34]. On this basis, [42] observed that switching from the use of charcoal to briquette has the potential of curtailing particulate matter PM and carbon monoxide (CO) emissions by 14% and 80%, respectively. However, this may vary with the type of material used in the production. For example, [43], observed that briquettes made from rice husk char emit a higher level of $CO_2$ (13.2–15.5%) compared to those of rice husk (11.5–14.3%). Though, the same study observed a higher level of CO and nitrogen oxides (NOx) emission in rice husk briquettes as compared to briquettes made from rice husk char. Therefore, it is important to have a comprehensive knowledge of the feedstock material as well as how its synthesis to energy could impact the environment.

## 3 Renewable energy

The use of renewable energy is gradually increasing across the globe. It increased by 3% in 2020 as a result of the decline recorded in the demand for other energy sources [44]. Renewable energy has the potential of supplying about two-thirds of the global energy demand, at the same time enhancing the mitigation of greenhouse gases, thus, enhancing the attainment of the targeted global surface temperature below 2 °C from now to 2050 [45].

Renewable energy is an energy source that does not deplete and can be replenished over a certain period. They are perceived as being environmentally benign with the potential of replacing fossil fuels [4, 46]. The transition from non-renewable to renewable energy sources is gradually progressing. In recent years, the G7 countries (Canada, France, Germany, Italy, Japan, the UK, and the USA) have recorded a significant shift from the use of non-renewable energy to renewable energy [47]. However, due to insufficient modern technologies, renewable energy sources are still poorly harnessed in most developing countries. Thus, to attain a swift transition, renewable energy must be made affordable and available to all [46]. In terms of global carbon neutrality, there has been remarkable progress in the transition process [3]. It was observed by [3], that the development of renewable energy sectors will help alleviate global energy poverty. Thus, more countries are required to subscribe to various international consensus that recommends using low-carbon energy through the formulation of policies and measures that will enhance the development of the renewable energy industry [3].

### 3.1 Biomass energy

Biomass is non-fossilized and biodegradable biological material derived from living organisms, animals, and plants [23]. They are typically composed of lignin, cellulose, hemicelluloses, and extractives like fats, resins, and ash [6]. Thus, they can be classified as lignocellulosic (fibrous and non-starchy) and non-lignocellulosic (non-fibrous and starchy) [48]. Biomass can be transformed into energy through direct combustion in their loosed or densified forms (briquettes/pellets) or indirectly into bio-fuels (biogas, biodiesel, bioethanol, etc.) through anaerobic digestion and pyrolysis [49].

In recent years, biomass energy has shown promising potential that made it one of the major and affordable renewable energy sources [22]. Globally, biomass accounts for almost 80% of the entire renewable energy and contributes about 10% of total energy supplies [37]. Its environmental benefits coupled with its potential to replace the use of fossil fuels have made it attract a lot of research interest [50]. Now that global societies are shifting towards a bioeconomy, biomass is becoming more valuable and demanding [51]. On that basis, it is considered one of the most important renewable energy sources in the world [23].

While the use of biomass for energy generation has been recommended, its low density makes it difficult to be used, stored, and transported efficiently. Therefore, densifying into briquettes and pellets is recommended [23, 52]. With densified biomass (briquettes), over-reliance on solid fuels (fuelwood and charcoal) especially in developing countries will reduce. Consequently, the impacts on users in terms of household air pollution (HAP), cost, and time expended in sourcing and cooking would be drastically minimized. Deforestation as the major act yielding firewood and charcoal would equally be curtailed.

## 4 Biomass briquetting technology

Briquetting is a form of biomass densification that involves the mixing and compaction of feedstocks with the aid of pressure [22]. It enhances the density of loosed biomass into a more compact and uniformly stable product called a briquette [53]. Briquettes are solid biofuels produced through a controlled densification process under specified process variables [54].

In recent years, briquetting technology is gaining global popularity especially as other forms of cooking energy are becoming more expensive and unavailable in some parts of the world. In line with this, research interest in briquetting has equally increased. It has gone beyond the use of biomass and now advanced to the use of industrial waste such as steel production waste [55, 56], and mineral deposits such as coal [57, 58] and limestone [59]. Though, applied in various forms and not purely cooking.

## 4.1 Process of briquetting

A briquetting process is an agglomeration approach that involves transforming loosed solid biomass into a compact end product following a series of steps as highlighted in Fig. 2 and elaborated below.

a. Biomass collection

The collection of biomass or raw materials is the first step in briquetting. This includes the collection of both biomass fibers and binding material. At this stage, it is encouraged to use biomass waste materials that are largely available in an environment to have a sustainable production and also enhance environmental waste management. This may include plant and animal waste which can be found both on land and in water. However, with recent advances in briquetting, most of the biomass reported in the literature are non-woody lignocellulosic biomass. This is to further control deforestation and improve carbon capture. In addition to using lignocellulosic biomass, some recent studies are now evaluating sludge, microalgae, municipal solid wastes (MSW), and plastics in briquette production.

b. Biomass feedstock characterization

The characterization phase usually involves the determination of the physical and thermochemical properties of the feedstock. Parameters such as moisture content, bulk density, particle size distribution, lignocellulosic composition, gross calorific value, and proximate and elemental composition are determined following a standard laboratory method. The results of these analyses usually give an insight into the feedstock's densification potential as well as an estimate of the quality of the briquettes that will be produced from the feedstock [18]. For example, the level of ash from the proximate analysis indicates the slagging behaviours of the feedstock during combustion, and the lower it is, the better the heating value [16]. Based on this, an ash content of less than 4% is generally preferred for briquetting as it reduces slagging potential [14]. For Research and Development (R and D) use, it is important to characterize the collected biomass as received to know their properties and potential performance during and after densification. This will help in subsequent stages, especially in selecting a pre-treatment or pre-processing option. However, if not for scientific investigation, this stage (characterization) may be skipped.

c. Pretreatment

Pretreatment is the various modifications made to feedstocks to activate the energy and binding elements to improve the resulting fuel quality and efficiency. This phase of briquetting becomes necessary as biomass materials have a diversity of properties that are in principle beneficial and in certain applications disadvantageous [51]. Pretreating a feedstock enhances its particle grade distribution and by extension saves the cost of energy incurred in milling or size reduction [16]. Furthermore, in briquetting, the smaller particle sizes yield higher mixing and binding uniformity, which enhances the overall physico-mechanical and thermal properties of the briquettes [60]. The two most reported pre-treatment methods in briquetting are physical (screening, milling, drying, etc.) and thermal (torrefaction,

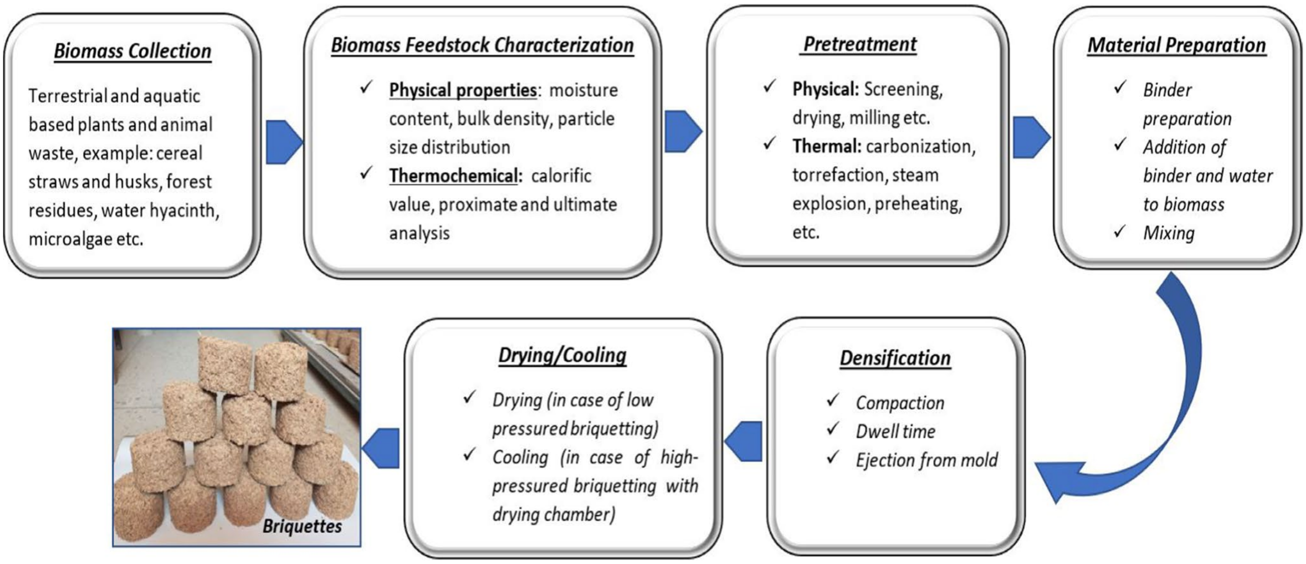


**Fig. 2** Process of briquetting

carbonization, steam explosion, etc.). The selection of a certain method depends on the type of feedstock, its properties, and the method of densification to be applied. Irrespective of the applied method, studies have shown that pre-treated feedstocks are generally more efficient than raw biomass. For example, in recent findings, fuels produced from torrefied biomass were found to have a better energy density and storability, and significantly improved corrosion behavior through a reduction of Cl concentrations up to 90% than those made from raw biomass [51].

d. Material preparation

The material preparation phase is a very essential phase of briquetting. In this phase, the binding material is gelatinized and mixed with the required quantity of biomass and water. The matrix composition depends on the type and nature of materials involved and the potential quality of the briquette required. Generally, the higher the applied pressure the lower the quantity of binder required and vice versa. However, the rule of thumb remains "The lower the binder the better the combustion performance'', because most binders contain emissive substances. Mixing can be done manually or mechanically using mixers. In both approaches, mixing continues until the biomass and binder are homogenized completely.

e. Densification

Densification involves compressing the mixed materials into a compact form. Different machines are employed in this stage, ranging from simple hand presses, such as plungers to mechanically driven hydraulic presses and extruders. [11] in their review have reported the various feedstock densification systems, where hydraulic, mechanical, or roller presses are reportedly the most used briquetting machines. In this phase, the mixed materials are fed into a mold and subjected to compression for a certain dwelling period.

f. Drying/cooling

Immediately after ejection from the mold, the briquettes are usually dried for a certain period depending on the drying temperature and medium. Generally, briquettes are dried for a few hours to days in an oven, to days or weeks under the sun. In some cases, briquettes produced by the high-pressured technique are usually dried in a chamber incorporated into the machine before ejection. In such cases, the briquettes are ejected at high temperatures from the mold and must be cooled for a certain period before evaluation or use. However, cooling also applies to some low-pressured techniques where the briquettes are dried at a very high temperature. Thus, must be kept at room temperature to cool down and relax for some time before evaluation or use.

## 4.2 Briquetting process parameters

The process parameters are the various variables used in the production process. As reported by [6], they include compression conditions (temperature, pressure, dwell time) and feedstock properties (moisture content, particle size, shape, and feedstock composition). While these parameters are impacting the mechanical strength (compressive strength, durability, drop strength, and water resistance index) and other properties of the briquettes, it is worth noting that each parameter impacts the process differently and the impact may not necessarily be significant when considered alone, until it is combined with one or more other parameter. On this basis, it is important to carefully select the parameters and set out good combination criteria that would yield good quality products [61].

### 4.2.1 Impact of briquetting temperature on the mechanical strength of briquettes

Briquetting temperature is the temperature at which feedstocks are densified into briquettes. According to [49], temperature is the most important parameter that determines the performance of briquettes. Briquettes could be produced at room temperature, moderate, or high temperatures, or simply at low and high temperatures as reported in some studies. Each temperature type impacts the briquette's mechanical strength differently. Briquetting above room temperature is achieved with mechanically or electrically driven machines that have a heating unit. While it is largely believed that briquetting at high temperatures aids in melting lignin which serves as a natural binder that improves the density and mechanical strength of briquettes, [62] believed that the temperature must not go beyond 100 ˚C as doing so reduces the compressive strength of briquettes as a result of intense moisture evaporation which transforms the briquettes into a brittle form. However, [49] observed a temperature of 110 ˚C as being the optimum, whereas in the review of [26], 120 ℃ is the most reported briquetting temperature. In the study of [60], the compressive strength of briquettes was found to be directly proportional to temperature. As such, the maximum compressive strength was achieved at the highest temperature range of 90 to 95 ˚C. Similarly, [63] varied the temperature from 90 to 120 ˚C, and observed that an increase in temperature increased the water absorption resistance of briquettes. Other briquetting temperatures evaluated within the high-level phase include 80 °C [69], 80–110℃ [70], 60–120 °C [71], 90 °C, and 120 °C [72], 120 °C [73], 100–150 °C [74], and 150 °C [75].

On the other hand, briquetting at low or room temperature is usually achieved with manual presses such as plungers or manual hydraulic piston presses as most of such machines are without a heating element. However, in cases where temperatures are required to be increased when using the stated machines, then the most reported approach is to preheat the feedstocks before densification, mix with hot water or heat the mixture in a microwave or oven as done by [49]. Most of the reported studies within the stated temperature range have indicated that the developed briquettes are generally of low mechanical strength. This includes the study of [64] where the briquettes were observed to have low-density values (0.24–0.37 g/cm3) and a relatively good drop strength of 79.18–99.9%. Similarly, [27] densified at room temperature and obtained a maximum compressive strength and durability of 2.54 kN and 91.9%, respectively. However, in a few instances such as [65], where despite compressing at ambient temperature (25 ˚C), a high value of compressive strength (305 MPa) was recorded due to the nature of the biomass (sawdust), high application load (60 kN) and pressure. Hence, this validates the fact that a single process parameter may not necessarily determine the overall strength of the resultant briquettes. Meanwhile, few studies have successfully produced briquettes at low-temperature levels such as 38 °C [66], and at room temperature [76, 77]. Although, [76], noted that densifying materials such as maize cobs at room temperature will not give briquettes with adequate compressive strength. Hence, it is worth knowing that briquetting temperature largely depends on the type of feedstock to be used.

With the advancement in research, a heating element or unit has been incorporated into the designs of briquetting machines. Some of these machines have been used by [66], and [67] to heat the piston die and feedstocks in the feeding unit during consolidation. Although briquettes densified at high temperatures have been reported to be more efficient in terms of density and stability, they are, however, uneconomical, energy-intensive, and emit gases [68]. [26] observed that briquetting at high temperatures of 120 ˚C and 130 ˚C or more should only be considered when densifying at room temperature fails. In the study conducted by [67], it was reported that high-temperature briquettes give better physical properties, while moderate-temperature briquettes give better combustion properties. On this note, it is important to determine the optimum temperature needed for a given process. This could be obtained from the experimental design and process optimization. Having an optimum temperature will not only save costs but would minimize negative environmental impact.

### 4.2.2 Impact of briquetting pressure on the mechanical strength of briquettes

The briquetting pressure is the measure of the total force applied per unit area of the mold during densification. Depending on the type of machine and compaction pressure, briquetting is classified into high, medium, and low-pressured [22]. [78], further elaborated the classes of pressure as low (5 MPa), medium (5–100 MPa), and high (100 MPa and above). However, the required pressure per densification depends on the feedstock type, moisture content, particle size, and shape [6]. This indicates that applying high pressure does not necessarily translates to having briquettes with the best performance [26]. Table 1 reports some briquetting pressure values used on various biomass.

a. Low and medium-pressure briquetting

This is the briquetting conducted with an applied pressure of ≤ 5 to 100 MPa. When densifying at low-pressure, a binding agent is required to bind the particles [6]. Briquetting at this pressure range is less costly and can easily be practiced as it does not involve the use of sophisticated machines. Hence, a simple hand press or a manual hydraulic press are commonly used. At low-pressure levels, mechanical strength is usually low, thus, as pressure increases, the strength also increases. This is as observed in several studies, including [64] where the shatter index increases as pressure increases from 5.1 to 15.3 MPa, though, briquetting at this pressure yields briquettes with low density and strength. Recent studies have shown that within a moderate pressure level, highly durable briquettes could be produced [6]. This includes the study of [76], where an impact resistance as high as 500% was recorded within a pressure level of 20 to 50 MPa. However, if the pressure is very low as in the study of [79] (100 Pa) where a very low compressive strength of 0.23 to 0.37 MPa was obtained, attaining good mechanical strength becomes difficult despite the influences of other parameters. This is because other process parameters are highly dependent on applied pressure. Unlike the high-pressured process that usually contains a heating chamber, briquettes made through the low-pressured technique need to dry for days or weeks before testing. Overall, most of the reported studies compressed within the medium pressure range (5–100 MPa) (Table 1).

b. High pressure briquetting

This is the process of densifying feedstocks at a pressure level ≥ 100 MPa. Contrary to low-pressure briquetting that requires external binding agents, high-pressure briquetting can activate and utilize natural binding elements such as lignin, starch, protein, and pectin [6, 80]. High-pressure briquetting is usually employed on a commercial scale and requires the use of more sophisticated machines such as extruders. Densification at this pressure is usually carried out within a pressure range of 100–150 MPa or higher in pellet mills, and within 100 – 200 MPa (and above) in roller press [80]. Other conventional high-pressure driven processes such as screw press, piston press, extrusion, or hydraulic piston press are also densified at 100 to ≥ 200 MPa [22].

**Table 1** Briquette process parameters and their impact on briquette quality

| Biomass type | Machine | Pressure (MPa) | Briquetting Pressure Type | Temp (℃) | Dwell Time | Compressive Strength (MPa) | Impact Resistance (%) | Water Resistance (%) | Durability (%) | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Maize cob and sawdust | Manual Hydraulic Press | 20—50 | Medium | RT | 10 s | 0.12—59.2 N/mm | 0—500 | - | - | [76] |
| Carbonized Banana Stalk and Corncob | Manual Hydraulic Press | 0.05 – 0.09 | Low | RT | 2 min | 43—96 kN/m$^2$ | 38.22–89.34 | 11 and 23 min | - | [82] |
| Sawdust | Hydraulic Press | 60 kN | Low | RT | - | 121–305 | 22.21–99.16 | - | - | [65] |
| Rice husk, maize cobs, palm kernel shell, and sawdust | Manual Hydraulic Press | 10, 20 and 30 | Medium | - | 10 s | - | 71.4—500 | 47.5—92.9 | - | [83] |
| Sawdust, leaf litter, rice husk | Compression testing machine | 150 | High | - | 20—30 s | - | 89 | 65.9 | - | [84] |
| Sawdust | Manual Hydraulic Press | 10—50 | Medium | RT | 10 s | 15.81—44.58 | - | - | - | [85] |
| Rice husk and bran | Hand Press | 4.2 | Low | RT | 10 s | 0.05—2.54 kN | - | - | 0—91.9 | [27] |
| Cassava rhizome waste | Hydraulic Press | 102, 153, & 204 | High | RT | 60 -120 s | 0.41—1.29 | - | - | 65.3—94.1 | [86] |
| Millet bran | Universal Material Testing Machine | 113—147 | High | 73—107 | 10 s | - | 94.12–99.19 | - | 63.48—92.9 | [70] |
| Corncobs and oil palm trunk bark | Manual Hydraulic Press | ≤7 | Medium | 28 | - | 10.26—22.33 | 98.16—99.20 | 86.20—93.20 | - | [77] |
| Olive mill waste | Thermal–mechanical press | 100, 125, and 150 | High | 38 | 15 min | 130—4581 kN | - | - | - | [66] |
| Sawdust | Hydraulic Press | 9, 12, and 15 | Medium | 100 -150 | 15–30 min | - | - | 23.81—84.62 | - | [74] |
| Carbonized corncob | Hand Press | 0.05—0.15 | Low | - | 120 s | 1.02—8.32 | - | - | - | [87] |
| Rice straw | Manual hydraulic Press | 13.8, 20.7, 27.6, 34.5, 41.4, and 48.3 | Medium | - | 40 s | - | 0—95.8 | - | - | [68] |
| Maize cob | Hydraulic Bench Press | 150, 200 and 250 | High | 20—80 | 20 s | 10—38 | 17.7—99.8 | - | - | [69] |
| Spent coffee grounds | Hydraulic Press | 120—160 | High | 60 | 3 s | 6.2—22.2 | - | - | - | [88] |
| Pre-treated wood fines and coal | Hydraulic Press | 28 | Medium | - | - | 0.86—4.0 | 150—1350 | 90.3—98.2 | - | [89] |
| Sugarcane bagasse and rice bran | Hydraulic Press | 8, 10 and 12 | Medium | 150 | 30 min | 50—122.4 | - | - | - | [75] |

*(a) RT = room temperature**,** (b) Values carrying S.I. units beside them are having units different from that of the heading, (c) several studies reported the durability in terms of impact resistance except for some few including the studies having values on durability column

The improved interparticle adhesion and mechanical interlocking of feedstocks achieved in high-pressure briquetting yields briquettes that are compact and uniformly stable with densities between 1200 and 1400 kgm$^{-3}$ [22, 81] and higher mechanical strengths. While it is observed that as pressure increases, the mechanical strength of briquettes also increases, [70] observed that the pressure must not go beyond 140 MPa, or else the strength will decrease. This may not be unconnected to the fact that high pressure develops solid bridges through the diffusion of molecules from the individual feedstock particles [80]. Table 1 shows briquette process parameters and their impact on briquette quality.

c. Optimum briquetting pressure

While various pressure levels have been reportedly applied in briquette production, it is important to know the optimum range required for improved performance. In addition to feedstock type, binder type and quality, attaining a durable and physico-thermally efficient briquette is a function of applying an optimum pressure. On this note, several studies have reported a range of optimum briquetting pressure for both high, medium, and low-pressure briquetting. [90] reported 6.86 and 9.81 MPa as optimum for homogeneously compacting sawdust and rice husk when using low to medium-pressure machines. In the same study, predicted values ranging from 7.10 to 9.75 MPa were reported for heterogeneous compaction. Similarly, [68]**,** observed that a medium compression pressure of 34.5 MPa is sufficient in producing briquettes with a stable density of > 600 kg/m$^3$, while [70] noted a pressure of 122.7 MPa as optimum in densifying millet bran using the high pressured machine. Generally, it can be inferred that there isn't a unified optimum pressure range for briquetting but rather an optimum range per material and machine type. On this note, while reference can be made to previously optimized experiments, it is worthwhile to always optimize the process parameters in a new experiment.

### 4.2.3 Impact of dwell time on the mechanical strength of briquettes

This is the consolidation period where the piston compresses the blended mixtures in a mold to prevent the spring-back effect of the compressed particles. Similar to other process parameters, the dwell time is also a function of the material type. While some materials can easily consolidate under low dwelling time, some may require a longer period. Generally, most of the reported studies used an average of 10 s–5 min dwell time. However, very few studies including Obi (2015) used a longer period. Some recently reported dwell time includes 10 s [27, 76, 83], 20–30 s [84], 30 s [91], 40 s [68], 1 min [79, 92], 1 min 40 s [93], 120 s [94], 3 min [95], 4 min [73], 5 min [17, 96], 7.5 min [63], and 30 min [67].

Generally, as dwell time increases, the mechanical strength of briquettes increases because there is an improved interparticle bonding. This was observed in several studies including [63], where the dwell time varied between 7.5 and 15 min, and the water resistance of the briquettes increases over time. Similarly, in the study of [97], dimensional stability was observed to have an increasing effect as dwell time increases between 45 and 90 s.

## 4.3 Briquetting feedstocks

Several feedstocks have so far been evaluated in briquette production. While some are still emerging, some have been used over time with various strengths and weaknesses. Some of the emerging feedstocks include; grass as reported in the review of [98], water hyacinth [99], palm kernel shell [61, 83], waste of oil palm bunch [81, 100], olive mill waste [66], citrus peel [79], bamboo powder [101], coffee by-products [53, 88], tea waste [102], *pterocarpus indicus* leaves [103]. Others include forest and wood residues such as shredded logging residues [71], *macauba epicarp* and pine wood waste [54], Ulin and Gelam wood residue [93], and sawdust [63, 65, 79].

Agricultural residues are so far the most reported feedstocks used in briquette production. This is because they are the most abundant and easily accessible forms of biomass [79]. Residues such as rice husk and rice bran [27, 75, 95, 106], maize cob [14, 83, 107], and sugarcane bagasse [14, 75] have been widely used in briquette production.

To effectively understand the suitability of a feedstock for briquetting, it is imperative to know its properties [22, 101], as its components such as lignin, cellulose, hemicellulose, and extractives give an insight into its suitability for densification [6]. However, some feedstocks not suitable for densification can be pre-treated to activate the embedded elements, thereby making them suitable. In addition to pre-treatment, such feedstocks can be co-densified with another to improve the resultant performance [26]. This is conducted by [108] using Corncob and Rice Husk, [106] using sawdust and rice husk, and [79] with citrus peel and rice husk, etc. By and large, the choice of feedstock should be largely focused on availability and sustainability [109].

### 4.3.1 Feedstock pre-treatment

When dealing with bioenergy conversions or generation, pre-treatment is a vital aspect applied to enhance the resultant characteristics as it yields bio-fuels that are instrumental in boosting the global bioeconomy [51]. In briquetting, feedstock pre-treatment is a very important aspect as it activates the embedded elements responsible for quality enhancement. Hence, it is generally recommended because it saves energy and yields high-quality briquettes [11, 22, 48]. However, depending on feedstock type and properties, some may not necessarily require pre-treatment. Based on this, characterization becomes important before selecting a pre-treatment method.

Several pre-treatment methods have been reported. They are mainly classified into physical, thermal, biological, and chemical. However, the physical and thermal methods are the most reported in briquette production as they are more promising [11]. The physical method includes screening, drying, grinding, and sieving while the thermal pre-treatment includes steam explosion, preheating, torrefaction, and carbonization. The choice of a particular method depends on the feedstock's natural characteristics and the availability of technology [26]. While thermal pre-treatment (carbonization and torrefaction) is one of the commonest, it is energy intensive as it requires heating in specially designed systems to an elevated temperature of 180 to 500 ◦C or more [26, 50]. Hence, it is important to carefully select a pre-treatment method while considering the overall targeted quality.

### 4.3.2 Influence of some feedstock properties on briquettes performance

a. Moisture content The feedstock moisture content is a vital parameter usually the first that needs to be determined before proceeding to further processing. The obtained value tells whether the collected feedstock requires drying before milling or densification as the case may be. Generally, moisture content ≤ 10% is sufficient and does not require drying [110]. Within the stated range, [70] noted a moisture content of 5.4% as optimum for densifying millet bran. In a different report, a level between 10 and 15% was recommended [18, 111]. However, under special conditions such as when densifying at room temperature, a feedstock with a moisture content of 12–20% (w.b.) is sufficient [80]. But if the value goes beyond 20% (w.b.), it is practically impossible to proceed [80]. While many studies tend to neglect this phase, it is important to note that this initial moisture content affects the briquette's performance.

It is worth knowing that feedstock moisture content differs from the briquette's moisture content. Although they both have similar permissible ranges, the former is usually preferable at ≤ 10 to ease milling and densification, while the latter can go above but still preferable when kept below 10%. According to [27], optimal briquettes' moisture content should lie between 5 and 10% wb, to maintain its physical properties. In a different report by [22], a range between 5 and 15% was recommended. While [107] maintained a range of 8–10%, [77] also reported 9.24–10.24%.

b. Carbon content Carbon content also referred to as fixed carbon or organic carbon is an essential ultimate parameter that affects the performance of briquettes, especially the thermal performance. The more the carbon content of a feedstock, the more its calorific value and vice versa [112]. In the study of [92] which focused on physical properties, carbon content was found to be inversely proportional to the briquette's bulk and relaxed densities, water, and abrasion resistance. It was hence established that a high concentration of carbon yields briquettes with low water resistance, durability, and compaction ratio, whereas low concentration results in a correspondingly high density and relaxation ratio. This indicates that higher carbon content enhances thermal and combustion performances but reduces the physical quality performance.

c. Particle sizes Feedstock particle size is an essential factor that affects the strength and durability of briquettes and pellets [113]. Generally, the finer the size, the better the durability [80], because feedstocks with small particle sizes are easily compressed and give a well-densified briquette. This has been validated in the study of [82], where the mechanical strength of briquettes made from carbonized banana stalk and corncob was observed to increase as the particle size decreases. However, contrary to most studies that suggested the use of small particle sizes (< 1 mm) for briquetting, [92] observed that briquettes made from feedstocks with particle sizes between 1 and 2 mm have better performance compared to those of particle sizes < 1 mm. In a different view, [68] reported that a well-stable density and durable briquettes are obtained from feedstock particles of < 2 mm or a combination of particles with larger sizes (10–150 mm) and those of smaller sizes (< 10 mm). By and large, several authors believed that feedstocks with more percentage of fine particles yield briquettes with better strength and durability. [11] added that finer particles are advantageous because they contain a large number of surface areas which improves bonding and surface energy.

## 4.4 Briquetting binders

Binders are materials that bind particles together and prevent them from disintegrating [99]. They are essential inputs in briquette production. Hence, the quality of the briquette depends largely on the quality of the binding material [25, 99]. The binders used in briquetting are mainly divided into three, viz: organic binders, inorganic binders, and compound binders [25]. While organic binders are good in interparticle adhesion and combustion performance, they have poor mechanical strength and thermal stability [25, 60]. Despite their limitations, organic binders are gaining popularity because they are widely available, affordable, possess good calorific value, and have low ignition temperatures [23]. There are four types of organic binders, viz: biomass (agricultural residues, animal and forestry waste, etc.), petroleum bitumen and tar pitch (tar residues, coal tar pitch, etc.), polymer-based and lignosulphonate binders (resins, polyvinyl, and starch) [23]. One of the organic binders that are recently gaining popularity and emerging as a potential binder in briquette production is microalgae. These are microorganisms with photosynthetic and free-floating features with the ability to adapt to extreme ecological conditions [114]. The use of microalgae as binders in briquette production has been reported in several studies and reviews, including the review of [5] and [115] where it was reported to have exhibited good binding performance and combustion efficiency in several studies. Thus, was recommended for further investigation with other biomass materials and commercial binders. [116] evaluated microalgae alongside treated biosolids and cassava starch as briquettes binders, and observed that the briquettes bonded with microalgae were found to be more durable and energy-efficient than those made of cassava starch and treated biosolids. Similarly, [117] used microalgae as a binder in densifying fuelwood residues and realized that due to its micro-spherical shape, rolling friction is intensified and was observed to minimize energy consumption during compression. This was in addition to the improved bulk density and mechanical durability that was observed in the produced briquettes. Another novel binder currently under study is sludge from wastewater treatment plants and agro-processing industries such as palm oil mills. [118] evaluated palm oil sludge as a binder in the production of briquettes from cotton flocks. It was observed that the binder bonded well, as a density of 816 kg/m3 and a shatter index of 99.5% was obtained. Similarly, [119] also obtained durable and thermally efficient briquettes from rice milling by-products using palm oil sludge as a binder. Inorganic binders have excellent thermal properties but with poor ash content, low fixed carbon content, and combustion efficiency [25]. Briquettes made with inorganic binders possess higher physico-mechanical properties (compaction ratio, compressive strength, and hydrophobic nature) compared to those made with organic binders [6]. Some common examples of inorganic binders are clay, cement, lime, plaster, and sodium silicate [6].

Combining two or more binders belonging to both the organic and inorganic groups gives the compound binder [6]. This form of binder performs better than others as they combine the properties of two or more binders [25].

The selection of a binding material depends largely on some factors which include the expected or desired binding strength, availability, cost, sustainability, and level of emission as well as the overall effect on thermal and combustion performance [23]. While these factors may differ from place to place and the overall target of the product, the following are some of the binders reported in briquette production; cassava starch [42, 67, 90, 95, 107, 120, 121], banana waste pulp [122], paper waste pulp [64, 123], sawdust [68], corn starch [66], starch paste [92, 106], cassava peel [95], molasses [124], maize straw treated with sodium hydroxide [60], bentonite [57], etc.

Lignin, which is a natural binder in plant materials is gradually emerging as a popular binder due to its phenolic nature [125]. Its presence in most agricultural residues made it possible to densify feedstocks without additional adhesive or binder. Based on this, [86] successfully densified cassava rhizome waste at high pressure without a binder. However, it is important to note that this is most feasible in high-pressure and temperature briquetting. In low-pressure briquetting, the use of a binder is inevitable [6, 90]. However, with certain high moisture feedstocks like water hyacinth, it is possible to obtain good quality briquette at low pressure without a binder [99]. Furthermore, at medium pressure, it is also possible to densify without a binder. This was proven in the studies of [76, 104] (Fig. 5b) where maize cob and sawdust were densified at variable medium pressure of 20 to 50 MPa without a binder.

However, while feedstocks are being densified without a binder, it is evident that most binder-less briquettes have a short shelf life and cannot be easily transported [25]. As studies are now advancing to low or zero binders, some studies including [81] used as much as 60% binder. Overall, not using a binder depends on the type of feedstock, particle sizes, and properties, as some are higher in lignin than others. One major property required of binders is that they should be combustible, however, in the absence of such binders, a non-combustible binder may be used in small quantities [22]. While several binders have been used in briquetting, starch-based (cassava starch and flour, corn starch, maize flour, wheat flour, rice flour, wheat starch, potato starch, etc.) binders are the most ideal and common type of binder [25]. They are however expensive with poor water resistance [25]. Hence, to have an overall cost-effective briquette, it is essential to select binders that are less costly and readily available [122]. To curb the issue of cost, [124] used molasses (a by-product of sugarcane processing) blended with crude glycerol (a by-product of biodiesel production processes) as a binder. In another approach by [60], maize straw treated with sodium hydroxide was used as a binder. Locust bean pulp is also recently evaluated as a potential binder. Figure 3a shows sample briquettes of rice husk bonded with locust bean pulp.

#### 4.4.1 Optimum binder content for briquette production

Unlike high-pressure briquetting where very low or no binding material is required, in low-pressure densification,

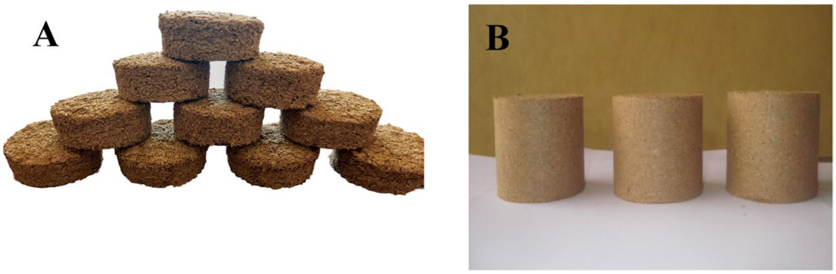


**Fig. 3** Briquettes. (**a**) briquette of rice husk and locust bean pulp binder (**b**) sawdust briquette without a binder [104]

binders are required. However, the optimum content required depends on the feedstock properties, application pressure, pre-treatment, and method of briquetting. In a study conducted by [43], it was discovered that glycerin in the proportion of 5–10% is optimum in the production of fuel briquette with good thermal and emission performance. [27] found that a binder content of 10% is optimum in attaining durable briquettes but a content of 15% may be used for improved strength. This is similar to the study of [77] where 10% wastepaper pulp was used, and [66] who observed a 15% corn starch binder as optimum that yielded briquettes with good mechanical properties. However, [25] noted that when using starch as a binder, a content within 4–8% is optimum for briquetting. Contrary to all the aforementioned, the ISO standard recommended < 4 wt% of binder in all forms of briquette production [22]. While all the aforementioned studies fall within ≤ 4–15%, [126] reported a higher value of 45.00% wb as optimum with molasse as binder following response surface methodology (RSM). The diverse range of reported values is an indication that binder content depends on several factors. Hence, there is no fixed proportion. However, it is largely observed that binders are kept to the barest minimum in briquetting to save cost and enhance thermal performance.

## 4.5 Briquettes quality parameters

Briquette quality parameters are the performance indicators that show how good a briquette is in terms of strength and durability. To assess the quality, the following parameters are evaluated based on certain standards: density, impact or shatter resistance, abrasion resistance (mechanical durability), compressive strength, and water absorption resistance [6]. The quality parameters are classified into physical (density), mechanical (compressive and tensile strength), and thermal properties (proximate parameters, burning rate, heating value, etc.).

### 4.5.1 Briquette density

The density is an important quality parameter as it serves as an indicator of other parameters. Usually, briquettes with higher densities show better performance than those of lower densities. The density of briquettes is expressed in terms of compressed density or relaxed density. The compressed density is the density computed immediately after ejection from the mold while the relaxed density is the density measured after a certain period when the briquette has dried and is ready for analysis or use [23]. [127], measured the relaxed density after 21 days, [28] measured it after 27 days while [77, 128, 129], and [83] measured it after 30 days. The density is computed as the mass of the briquette per unit volume.

### 4.5.2 Impact resistance

An impact resistance test also called shatter resistance test or drop test, simulates the forces experienced in the course of discharging or offloading the briquettes from trucks onto the ground [83]**.** Briquette's impact resistance test is regarded as the overall best diagnostic of briquette quality [130]. It is determined by dropping the samples from a certain height usually 1–2 m unto a concrete surface or a steel plate several times (Fig. 4). After the drop, the weight loss is determined using Eq. 1 and the impact resistance is estimated using Eq. 2.

[65, 77], and [105] determined the impact resistance following ASTM D440-86, which involves dropping the briquettes two to three times from a height of 2 m, and after each drop, the sample was passed through a sieve size of 2.36 mm to retain the unshattered mass while the Impact Resistance Index (IRI) was estimated using Eq. 1. In a different approach using the same standard, [83] used five drops instead of two from a height of 2 m and used Eq. 3 for IRI estimation. However, [69] and [119] tested the impact resistance by dropping the briquettes four times from a height of 1.85 m onto a metal plate, whereas the impact resistance was estimated as the percentage residual weight after the 4th drop.

While the number of drops differs in various studies, [130] believed that averaging a range of 3–6 drops from a height of 2 m is sufficient to give a good estimate. In general, briquettes produced for industrial or domestic use should have a minimum IRI of 50% [130].

$$IRI(\%) = \frac{B_z}{B} \times 100 \tag{1}$$

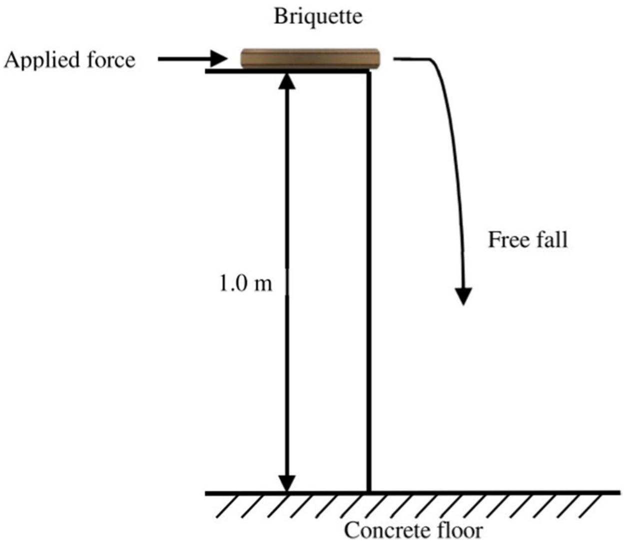


**Fig. 4** Schematic diagram of drop test [91]; Copyright, https://creativecommons.org/licenses/by/4.0/

$$\text{Impact resistance } (\%) = 100\% - \text{weight loss } (\%) \quad (2)$$

$$IRI = \frac{N}{n} \times 100 \quad (3)$$

where $B_z$ is the weight of the briquette after shattering and $B$ is the weight before shattering, $N$ is the number of drops and $n$ is the number of pieces that weighed 5% or more of the initial weight of the briquette after N drops.

#### 4.5.3 Compressive strength

Compressive strength is the maximum crushing force that briquettes can withstand before failure (cracking or breaking) [26]. The parameter is very important as it simulates the maximum compressive load a briquette can withstand during transportation, handling, and storage [23]. It is worth knowing that the compressive strength of briquettes largely depends on the properties of the biomass such as particle size distribution as well as the physical structure and resistance between the particles bond in the briquette [131]. The test involves placing the briquette sample between two horizontal plates (Fig. 5a) and compressing it at a constant rate until it breaks. In addition to compressive strength, some studies measured the tensile strength by applying a tensile load (Fig. 5b). The compressive strength test is usually carried out with a universal strength testing machine as used by [120, 132, 133], or a compressive testing machine as used by [69, 131]. The compressive strength is computed as the ratio of the applied load to the cross-sectional area of the briquette [133].

#### 4.5.4 Water retention resistance

Water resistance is a measure of how the briquette resists the absorption of water over a given period. This quality parameter is very important as it determines the resistance of the briquette during storage and transportation in a highly humid environment or when exposed to rain [23]. The duration to which briquettes could react when exposed to rain or humid condition differs depending on the binder type, biomass material, and the briquette's density. Hence, it is a measure of the hydrophobicity of the briquettes. Simulating this at a laboratory scale involves immersing the briquettes in a known volume of water for a given period. While the immersion time differs in various studies, [80] believed that short-term exposure to water could adversely affect the quality of briquettes. Hence, water resistance should be tested over short-term exposure. However, [84] believes that water resistance tests should involve immersion for a long period of up to an hour. In a different approach, Richard's method suggests immersion for 30 min with a checking interval of 10 min by applying finger pressure, after which if the briquette retains its form, it will be reweighed, and the water absorbed and water retention index (WRI) can be estimated

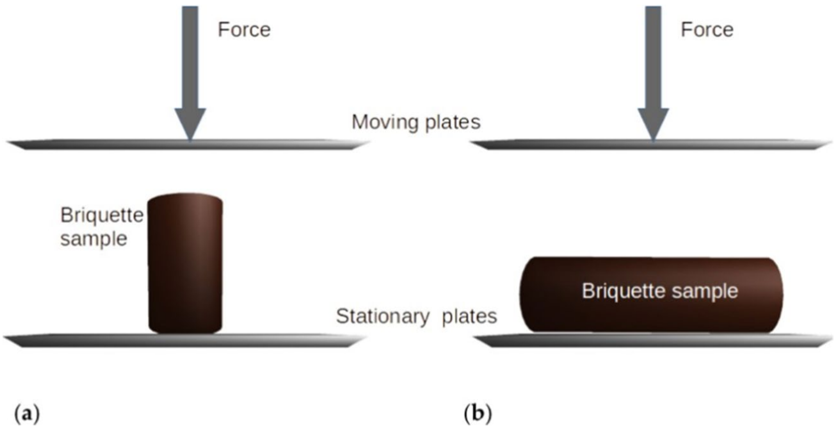


**Fig. 5** Typical orientation of biomass briquette sample during (**a**) compressive strength, and (**b**) tensile strength testing [23]; Copyright, https://creativecommons.org/licenses/by/4.0/

using Eqs. 4 and 5, respectively [130]. This method was used by [57]. In a different approach, [91] and [134] determined the water resistance by submerging the briquettes in water at room temperature for 30 s [77, 92, 127]. In a slightly different approach [77] immersed the briquette in water for 2 min.

$$\text{Water absorbed } (\%) = \frac{w2 - w1}{w1} \times 100 \tag{4}$$

$$WRI = 100\% - \text{water absorbed} \tag{5}$$

where w1 and w2 = initial and final weight of briquette

### 4.5.5 Abrasion resistance (mechanical durability)

Abrasion is the percentage of fines returning from the briquette after being subjected to mechanical or pneumatic agitation [135]. Hence, the abrasion resistance test simulates mechanical handling. It shows the ability of the briquettes to resist mechanical and abrasive forces during handling. A uniformly stable briquette is expected to have low abrasion and high strength values [136]. The quality of binding materials plays a vital role in improving briquettes' abrasion resistance [11]. The equipment commonly used in testing the durability of briquettes is a rotating drum and tumbler (Fig. 6) [23]. However, [137] used both the drop and tumble tests in assessing mechanical durability. In their study, each briquette was dropped onto a concrete floor via a tube of 10 cm diameter and 1.2 m height. After dropping, briquettes with weight loss below 10% were considered as "Pass", while those with weight loss above 10% were considered as "Fail." For the tumble test, they loaded the briquettes into a tumbling box and rotated the box at ~ 57 rpm (0.95 Hz) for 2 min. The mechanical durability of briquettes is estimated as the percentage of weight lost during tumbling [137]. [132, 138] evaluated the mechanical durability using the tumble test following EN ISO 17831–2 standard. Samples of briquettes weighing 2 ± 0.1 kg were rotated 105 times at 21 rpm in a rotary drum of 600 mm diameter [119].

## 4.6 Uses of briquettes

With the growing interest in briquetting, Briquettes are now applied in several places ranging from homes, industries, and farms. Table 2 shows some uses of briquettes.

## 4.7 Economic assessment of different biomass briquetting technology

Economic analysis or assessment involves costing and tracking of all the expenditures incurred in certain briquetting technology to determine whether it is profitable or otherwise. Hence, an economically viable briquetting technology is that which the overall production cost is lower than existing fossil fuels [139]. The economics of briquetting technology cannot be unconnected to specific sites and local conditions of regions being evaluated [139]. [140] observed that the raw material collection phase is the most expensive in briquette production. This shows that to assess the long-term viability of biomass briquettes, local conditions such as the availability of raw materials and technology are pertinent. On this premise, the use of locally available biomass feedstocks and the setting up of a briquette production plant close to the source of raw material is perceived as being profitable [5]. Being that briquetting is majorly targeted to users of traditional solid fuels such as coal, charcoal, and fuelwoods who are mainly residents of rural and peri-urban parts of developing countries, most of the reported studies on briquetting are within the low to a medium pressured level where simple and locally fabricated briquetting machines (e.g., manual piston press and plungers) are used. However, with the growing demand and the need to commercialize production, studies involving high-pressured techniques became imperative for large-scale and high-quality production.

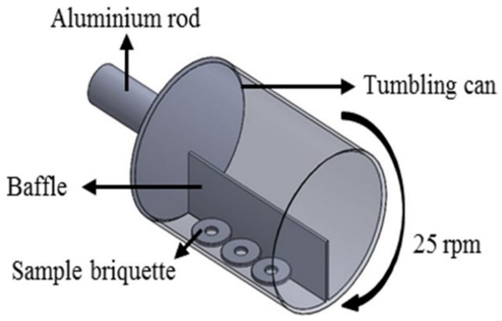


**Fig. 6** Schematic diagram of the tumbling test [91]; Copyright, https://creativecommons.org/licenses/by/4.0

The low pressured technique is more common in developing countries because it is more affordable and easier to carry out. Usually, there is no cost incurred in acquiring biomass materials as they are largely available. The major cost expended is mostly associated with transport charges [140], and the acquisition of the briquetting press, which in most cases is locally manufactured. However, being that starch-based binders are mostly used in relatively high quantities to commensurate for the low pressure, money is expended in the purchase and/or preparation of binders. With this, if a large-scale production will involve the use of starch-based binders which majorly emanates from food resources, then it becomes a threat to food security [5], and therefore not economical. However, if other biomass-based binders are utilized either completely or in blended form, it will reduce over-dependence on food-based, inorganic, and commercial petroleum-based binders [5]. Thus, to minimize the cost expended on binders, it is important to evaluate more

**Table 2** Potential applications of briquettes

| S/N | Areas | Possible application |
|---|---|---|
| 1 | Domestic | Cooking, water heating, and space heating |
| 2 | Commercial | Cooking, water heating, grilling, etc |
| 3 | Hospitality | Cooking, water heating, space heating (outdoor dining areas) |
| 4 | Industries | Powering of boilers and heating systems |
| 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 | Incubators and brooding |

Source: Modified from [12]

biomass materials which are economically viable and eco-friendly, or at least blend a biomass binder with an inorganic type. In line with this, [124] produced an economical bio-binder from molasses and crude glycerol.

Several studies have assessed the economic viability of biomass briquetting. This includes [139], where an economic analysis of a household scale briquetting project in Nigeria was conducted using a low-pressured technique (≤ 7 MPa) with a blend of corncobs and the bark of oil palm trunk as feedstocks. The study revealed that with a machine capacity of 5.79 kg/h actively operational for 300 days in a year, a total of 13,896 kg briquettes will be produced at a cost of USD2932.00, and if sold at a unit cost of USD0.16, an annual revenue of USD3637.70 will be generated. In a different study in Cameroon, [140] evaluated the economic viability of briquetting four agricultural residues (rattan waste, coconut shell, sugarcane bagasse, and banana peel) in a low-pressured (5 to 7 MPa) plant. The result showed that coconut shell and rattan waste briquettes are economically viable with a net present value (NPV) of 67,189 € and 66,526 €, and profitability index of 2.68 and 2.66 respectively. [17] assessed the economic value of briquette production (using a 29.4 MPa press) from cashew nutshell in Eastern Indonesia, and discovered that at an annual production capacity of 2,000 tons, a total production cost of USD842,304 is required, and if briquettes products can be sold at 1,052,878 USD/year, a net profit of USD147,402/year will be generated. [141] performed a techno-economic analysis of briquettes production from forest residues in the United States using a commercial-scale hydraulic press and observed a minimum selling price (MSP) of $161.5 and $274.3 per oven-dry metric ton with a nominal internal rate of return of 16.5% for non-torrefied and torrefied wood chips briquettes, respectively. Thus, almost all the reported studies concluded that it is economically viable to produce briquettes from the specified feedstocks.

### 4.8 Biomass briquettes combustion

Biomass briquette combustion is an important aspect of biomass briquetting as it is one of the phases that distinct biomass briquettes from other solid fuels in terms of thermal and emission performance. While several lignocellulosic biomass materials have been reported as emission neutral, it is important to ensure that at least the neutrality is maintained when densified into briquettes. Thus, careful attention must be made to material selection and matrix ratio to avoid the emission of toxic gases. On this basis, [142] studied the combustion mechanism of biomass briquette and found out that the process is influenced by the medium temperature, ambient air, biomass material, particle size, reaction time, gas–solid mixing ratio, and proximate parameters like moisture content, ash content and fixed carbon of the briquette. While combustion performance encompasses both thermal (combustion efficiency, proximate parameters, calorific value, etc.) and emission properties, several studies including [96, 143, 144], reported the combustion performance in terms of proximate parameters (i.e., moisture content, volatile matter, ash content, and fixed carbon) and calorific value only, as it is perceived to simulate the actual combustion of fuel briquettes, while some, including [143] combined both proximate and ultimate analysis to discuss the combustion performance. However, only a few studies carried out a real-time combustion test in heating devices following standard testing protocols. This includes [145] where fuel moisture content was found to have an inverse relationship with combustion performance in a biomass cookstove. Thus, as fuel moisture decreases, combustion temperature and combustion efficiency increase. The combustion of carbonized rice husk briquettes in a fixed bed medium was also investigated [146], where binder and air-mass flux were found to affect combustion performance.

### 4.8.1 Overview of recent studies on toxic gas emission from the combustion of biomass briquette

Several studies have evaluated the combustion performance of biomass briquettes to specifically measure the emission of gases. This includes [147], where the impact of wheat straw and tree bulk briquetting on $SO_2$ and NO emission, combustion properties, and kinetic characteristics during combustion were investigated. It was discovered that on densifying the feedstocks into briquettes, the sulfur release ratio reduced from 34.7 to 4.3% and from 12.4 to 1.6% at a reaction temperature of 900 ℃ for tree bulk and wheat straw, respectively. On increasing the reaction temperature to 1000℃ the sulfur release ratio reduced from 73.4 to 30.4% and from 58.4 to 10.2% for tree bulk and wheat straw, respectively. In the same vein, a substantial reduction in NO release ratio was recorded with the wheat straw sample having more release ratio. Similarly, [43] evaluated the combustion characteristics and emissions of biomass briquettes made from rice husk and rice husk char bonded with molasses and glycerin. Therein, $CO_2$, CO, NOx, and Acrolein gas emissions of 11–15%, 465–1128, 37–154, and 0.1–35.3 ppm, respectively were obtained from the sample briquettes. The emissions were reportedly having an increasing effect as the content of glycerin increased. Thus, a level within 5–10% was recommended as the safe level for glycerin content. [148] also confirmed that densifying wheat straw, rice straw, and maize straw into briquettes reduces sulfuric and nitrogen-based emissions compared to when burned in their raw forms. In a different approach, [149] evaluated the emission performance of biomass briquettes in industrial applications, and the resultant emissions of $CO_2$, CO, and $SO_2$ from the briquettes were observed to have decreased by 57.28%, 95.45%, and 98.06%, respectively, compared to coal. Similarly, [150] discovered that the emissions of greenhouse gases are curtailed by $1.25 \times 105$ $tCO_2eq$ per annum in using biomass briquettes in a large-scale steam heating system. Overall, several studies have demonstrated that in using biomass briquettes, emissions are minimized compared with the use of coal, fuelwood, and other raw biomass materials. However, the type and content of binding material are reportedly having a significant effect on toxic gas emissions. Thus, the use of biomass binders is encouraged over non-biomass and inorganic binders.

### 4.8.2 Impact of biomass briquette combustion on coal-based power plant

Coal-based power plants are one of the oldest forms of generating electricity. Though coal is a fossil fuel, it emits less carbon than oil, but higher than biomass [151]. The energy transition from fossil fuels to biomass-based solid fuels has been perceived as one of the sustainable solutions to the increasing emission of greenhouse gases [152]. Thus, power generation from coal-based power plants has recently gained advances in the reduction of carbon footprints. While it has over the years offered a stable power supply in some parts of the world, it has left several environmental impacts [153]. This includes the emission of toxic gases and coal fly ash. Coal fly ash (CFA) is one of the major pollutants from coal-based power plants which is being emitted in millions of tons per annum [154]. However, with recent advancements, the sector is gradually being transformed to contain carbon capture and emission reduction technologies [155]. One such technique that has been verified to be cost-effective is the co-combustion or co-firing of biomass and coal for power generation [152]. While this has reportedly curtailed emissions from the use of pure coal, it still has the potential of emitting particulate matter and fly ash, as biomass is used in raw form. However, when pulverized coal is blended with biomass and densified into briquettes, it reduces more emission. [156] reiterated the importance of densifying pulverized coal with blended biomass materials into pellets or briquettes to curtail the impact of coal-based emissions in power plants. This has been assessed to be economically feasible in biomass-producing regions including India where through the technique, a carbon dioxide mitigation potential of 205 Mt was estimated by 2030 to 2031[157].

## 4.9 Overview of recent studies on briquette production

In line with the growing interest in developing alternative fuel from biomass feedstocks [22], several studies have been conducted on briquetting over the years. This includes the study of [106] where briquettes were made from a mixture of rice husk and sawdust using starch and clay binders. Therein, the process variables were optimized using response surface methodology (RSM), and optimum values of binder, feedstock, and die pressure were obtained as 15%, 28%, and 9 MPa, respectively, yielding an energy value of 5.69 kcal/g and 3.35 kcal/g for briquettes made with starch and clay binder, respectively. [107] in a different approach, compared the thermal performances of briquettes made from blended maize cob and stalk with that of a pure maize cob, and discovered that briquettes made from blended maize cob and stalk perform better with 17.3% thermal efficiency, 0.97 kg/hr fuel consumption and 20 min boiling time.

In another study by [79], briquettes were produced from the blends of citrus peels and rice husks using a gelatinized grounded potato (Irish) peel as a binder. On evaluation, the briquettes were found to have average values of apparent density between 0.35 and 0.46 $g/cm^3$, moisture content of 10–19%, and ash content of 3.9–4.9%. In the same vein, the calorific values consisting of a higher heating value (HHV) ranging from 14.6 to 17.2 MJ/kg and a lower heating value

(LHV) ranging from 13.1 to 15.8 MJ/kg were recorded. The study however differs from that of [27] where rice husk of constant weight was mixed with bran, water, and three different binders (cassava wastewater, CSW; rice dust, RD; and okra stem gum, OG) at different ratios. The performance result revealed that the briquettes bonded with 15% cassava starch wastewater and 10% bran had the highest density (471.3 kg $m^{-3}$), while that produced with 10% rice dust, 70% water, and 0% bran had the highest durability (91.9%), and the highest compressive strength (2.54 kN) was noted at 15% rice dust, 60% water, and 0% bran combination. This is an indication that briquette performance differs with material type and mixing ratio. While some materials will thrive better in terms of physical performance, others may thrive better in mechanical or thermal performance. Based on this, it is important to characterize materials before densification to have a glimpse or idea of their potential performance. In addition, optimizing the input materials and process parameters will be a better option for saving costs and maximizing output.

[120] in a different approach compared the compressive strengths of briquettes made at variable particle sizes (0.25, 1.0, and 1.75 mm), mixing ratio (80:20, 70:30, 60:40, and 50:50), and compaction pressure (25, 50, and 65 kPa) using corncob and rice husk blend. The briquette made from 0.25 mm particle size, 80:20 mixing ratio, and 65 kPa compaction pressure had the highest compressive strength of 111 kN/$m^2$.

Similarly, [83] produced and characterized charred briquettes using rice husk, maize cobs, palm kernel shell, and sawdust at variable particle sizes (0.6 mm, 1.8 mm, and 2.36 mm) and briquetting pressures (10 MPa, 20 MPa, and 30 MPa). The briquette made with palm kernel shell with 0.60 mm particle sizes, densified at 30 MPa indicated the best performance, with a moisture and ash content of 3.5% and 2.7%, compressed and relaxed density of 411.85 kg/$m^3$ and 753.291 kg/$m^3$, respectively.

In another study by [95], briquettes were made from rice husk using the variable ratios of cassava peel and cassava starch binders. The production was at a constant pressure of 80 bar and a dwell time of 3 min. The briquettes were characterized accordingly and observed that those bonded with cassava peels have better physical and combustion properties than those of cassava starch binder where a density range of 977.6 to 1176.5 kg/$m^3$, moisture content of 10.36–12. 31% and a burning rate of 1.03–1.96 g/min were recorded.

[42] assessed the properties of briquettes made from a mixture of charred feedstocks (rice husk, sawdust, and coconut husk) using cassava starch as a binder under low pressure (89.14 kN/$m^2$). The result showed an ash and moisture content of 5.60% and 7.30%, a calorific value of 24.90 MJ/kg, and volatile matter content of 61.38%. In a similar study by [43], briquettes were made from rice husk and rice husk char using molasse and glycerin as binders. Briquettes made from rice husk char possess a higher calorific value (13.9–17.3 MJ/kg) compared to that of rice husk with a calorific value of 13.2–15.9 MJ/kg.

As a way of improving sustainability in briquette production coupled with the interest to enhance environmental waste management, studies on briquetting have now advanced to blending biomass with available municipal and industrial wastes (such as food wastes, plastics, sludge, etc.), biosolids, coal, and dung. Although there are concerns about emissions from burning non-biomass materials such as plastics, it is believed that when blended with biomass in a proportion below 10%, it has no significant effect [158]. Table 3 has highlighted some advancements in briquetting in terms of blending and co-densification with non-biomass waste materials.

## 5 Limitations of the current review

The current review was mainly limited to the technical aspects of biomass briquetting. Hence, it discusses more of the process factors and quality parameters, as other aspects such as the economic and environmental (emissions) were only highlighted in brief to give an insight into the practicability of the technical aspects.

## 6 Outcome of the present review

The present review has found that biomass briquetting is a sustainable means of energy production, which has the potential to replace coal, fuelwood, and charcoal. While the production process involves some technical steps, it was observed that briquettes can be produced locally using locally available materials and technology. However, briquettes produced from such low-pressured techniques are less durable and efficient than samples made from moderate to high-pressured technology.

The present review also found out that briquetting lignocellulosic biomass is a measure to curtail deforestation and the emission of toxic gases from the use of fossils and other forms of solid fuels such as fuelwood and charcoal as they emanate from woody biomass. This has the potential to improve the health and well-being of its users, especially in Africa where over 82% of the population uses solid fuels [10].

The review also observed that co-briquetting two or more biomass materials yields briquettes with better quality than briquetting single biomass. In the same vein, it was discovered that biomass can be blended with municipal solid wastes such as plastics, sludge, food waste, and animal waste. Furthermore, co-briquetting and co-firing of biomass and

**Table 3** Recent advancements in briquetting technology

| S/N | Description | Feedstock used | Process parameter(s) | Major findings | Remark | References |
|---|---|---|---|---|---|---|
| 1 | Blending and co-densification of biomass with coal | • Coal and fermented cow dung (treated with bio activator), blended in the ratio 9:1, 8:2, and 7:3 | • NA | The developed bio-coal briquettes were observed to have an enhanced combustion efficiency and emit fewer gases compared to raw coal | In addition to biomass blending, a microorganism was incorporated into the mix to aid desulfurization | [159] |
| | | • Coal fines (80%–97%) and pre-treated wood fines (3%—20%) | • 28 MPa die pressure | Briquette sample produced from 97% coal and 3% torrefied biomass had the maximum mechanical strength (compressed density of 1.18 g/cm$^3$, compressive strength of 4 MPa, and impact resistance of 1350%). Also, the elemental composition of briquettes made from blended samples was higher than that of raw coal | While it was observed that the quality of the briquettes reduced with an increase in torrefied biomass, it is important to evaluate non-torrefied wood fines and other dense biomass | [89] |
| 2 | Briquette production from blended biomass and food waste | • Food waste (scenario 1: regular food waste, and scenario 2: decomposed food waste), charcoal dust, sawdust, and coconut waste | • NA | The briquettes had a bulk density between 810 and 1060 g/l, average calorific value of 15.5 ± 2.2 kJ/g and 17.1 ± 4.1 kJ/g, and a mean burning rate of 1.91 ± 0.62 g/min and 1.70 ± 0.59 g/min, for scenarios one and two, respectively | Non-carbonized food waste was discovered as a good briquetting feedstock. Though, the food waste has to be air-dried or decomposed to improve its calorific value | [160] |
| 3 | Briquetting using sewage sludge without a binder as a media in liquid-phase adsorption | • Sewage sludge from a waste-water treatment plant | • 5–50 MPa die pressure, 3 min dwell time, pyrolyzed at RT—600 ℃ for 0.5 h and activated at 800 ℃ for 0.5 h | The briquette's adsorption capacity and mechanical performance were optimum at the initial moisture content of 30 wt% and compression pressure of 25 MPa, yielding good adsorption kinetics with an axial compressive strength as high as 22.2 ± 3.1 kg/m$^2$ | Briquettes have gone beyond their conventional use as fuel and have advanced to industrial applications like the removal of impurities from solutions | [161] |

Table 3 (continued)

| S/N | Description | Feedstock used | Process parameter(s) | Major findings | Remark | References |
|---|---|---|---|---|---|---|
| 4 | Briquette production from blended biomass and plastic waste | • Sawdust, date palm trunk, and plastic waste | • 22–67 MPa pressure, RT–130 ℃ temperature, | Briquettes were successfully produced without a binder. Samples made from blended date palm trunk and plastic presented the best performance with durability greater than 97% and density ranging from about 570 kg/m$^3$ to > 1000 kg/m$^3$ | Plastics present good adhesion during densification. Thus, produces durable and mechanically efficient briquettes. However, there is a risk of emission during combustion. Hence, the quantity of plastic must be kept low, preferably below 10% | [162] |
| | | • Sawdust, waste plastic bottles | • NA | Although the presence of plastic blend in the briquettes was observed to have improved combustion, CO emission increases from 10 to 30% compared to briquettes made from pure sawdust. However, nitrogen oxide emissions decreased between 20 and 35% as the blended plastics are mainly made of polyethylene which has low nitrogen content | Because plastics differ in characteristics, it is important to go for those with less polyethylene content as they emit fewer gases | [163] |
| | | • Waste sachet water bags and polythene bags, sawdust, maize husk, and coke | • NA | The mechanical strength and combustion performance of the briquettes was observed to have a decreasing effect as the quantity of coke increased but increased as the quantity of biomass increased | | [164] |

*NA* not available

coal have been suggested as a way of minimizing coal-based emissions, especially in coal-based power plants. However, it was observed that when blending biomass with non-biomass materials that emit toxic gases such as plastics, the matrix must be kept below 10% to avoid emission.

In addition to the use of low binder content, the review observed that it is possible to produce briquettes without a binder at a moderate to high-pressure level. Also, in addition to binder-less briquetting, microalgae were observed to have emerged as a potential binder in briquette production.

Overall, biomass briquetting technology has been reported as an economically feasible technology in almost all the reported studies that assessed its economic viability.

## 7 Suggestion for future research

With the target users of briquettes being predominant in rural and peri-urban households, it is important to carry out a comprehensive economic analysis of small-scale production to know the cost implication per process per quantity. This would further convince the targeted users of the need to transit to the technology if found more affordable. However, advancements usually come with cost implications; hence, aspects such as the production system (briquetting machine) could be downscaled and modified with emphasis on the use of locally available materials. In terms of the binding material, studies should explore more non-edible organic materials, especially those largely available and considered as waste in an environment.

In addition to being an alternative source of energy, another central idea behind the use of briquettes is to curtail deforestation. On this note, studies need to correlate briquetting to deforestation, by estimating the number of briquettes commensurable to a given number of trees and vice versa. To this end, it is necessary to also consider modeling and simulation, to forecast future impacts of the current approach. This will give a clearer picture of the extent to which deforestation could be curtailed through briquetting and will further interest policymakers especially as the globe is faced with climate change. Most importantly, it will provide a comprehensive report on the extent to which briquettes could mitigate climate change. The outcome may also help policymakers in the formulation of policies that may scale up the study in different settings and then use the findings as a basis for policy review, formulation and service delivery protocol to improve forest conservation and the use of agricultural waste which may at the long run culminate in the reduction of deforestation.

Though biomass briquettes are reportedly less emissive compared to coal, raw biomass, fuelwood, and charcoal, there is a need to carry out a comprehensive life cycle assessment (LCA). This will give a better understanding of its environmental impact compared with other forms of energy right from raw material extraction to end life. In the same vein, feedstocks that are less harmful to the environment will be determined.

## 8 Conclusion

Briquetting is gradually becoming a prominent energy production method globally. This has been induced by the global increase in population which has led to an increase in energy demand. This paper reviewed recent studies on briquetting with emphasis on the key process parameters (pressure, temperature, and dwell time), feedstocks, and binding materials. Through this, it was observed that briquettes made from different material types (feedstock and binder), combinations, and process parameters have different performances. Irrespective of the method and materials involved, the ultimate goal is focused on having a cleaner, sustainable, and affordable option. Most importantly, the review identified briquettes as a potential and sustainable replacement for fuelwood and charcoal which are instrumental in the increased rate of deforestation. In addition, the technology has been evaluated as a measure of improving or enhancing the density and energy value of loosed biomass, thereby easing storage and handling as against the conventional way of handling. Therefore, it can be inferred from the review that briquetting is a sustainable method of energy generation. Hence, it is important to disseminate the technology to go far and wide through relevant interventions.

**Acknowledgements** The authors are grateful to the German Federal Ministry of Education and Research (BMBF) for funding the study through the West African Science Service Centre on Climate Change and Adapted Land use (WASCAL), under the Graduate Research Programme on Climate Change & Land Use (CCLU), College of Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

**Author contribution** All authors contributed to the study conception and design. Suleiman Usman Yunusa: conceptualization, literature search, writing; Ebenezer Mensah, Kwasi Preko: supervision, visualization, writing—editing; Satyanarayana Narra, Aminu Saleh, Safietou Sanfo: writing—original draft preparation, editing, methodology. All authors have read and agreed to the published version of the manuscript.

**Funding** This study was funded by the West African Science Service Centre on Climate Change and Adapted Land use (WASCAL).

**Data availability** Not applicable.

## Declarations

**Ethical approval** Not applicable.

**Competing interests** The authors declare no competing interests.

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