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Densification of raw and torrefied biomass: A review

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ABSTRACT

Densification and torrefaction are potential technologies to valorize lignocellulosic residues into cleaner and sustainable alternative energy carriers for domestic, institutional, commercial and industrial thermal energy applications. Therefore, this review paper has focused on sources of lignocellulosic biomass for energy production. Furthermore, the processes involved in production of raw and torrefied briquettes/pellets have been discussed. Additionally, the physicomechanical, emissions and combustion properties of raw and torrefied briquettes produced from lignocellulosic residues have been presented. Also, the economics of briquetting lignocellulosic biomass materials have also been reviewed. The quality of densified solid biomass fuels from lignocellulosic residues was found to dependent on the feedstock and pretreatment conditions. Additionally, torrefaction and densification have been reported to upgrade the energy properties of loose biomass materials, as potential alternative fuel to firewood and charcoal. Finally, the economic profitability of densification projects has been found to be dependent on the availability of feedstocks, technology used and market potential of the product.

1. Introduction

The shift from traditional use of biomass to modern bioenergy as part of global energy transition agenda can potentially lead to attainment of the 7th and 13th United Nation's Sustainable Development Goals (SDGs). Primarily, the 7th goal focuses on ensuring access to affordable, clean, reliable, sustainable and modern energy for all while the 13th goal focuses on climate action [1]. The versatile modern bioenergy contributes more than half of global renewable energy supply today and its overall production increased by 5 % in 2022 to reach 40 EJ. More specifically, solid biofuel accounts for the vast majority of the currently produced biofuels for heating, cooking and electricity generation [2]. In the IRENA's 1.5 °*C* scenario, 153 EJ of biomass primary supply per annum will be needed by 2050, which is triple today's use. For this reason, waste streams, which do not require any specific land use are expected to contribute almost half of the total modern bioenergy supply in 2050 according to the Net Zero Scenario (NZE) [3].

The uptake of densified solid biofuel has been successful in Europe and America but still sluggish in Africa and Asia. For instance, in the year 2021, out of nearly 2.3 billion people worldwide who lacked access to clean cooking fuels and technology, 50 % and 45 % were from Africa and Asia respectively [1]. The traditional use of biomass, which is still predominant in developing nations, is the main cause of about 3.6 million premature annual deaths, a source of greenhouse gas (GHG) emissions, and major barrier to women to pursue education and participate in the workforce. Generally, the current global effort to transit from the traditional use of biomass to renewable electricity and cleaner modern biofuels (ethanol fuel, wood briquettes and pellets) is aimed at reducing the effect of its inefficient utilization on the environment and public health [4].

Large quantities of lignocellulosic residues are generated annually in developing countries. For instance, the estimated energy potential of agricultural crop, municipal and/or industrial residues in Nigeria and Cameroon are 3635.95 PJ/year [5] and 606 PJ/year [6] respectively. However, these residues are most times treated as wastes and openly burnt without recovering their energy contents, disposed of by dumping and/or left to rot in-situ [7]. These practices lead to numerous environmental and health concerns yet the residues can be salvaged into modern bioenergy [8,9]. However, the inherent characteristics of lignocellulosic residues such as hygroscopicity, structural heterogeneity, low bulk density, low volumetric calorific value, high moisture content and fibrousness limit their direct use in combustion [10,11]. These

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properties lead to poor combustion characteristics as well as handling, transportation and storage [9,11–13], hence necessitating their pretreatment [14].

Torrefaction and densification are some of the modern and efficient techniques of utilizing biomass residues [15]. Torrefaction is a thermal pretreatment method conducted at temperatures between 200 and 300 °C in an inert atmosphere with the aim of modifying physical, structural and chemical properties of biomass [16]. Torrefaction enhances biomass resistance to microbial attack, energy density, ignition, combustion efficiency, grindability, hydrophobicity, homogeneity as well as carbon to oxygen and carbon to hydrogen ratios [17].

Further treatment of bio-char via densification to produce pellets or briquettes enhances its energy density [18]. For instance, densification of wheat straw torrefied at 250 °C increased the energy density by 3.6 GJ/m^3 while that of corn cob torrefied at 260 °C increased by 1.3 GJ/m^3 [19]. Densification may involve either pressure or non-pressure agglomeration of feedstock into higher density, uniform shape and size, low moisture content, and higher volumetric calorific value product [20]. For example, densification increased the energy density of cassava rhizome waste from 2.04 to 15.7 GJ/m^3 [21].

The quality attributes of briquettes/pellets such as physicomechanical, combustion and emissions characteristics influence their uptake by users [18]. Good quality briquettes/pellets for domestic use are expected to burn for a longer time, be easily ignitable [22] and have low particulate matter ($PM_{2.5}$ and PM_{10}) and carbon monoxide (CO) emissions, which are the main pollutants released when they undergo incomplete combustion [23,24]. These pollutants have the potential to cause environmental and adverse human health effects [25,26]. For example, atmospheric photochemical reactions that are associated with carbon monoxide indirectly increase greenhouse gas (GHG) levels, hence leading to global warming [27,28]. Additionally, CO has higher global warming potential per kilogram of carbon, than carbon dioxide (CO_2) [29]. So, good quality briquettes/pellets should have CO emission level <10 mg/m^3 in 15 min while $PM_{2.5}$ and PM_{10} concentration levels should be $< 15\ \mu$ g/m^3 and 45 μ g/m^3 in 24 h respectively [30]. Generally, the emissions characteristics of solid biofuels are dependent on the nature of the feedstock as well as pretreatment and combustion conditions.

Besides, the values of physicomechanical properties of densified products are used as indicators of their ability to resistance destructive forces experienced during handling, storage and transportation [31]. The chemical, physicomechanical, emissions and combustion properties of briquettes produced from different raw and charred lignocellulosic residues such as corn straw bio-chars [32], tea processing plants, pruning residues of persimmon, tomato stalk and pruning residues of peach tree [33], charred rice husk, maize cobs, palm kernel shell, and sawdust [34] have been studied. However, few studies have been done to compare the effect of torrefaction on the combustion and emissions characteristics of biomass briquettes and pellets.

Knowledge of economic indicators such as net present value, internal rate of return, benefit-cost ratio, and payback period [35] are required for successful implementation of a briquetting project. The economics of densifying biomass residues such as charred Durian peel-spent mushroom compost blend [36], sawdust forest biomass [31], sugarcane-coconut shell, sugarcane bagasse-rattan waste, banana peels-coconut shell and banana peels-rattan waste composites [37] and sugarcane bagasse pith [38] have been studied. Literature has indicated that availability of feedstock, technology applied and market demand of the product are the main factors, which affect economic profitability of biomass densification projects [31].

Although multifarious studies have been conducted on densification of lignocellulosic residues, there is scattered scientific information regarding comparative studies on physicomechanical, combustion and emissions characteristics of raw and torrefied briquettes/pellets. Therefore, this review is tailored to recent studies on characterization of briquettes/pellets produced from raw and torrefied lignocellulosic residues so as to shed light on the glaring knowledge gaps in the area. Additionally, the review also focused on gathering scattered scientific information on economics of densifying lignocellulosic residues from different regions so as to inform future researchers.

2. Methodology

The literature used in this paper was searched and downloaded from Google scholar and Science direct online databases. The Boolean operator "AND" was used to encompass different key words in a single search. Furthermore, the search terms used included densification of raw and torrefied lignocellulosic residues, biomass densification technologies, factors affecting the quality of densified biomass, emissions and combustion characteristics of raw and torrefied biomass residues, physicomechanical properties and economic feasibility of briquetting/pelleting raw and torrefied briquettes/pellets. References from the downloaded articles were further examined to identify other literature related to the topic under study. The inclusion and exclusion criteria used in selecting the articles were based on their relevance to the topic under review. The main focus was on economic feasibility of briquetting/pelleting, densification as well as emissions and combustion characteristics of raw and torrefied lignocellulosic residues. The search was limited to articles published between the years 2013–2023 with the exceptions of areas having limited articles. However, geographical restrictions were not applied in the search.

The search term densification, emissions and combustion characteristics of raw and torrefied lignocellulosic residues generated a total of 126 articles that were published between 2013 and 2023 on the online database of science direct. These were within the research areas of energy, materials science, chemical engineering, engineering and environmental science. Out of 126 articles, 60 were review articles while 66 were research articles. Fig. 1 revealed an increasing trend in articles published in this area over the years, which could be attributed to adherence to international protocols and conventions such as the Bamako and Basel Conventions [39], and the Kyoto Protocol, particularly the Clean Development Mechanism (CDM) projects [40] inter alia. These global policy actions specifically promote effective and efficient utilization of biomass resources for bioenergy generation with the prime goal of combating environmental pollution, global warming and climate change.

3. Biomass

Biomass refers to all organic matter in the biosphere originating from phytomass and zoomass or materials resulting from their natural or artificial transformation [41]. The global energy potential of biomass originate from sources such as agriculture, forestry or waste sector is expected to be 150 EJ in the next 20 years [42]. Fig. 2 depicts the main sources of biomass for bioenergy production.

3.1. Structural and non-structural components of biomass

Lignocellulosic and non-lignocellulosic biomass materials differ in their main structural and non-structural components. For instance, lignin, cellulose and hemicellulose are the main structural components of lignocellulosic biomass while lipids, protein, starch, water soluble extractives and inorganic elements are their non-structural components [44]. On the other hand, lipids, proteins, starch, inorganics and minerals are the primary components of non-lignocellulosic biomass, whereas lignin, cellulose and hemicellulose exist in less proportion [45]. The percentage composition of structural and non-structural components of biomass plays a very significant role in biofuel production as highlighted in the next section.

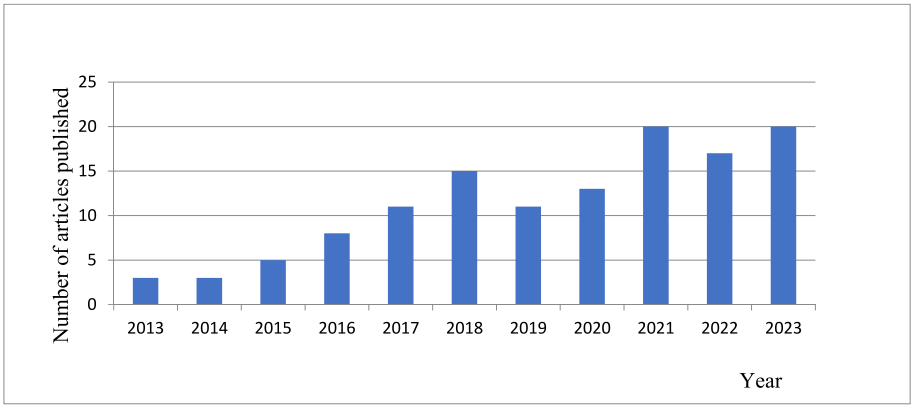

Fig. 1. Trend of articles related to densification, emissions and combustion of raw and torrefied lignocellulosic residues published from 2013 to 2023.

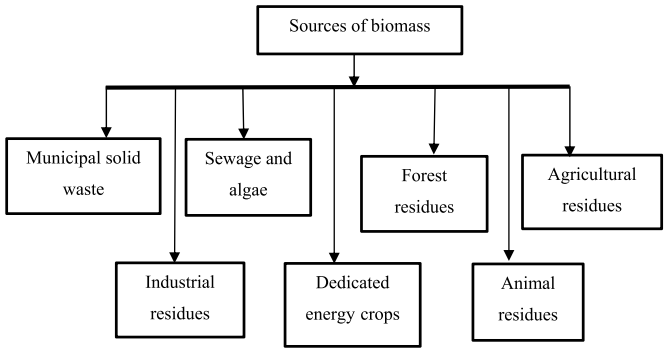

Fig. 2. Sources of biomass [43].

3.2. Effect of biomass structural composition on biofuel production

The bioconversion route, grinding energy requirements, bond formation during densification and physicomechanical properties of densified products are affected by the amount of structural and nonstructural components of biomass feedstock. For instance, thermochemical process can handle biomass with different proportions of hemicellulose, cellulose and lignin while biochemical conversion requires biomass with high cellulose to hemicellulose ratio [46]. Additionally, biomass with high amount of lignin and cellulose has greater grinding energy requirements due to highly branched structure of lignin and high degree of crystallinity of cellulose [47], which makes it difficult to disrupt the cell wall structure. Unlike hemicellulose with negative effect on properties of briquettes, high cellulose content improves the mechanical properties of briquettes, whereas high lignin content increases water penetration resistance and thermal stability of briquettes [48]. Furthermore, lignin acts as a natural binder and is softened at elevated pressure and temperature, thus leading to formation of an adsorption layer within the biomass [49], hence strengthening the bonds between the particles. According to Lubwama et al. [50], cellulose composition of biomass feedstock above 30 wt% is a requirement for enhancing mechanical properties of briquettes. On the other hand, non-structural components of biomass such as starch, protein, lipids and water-soluble carbohydrates serve as natural binders when activated thermally during densification process [51]. Feedstock which lacks plasticity usually, requires addition of external binders during the process of densification in order to produce briquettes/pellets with good physicomechanical properties [52]. The percentage compositions of lignin, cellulose, hemicellulose, extractives/volatiles and inorganic compositions of biomass residues contribute to the properties highlighted in the next section.

3.3. Properties of biomass residues

Biomass residues are fibrousness and hygroscopic, have high moisture content, low bulk and energy density, high oxygen content, high alkali metal content and high heterogeneity [10,53]. These inherent properties make them unsuitable for energy production owing to the challenges highlighted in Table 1.

3.4. Densification of biomass

Densification involves agglomeration of fine biomass particles into higher density, uniform shape and size, low moisture content, and higher volumetric calorific value product [13,20]. Densification increases the bulk density of biomass from roughly 40–200 kg/m^3 up to 600–800 kg/m^3 [55]. Pressure and tumble agglomerations are two primary agglomeration approaches. Unlike the latter approach, the former does not require addition of binding agents [56,57]. Usually, biomass densification methods include briquetting, pelletizing, bailing, and cubing [58]. However, the commonest densification methods are briquetting and pelletizing. Briquettes and pellets can be differentiated from each other on the basis of their sizes. For instance, according to Austrian (ONORM M 7135) standard, the diameter and length of pellets range from 4.0 to 10.0 mm and 20–50 mm, respectively. In the case of the German (DIN 51731) standard quality of wood pellet, the diameter and length of briquettes can range from 16 to 400 mm and 10–200 mm, respectively [59–61]. In contrast to pelleting, briquetting can accommodate feedstocks with large particle sizes and high moisture content, which essentially reduces the energy requirement for drying and grinding [62]. During densification, different binding mechanisms are involved as described in the following section.

Table 1
Properties of raw lignocellulosic residues [5,11,54].

Biomass characteristics	Drawbacks
High moisture content	• Reduces the heating value • Requires energy intensive drying step • Reduces the efficiency of the conversion processes • Increases storage and transportation costs • Increases risks of biological degradation
Low bulk and energy density	• Increases storage and transportation costs
Fibrousness	• Increases grinding energy • Requires high feeding capacity • Leads to production of coarser particles
Hygroscopic nature	• Absorbs moisture during storage • Increases risks of biological degradation
High oxygen content	• Reduces the number of high energy C–H bonds • Reduces the heating value and energy density • Reduces thermal stability
High alkali metal content	• Makes ash-related problems more serious
Heterogeneity	• Increases transport, handling and storage costs

3.5. Biomass particle bonding mechanisms

Biomass particle bonding mechanism includes: solid bridges; adhesion and cohesion forces; forces of attraction between solid particles; mechanical interlocking; and/or interfacial forces and capillary pressure [63].

(a) Solid bridges

Solid bridges are formed when high pressure and temperature are applied to biomass particles, hence causing molecular diffusion from one particle to another at the contact points [64]. Additionally, solid bridges between particles may arise from crystallization of some ingredients, chemical reaction, hardening of binders, and solidification of melted components. They are predominantly formed subsequent to drying or cooling of densified products [65].

(b) Forces of attraction between solid particles

Biomass particles may adhere to each other under the action of short-range forces such as molecular electrostatic, and magnetic forces. These forces are weakened when particle sizes increase [66].

(c) Mechanical interlocking

Mechanical interlocking causes the fibers, flat-shaped and bulky biomass particles to interlock or fold about each other and form interlocking bonds. It provides sufficient mechanical strength to resist the disruptive forces caused by elastic recovery, which occurs after compression [67].

(d) Adhesion and cohesion forces

Highly viscous binders such molasses and tar adhere to the surfaces of solid particles to form strong bonds that are highly comparable to those of solid bridges. Most of these binders harden after cooling and form solid bridges [64]. Furthermore, the immobile thin adsorption layers ($\geq$3 nm thick) can form strong bonds between adjacent particles. This happens either by smoothing out surface roughness and increasing the inter-particle contact area or by decreasing the inter-particle distance and allowing the intermolecular attractive forces to participate in the bonding mechanism [67].

(e) Interfacial forces and capillary pressure

In wet agglomeration process for example, the liquid prevalent between the particles fills the interfacial spaces and causes the particles to experience forces of attraction, surface tension, and capillary forces [64]. Consequently, the capillary pressure and interfacial forces create strong bonds between the particles [65].

3.6. Biomass densification technologies

On the basis of compaction pressure, densification technologies can be categorized as low, medium, and high compaction pressures with typical pressure ranges of $0 < P < 5$ MPa, 5 MPa $< P < 100$ MPa, and $P >$ 100 MP respectively [68]. Low compaction pressure ($0 < P < 5$ MPa) requires use of a binder other than the natural binder for holding the particles of the feedstock together [20]. Bonding agents are normally added to aid in agglomeration of feedstock particles, especially when the biomass material lacks plasticity [52,69]. Medium pressure (5 MPa $< P < 100$ MPa) may or may not require the use of an externally added binder or heating device. High compaction pressure ($P > 100$ MP) facilitates sandwiching and sticking together of the feedstock particles so that no or minimal fragmentation occurs during storage, combustion, and transportation [70,71]. Additionally, high-pressure briquetting/pelleting increases the contact surface area, adhesion and mechanical interlocking between feedstock particles, hence leading to formation of stronger intermolecular bonding at the contact areas of the particles [49].

Biomass densification equipment can classified according to their working principles and these include piston press, screw press, roller press, manual presses and pelletizer [72]. The description and working principle of the equipment are briefly highlighted below:

(a) Screw press

Screw press technology (Fig. 3) is a type of mechanical press machine, which consists of a screw extruder and die with or without a heater [66].

In this type of equipment, the raw material is fed into the feedstock hopper and flows into the conical compression zone through a screw extruder and compressed to a high pressure [73]. In the case of screw press with heated dies, the biomass is continuously extruded by one or more screws through an externally heated tapered die [74]. Usually, the output of this machine has partially carbonized outer surface, which enhances ignition and combustion characteristics [20]. However, the limitations of this technology include restricted moisture content $<$12 % and particle size $<$4 mm as well as high rate of wear of the screw and power requirements [73].

(b) Piston press

Piston press is the simplest and most widely used briquetting technologies which comprises a piston and die. Fig. 4 illustrates a piston press briquetting machine.

Biomass is fed into the chamber, and a reciprocating piston at a high pressure compresses the biomass against the die to produce briquettes, which usually retain the shape of the die [73]. As the feedstock is thrust through the die, the heat generated causes release of inherent lignin, which acts as a natural glue to bind the material. After emerging from the die, the lignin solidifies and holds the particles of solid cylindrical briquettes [49].

Essentially, mechanical and hydraulic piston presses are the two types of piston presses with the same principle of operation. However, in the case of hydraulic press, the energy to the piston is transmitted from hydraulic motor via a high-pressure hydraulic system instead of electric motor as in the case of mechanical press [63]. Additionally, mechanical presses produce hard and dense briquettes in contrast to hydraulic presses, which produce less dense and sometimes soft and friable briquettes [49]. However, hydraulic press can tolerate higher moisture content than the usually accepted 15 % moisture content for mechanical

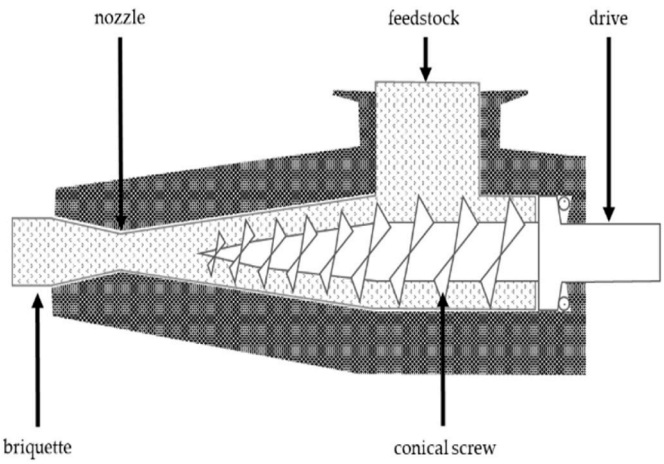

Fig. 3. Screw Press [35].

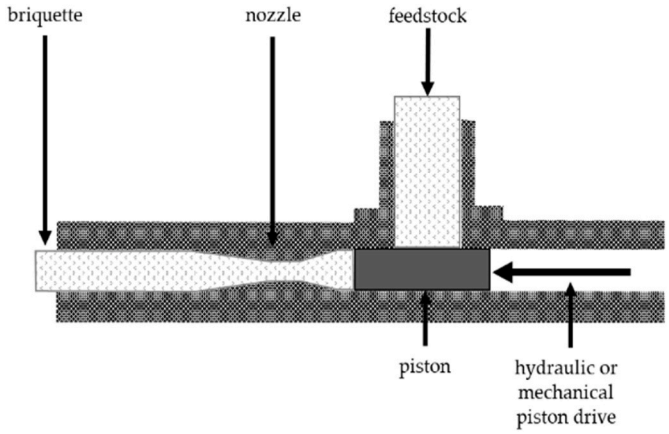

Fig. 4. Piston press [35].

piston presses [66]. Importantly, piston press technology is cost effective although it suffers from wear of the ram and produces less homogenous and friable briquettes since carbonization of the outer layer is impossible [20,49]. Presently, piston press and screw extrusion machines are two high-pressure technologies used for briquetting [72].

(c) Roller Press

A roller press consists of small dies, which are drilled circumferentially on a thick disc and produces small-sized densified product known as pellets. In this case, the biomass material is passed through a set of rollers, which rotate in opposite directions into flat or ring die and hence acquires the shape of the die [75]. Fig. 5 illustrates a roller press briquetting machine. This machine can briquette carbonized biomass but requires a binder in the briquetting process.

(d) Manual Press

Manual press (Fig. 6) may either be in the form of piston or screw

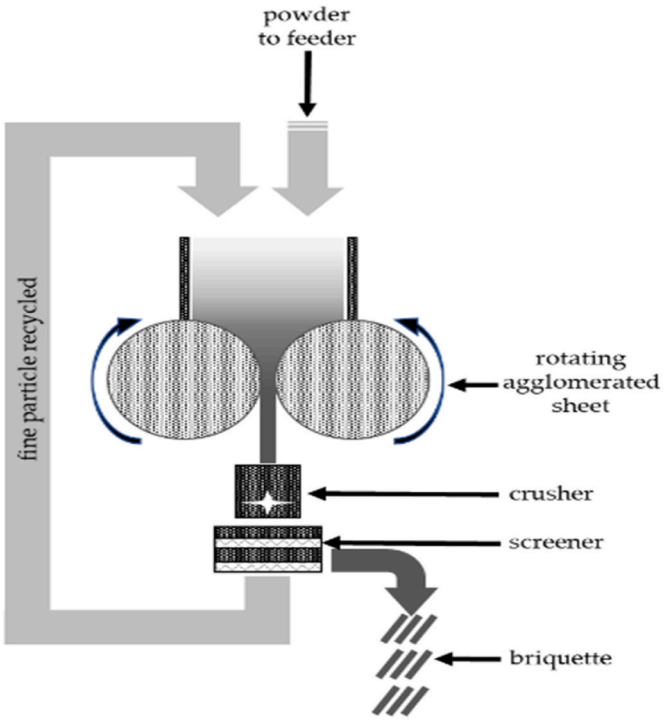

Fig. 5. Roller press [35].

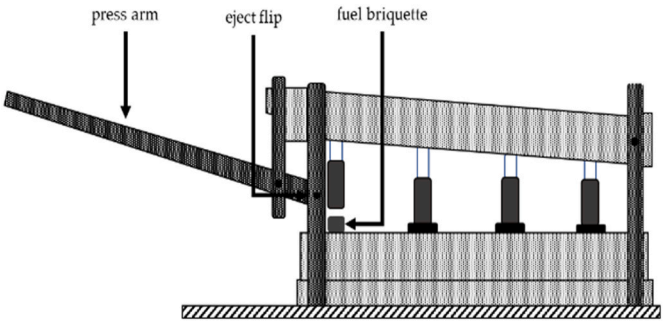

Fig. 6. Manual press [35].

press but is operated with bare hands.

Densification using this technology requires the use of a binder. In comparison to other technologies, this technology requires low initial cost, operating cost, and operating skill as well as minimal pressure. However, it has a low production capacity of about 5 kg/h or 50 kg in 10 h/day [35]. Additionally, hand molded compaction is another form of manual briquetting technology. In this case, the feedstock to be briquetted is pressed in the palm of hand or in small containers. Usually, the shape formed by the hood of the palm determines the shape of the final briquette, which may be shapeless but in most cases, ball-shaped [76]. Furthermore, the briquettes formed require sun drying or curing using furnace to form strong briquettes [20].

(e) Pelletizer

Pelletization is similar to briquetting, except that pelletizers use smaller dies to produce smaller densified products known as pellets [4]. For instance, according to Austrian (ONORM M 7135) standard, the diameter and length of pellets range from 4.0 to 10.0 mm and 20–50 mm respectively [59,60]. Additionally, pelletizers have a number of dies arranged as holes bored in a thick steel disc ring and the material is forced into the dies by means of rollers moving over the surface on which the raw material is distributed [77]. Therefore, pressure is generated by compression of the layer of material as the roller moves perpendicular to the centre line of the dies. Generally, pellet presses comprise the ring die and flat die types in which the die remains stationary, and the rollers rotate. Conversely, there are some rotating die pellet mills which have rollers that remain stationary during the production process [63].

4. Dry briquetting/pelleting process of lignocellulosic residues

The steps involved in production of briquettes and pellets include feedstock preparation, densification and drying or cooling the end product [49,78]. Usually, torrefied briquettes and pellets are produced either by densifying the torrefied feedstock or torrefying the densified material [79]. Therefore, the process scheme for production of raw and torrefied briquettes/pellets is summarized in Fig. 7.

4.1. Feedstock preparation

Usually, feedstock preparation depends on the nature of the substrate and desired end product. It may entail sorting/washing, drying, size reduction, torrefaction and blending/binder addition as described in the next subsections. Sorting and/or washing helps to remove foreign materials in the feedstock that can affect not only the quality of the densified product but also performance of the machine [35].

4.1.1. Drying the feedstock

Feedstocks are typically dried either by natural or industrial methods. Natural drying method involves irradiation of biomass with

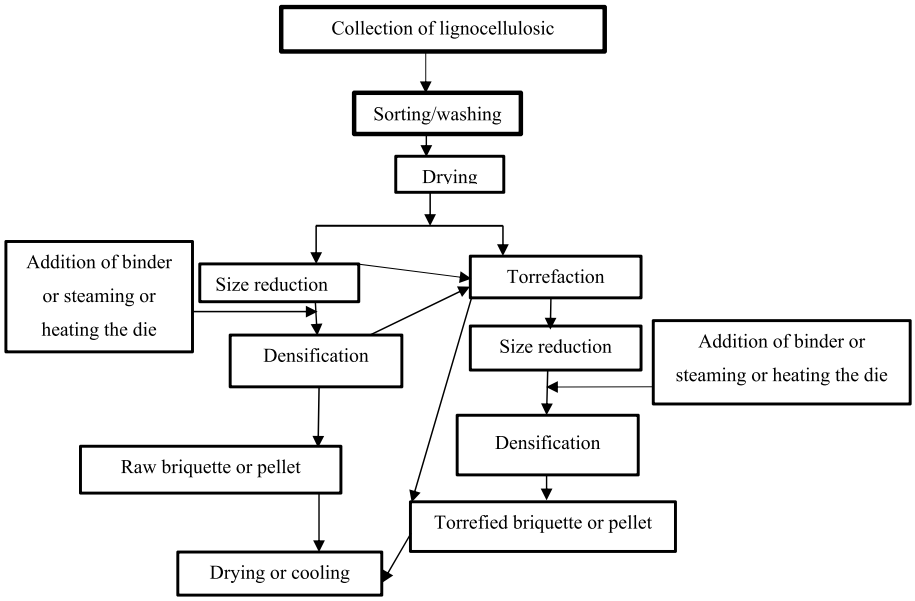

Fig. 7. Process scheme for production of raw and torrefied briquette/pellet.

solar radiation or exposing it to wind. Although this method is more simple and cheaper, it is highly dependent on weather condition [80]. In contrast, industrial drying involves the use of Pneumatic or indirect forced dryers. Indirect dryers are mostly used when the moisture content of the biomass is >50 % [81]. The moisture content of the feedstock, surrounding temperature and humidity determine the length of time to attain an optimum level of moisture suitable for densification [82].

However, sufficient amount of moisture needs to be present in the feedstock to ease densification process. In some cases, biomass materials are soaked in water for a number of days to make them loose and easy to compact either by machine or hand [49]. Basically, water serves as a binding agent and lubricant during briquetting and also facilitates formation of van der Waals' forces by increasing the area of contact between particles [66]. Additionally, moisture in the feedstock aids briquetting especially when water-soluble compounds such as starch, sugar, soda ash, sodium phosphate, potassium salt and calcium chloride are present [83]. Furthermore, moisture content of the feedstock affects the energy requirement for densification. For instance, the energy requirement for briquetting corn stover at a pressure of 5 MPa reduced from 12.64 to 11.18 MJ/t when the moisture content was increased from 5 to 15 % wb [84]. Conversely, high amount of moisture trapped within the particles of biomass hinders complete flattening and release of natural binders due to incompressibility of water [56]. Furthermore, high moisture content poses challenges in grinding as it would require excessive energy for drying [49]. Therefore, the acceptable moisture content of biomass feedstock to be used in densification ranges from 5 to 15 % [18,31].

4.1.2. Feedstock size reduction

Feedstock size reduction can be classified as chopped (50–250 mm), chipped (8–50 mm) and ground (<8 mm) [4]. The most common size reduction equipment includes hammer mill, knife mill, linear knife grids, and disk attrition [35]. Size reduction leads to partial break down of lignin, increase in total surface area of contact and stronger inter particle bonding [35], which ultimately improve the physicomechanical properties of briquettes. Additionally, smaller particle sizes enhance density, combustion period [85] and surface smoothness [49,86] and also lower porosity of briquettes due to their ability to fill void spaces much easily [87]. Consequently, successful and effective briquetting requires feedstocks with particle sizes ranging from 1 to 10 mm [88] with 10–20 % powdery components [66]. Briquetting biomass with coarse particles requires higher compacting power and also lowers the uniformity and stability of briquettes.

Many quality attributes of briquettes are affected by variation in particle sizes of the feedstocks. For example, increasing the particle sizes of water hyacinth from 0.5 to 4 mm caused the relative change in length of the resultant briquettes to range from 6.15 to 17.785 after immersion in water [89]. This is consistent with the results obtained by Orisaleye et al. [51] for corn cob briquettes in which the particle sizes were varied from <2.5 to >2.5 mm. In addition, particle size variation of spruce and pine from 150 to 300 μm caused the density of briquettes to decrease from 1178 to 950 kg/m [51]. Similarly, increasing the particle sizes from 0.5 to 3 mm at fixed densification pressure of 95 MPa reduced density of briquettes produced from fast-growing willows from 800 to 500 kg/m^3 [90]. Similarly, varying particle sizes of rice residues from ≤0.003 to 0.301–0.990 mm decreased the density of briquettes from 605 to 506 kg/m^3 [91]. On the other hand, reducing the particle sizes from 4.70 to 0.60 mm of corn cob with 20 % starch mutillage reduced the density from 750 to 600 kg/m^3 [74]. Although size reduction is necessary in production of quality briquettes, very fine particles are undesirable as they increase the cost of production [86] and lengthen ignition time of the resulting fuel [92].

4.1.3. Torrefaction

Biomass torrefaction can be performed as a pretreatment technique or part of feedstock preparation. Torrefaction is a thermal pretreatment conducted at temperatures between 200 and 300 °C in an inert atmosphere [93]. According to Tumuluru et al. [94] dry torrefaction comprises four simple steps: heating; drying (pre and post drying); torrefaction-isothermal heating; and cooling. Pre drying occurs at 100 °C with removal of surface water present on the biomass. On the other hand, post-drying, which ranges from 100 to 200 °C is characterised by removal of bound moisture and some light hydrocarbons. Torrefaction-isothermal heating, which starts at 200 °C leads to devolatilisation and carbonization of hemicellulose, depolymerisation, devolatilisation, and softening of lignin as well as depolymerisation and devolatilisation of cellulose. Devolatilisation occurs at temperatures above 200 °C [95]. Additionally, partial and selective degradation of hemicelluloses and some extractives lead to devolatilisation [96,97]. Consequently, volatiles and dark colored solid product called bio-char are formed [98].

Bio char, which is the main product of torrefaction [99] has

properties intermediate between precursor biomass and charcoal [100]. It has numerous areas of applications, which are not limited to co-firing [101], gasification [102], pyrolysis [103], adsorption [104], soil amendment [105], metallurgical applications [106] and densification [107]. Densification helps to enhance the energy density of the bio-char [19].

4.1.4. Addition of binder

Adding a binder to a feedstock during briquetting not only minimises mold wear but also enhances cohesion characteristics and mechanical strength of briquettes [52,108]. This eventually reduces transportation and storage costs [109]. It is recommended that, adding 5–25 % of adhesive to a feedstock produces high-quality briquettes [110]. Typically, organic (molasses, tar pitch and starch binders), inorganic (clay, lime, plaster, cement, sodium silicate and sodium silicate) and composite/-compound binders are used in briquetting or pelleting [109]. A binder can exist as a liquid or solid that forms a bridge, film, matrix, or causes a chemical reaction to occur and form strong inter-particle bonding [64]. Generally, quality binders should be non-polluting, environmentally acceptable, affordable and combustible [109].

The type and ratio of additive used affect the physicochemical and mechanical properties of briquettes. For example, increasing the concentration of cassava-wheat in carbonized groundnut shell from 25 to 35 g, increased the drop strength of briquettes from 70 to 85 % [111]. Additionally, varying the concentration of molasses, cow dung and clay binders from 10 to 15 %, in charcoal dust-rice husk-bagasse dust composite increased the density of briquettes from 628 to 703 kg/m^3, 576–645 kg/m^3 and 537–586 kg/m^3 respectively [112]. This study also revealed that unlike clay and cow dung, molasses had better gluing effect on the adjacent particles and produced briquettes with stronger bonds and minimal expansion after extrusion. The effect of binder on the physicomechanical properties of briquettes/pellets is further illustrated in Table 2.

The compressive strength of pellets made from rice husk bio-char using lignin, starch, $Ca(OH)_2$ and NaOH as illustrated in Fig. 9 increased with increase in proportion of each type of binder [117]. This is consistent with the results obtained by Aransiola et al. [116] as illustrated in Table 2 for carbonized corn cob separately blended with cassava starch, corn starch and gelatine. The increase in compressive strength with concentration of the binders can be attributed to enhancement in bonding between the particles of rice husk bio-char.

Hu et al. [117] revealed that the compressive energy consumption during pelletization of rice husk bio-char using lignin, starch, $Ca(OH)_2$ and NaOH decreased with increase in concentration of binders as illustrated in Fig. 8. The decrease in compressive energy with increase in proportion of the binders can be attributed to decrease in friction between the feedstock particles as well as between feedstock and the wall of the die.

The moisture uptake of pellets made from rice husk bio-char at 70 % relative humidity and temperature of 30 °C increased with increase in

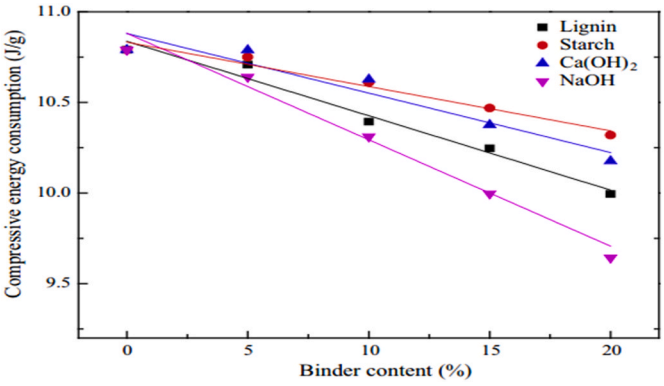

Fig. 8. Energy consumption of the bio-char pellet as a function of binder type and content [117].

Table 2
Effect of binder on the physicomechanical properties of densified solid biofuels.

Biomass material	Binder	Binder proportion (%)	Physicomechanical properties of briquettes/pellets					Reference
			Density (kgm^{-3})	Moisture absorption(%)	Compressive strength/ Tensile strength (MPa)	Shatter resistance(%)	Tumbling resistance(%)	
Sawdust	Okra waste	5–20	570.34–626.45	–	0.022	96.78–98.92	93.58–95.68	[113]
Rice husk* + bagasse*+charcoal dust	Molasses	10	628.0	–	–	–	–	[112]
		15	675.0					
		20	703.0					
	Clay	10	537.0	–	–	–	–	[112]
		15	565.0					
		20	586.0					
	Cow dung	10	576.0	–	–	–	–	[112]
		15	601.0					
		20	645.0					
Rice straw char	tapioca starch	4	764.3	–	25.34	–	–	[114]
		8	808.8		37.74			
		12	885.5		51.42			
	Corn starch	4	812.5	–	53.25	–	–	[114]
		8	865.2		49.40			
		12	916.8		68.01			
Sawdust	Steam-treated spruce sawdust	0	1044.6	16.85	0.31*	–	–	[115]
		10	1095.92	14.99	0.56*			
		20	1114.14	14.65	0.74*			
Carbonized corn cob	Cassava starch	10	1299.11	–	4.23	–	–	[116]
		20	1393.32		6.76			
		30	1437.42		8.32			
	Corn starch	10	1155.54	–	3.70	–	–	[116]
		20	1240.34		4.88			
		30	1308.75		5.42			
	Gelatine	10	1090.51	–	3.05	–	–	[116]
		20	1175.75		4.24			
		30	1231.53		5.05			

Note: * Tensile strength.

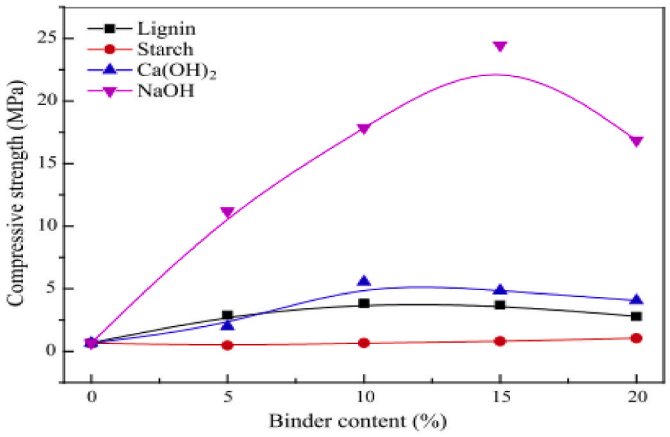

Fig. 9. The compressive strength of the pellets as a function of binder content [117].

the proportion of each type of binder. The level of moisture uptake by pellets made using different binders followed the order NaOH > lignin > starch > $Ca(OH)_2$ >no binder as depicted in Fig. 10 [117]. However, increasing the proportion of steam treated spruce sawdust in sawdust decreased the moisture absorption of the densified product as shown in Table 2 [115]. Generally, the moisture adsorption of pellets is affected by the degree of hydrophobicity of the binder used.

4.1.4.1. Effect of blending on combustion properties. Blending feedstocks potentially enhances the combustion characteristics of the resulting fuel [118,119]. Typical combustion properties of briquettes/pellets that can be affected by addition of additives include burn rate, burning time, ignition time and calorific value. For this reason, Table 3 provides an auxiliary explanation on the effect of binder on combustion properties of briquettes/pellets.

The effect of blending feedstocks on combustion properties of the resultant densified products is dependent on their inherent characteristics. For instance, increasing the concentration of groundnut shell in waste paper from 5 to 25 % at a pressure of 30 MPa and dwell time of 5 min increased the burn rate from 8.517 to 18.883 g/min [121]. Increasing the proportion of banana residues in rice husk from 0 to 40 % increased the burn rate from 0.1476 to 0.2055 g/min [120]. On the other hand, increment in concentration of plantain peels binder from 10 to 50 % in water hyacinth briquettes decreased the burning rate from 2.30 to 1.57 g/min [114].

A study by Davies [114] revealed that raising the concentration of plantain peels from 10 to 50 % increased the ignition time of water hyacinth briquettes from 66.61 to 107.92 s. However, increasing the concentration of spear grass in coal from 10 to 50 % reduced the ignition time from 186 to 33 s [122]. Similarly, increasing the concentration of molasses, clay and cow dung in rice husk-bagasse-charcoal composite

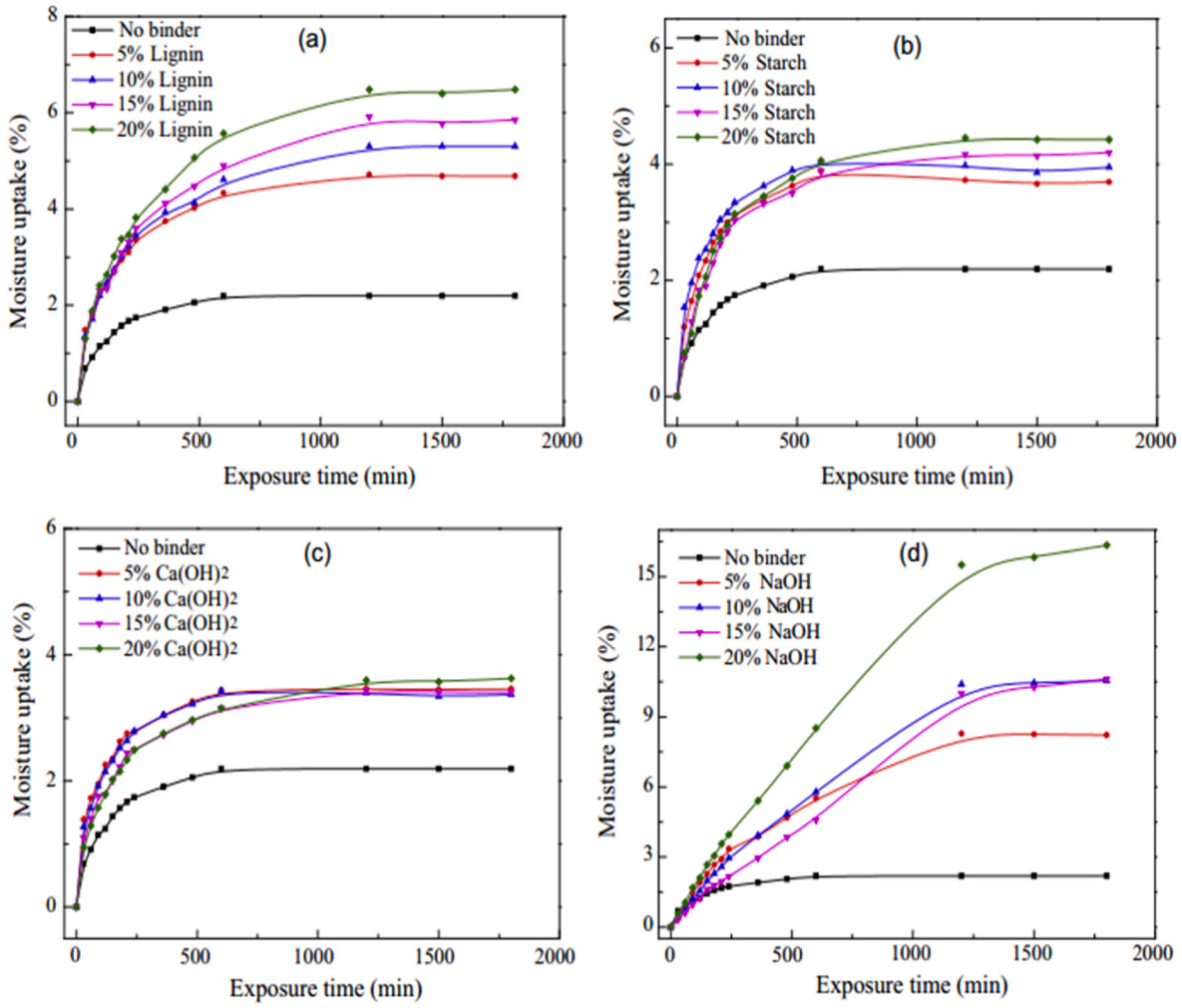

Fig. 10. Moisture uptake rate of the bio-char pellets compressed with different binders at a relative humidity of 70 % and a temperature of 30 °C: (a) lignin pellets, (b) starch pellets, (c) $Ca(OH)_2$ pellets and (d) NaOH pellets [117].

Table 3
Effect of binder type and concentration on combustion properties of briquettes/pellets.

Lignocellulosic waste	Binder	Binder proportion (%)	Combustion properties of briquettes/pellets				Reference
			Burning time (min)	Burn rate ($gmin^{-1}$)	Ignition time (s)	Calorific value (MJ kg^{-1})	
Sawdust	Okra waste	5	–	–	–	17.82	[115]
		10				17.61	
		15				17.49	
		20				17.38	
Water hyacinth	Plantain	10–50	–	2.3-1.68	66.61–107.92	–	[115]
Rice husk	Banana residue	0–40	–	–	–	19.60	[120]
Carbonized rice husk and bagasse + charcoal dust	Molasses	10	20.8	–	8.0	26.8	[112]
		15	29.0		11.0	26.1	
		20	35.2		14.6	25.2	
	Clay	10	40.0	–	15.0	14.6	[112]
		15	52.0		21.0	13.4	
		20	61.0		24.0	11.3	
	Cow dung	10	27.0	–	10.0	18.5	[112]
		15	32.0		13.0	17.6	
		20	43.0		17.0	16.1	
Rice husk bio-char	No binder	–	–	–	–	19.0	[117]
	Lignin	5	–	–	–	19.31	[117]
		10				19.36	
		15				19.49	
		20				19.34	
	Starch	5	–	–	–	19.35	[117]
		10				19.40	
		15				19.45	
		20				19.38	
	$Ca(OH)_2$	5	–	–	–	18.43	[117]
		10				18.08	
		15				17.15	
		20				16.20	
	NaOH	5	–	–	–	18.99	[117]
		10				18.65	
		15				17.89	
		20				17.79	
Rice straw char	Tapioca starch	4	–	0.08901	14.76	–	[114]
		8		0.08159	17.28		
		12		0.08371	17.92		
	Corn starch	4	–	0.09146	15.28	–	[114]
		8		0.07933	17.90		
		12		0.08191	18.19		
Groundnut shell	Waste paper	75	18.65	–	48.84	19.51-19.92	[121]
		80	20.91		45.97		
		85	23.43		45.33		
		90	24.64		43.67		
		95	26.07		41.34		

from 10 to 25 % increased the ignition time of the briquettes from 8.0 to 14.6, 15.0–24.0 and 10.0–17.0 s respectively [112].

Furthermore, varying the concentrations of molasses, clay and cow dung binders in charcoal dust-rice husk-bagasse dust blend from 10 to 25 % decreased the calorific values of briquettes from 26.8 to 25.3 MJ/kg, 14.6–11.3 MJ/kg and 18.5–16.1 MJ/kg respectively [112].

Typical burning characteristics of quality briquettes include long burning period, smokeless, odorless and ease in ignition. These are dependent on the nature of feedstock and binding agent used. Compared with weak binders, strong binders stick together the particles of feedstock and reduce the pore spaces in the densified product. This reduces the infiltration of oxygen and outflow of combustion products, hence increasing the burning duration and ignition time.

4.1.5. Steaming or heating the die

Steaming feedstock or heating the die containing the biomass material before densification helps to facilitate release and activation of the inherent natural binders such as lignin and water-soluble compounds. More specifically, lignin acts as a glue to bond cellulose fibers during binderless densification [49]. Steam is mostly used in conditioning feedstocks during pelletization [121–123].

4.2. Cooling or drying briquettes/pellets

As hot briquettes or pellets cool, the inherent lignin exothermically forms solid bridges, which help to strengthen the product. In contrast, formation of solid bridges during drying occurs endothermically [124]. Importantly, cooling helps to reduce the tendency of briquettes/pellets to crack due to stress between layers at different temperatures [61].

5. Effect of torrefaction

Torrefaction affects densification process requirements, physicomechanical and combustion properties of bio-briquettes as discussed in each of the following subsections.

5.1. Effect of torrefaction on biomass densification

Torrefaction process leads to loss of surface and bound moisture, lowering of volatile matter content and depolymerisation of lignin, which serves as a natural binder during high pressure and temperature densification [124–126]. This affects the specific energy, amount of moisture and binder required for densification of torrefied biomass.

Specific energy requirement for densification is the sum of

compression and ejection energy required to produce a unit mass of briquette or pellet [84]. Literature has shown that the specific energy requirement for densification increases with torrefaction severity. For instance, the energy requirement for densification of wheat straw torrefied at 250 °*C* exceeded that of its raw counterpart by 53 kWh/t [19]. Similar findings were reported for wheat straw and corncob in which the specific energy requirement increased from 46.6 to 99.9 and 63.1–82.1 $kWht^{-1}$ respectively [19]. Therefore, binderless production of torrefied briquettes or pellets from charred lignocellulosic residues requires high die temperature and greater compression pressure to obtain fuel of desirable qualities [127,128]. As a remedy, preconditioning torrefied biomass with about 10 % moisture renders the densification process relatively easier, reduces friction and improves bonding [129], hence the quality of densified product [130,131]. Usually, Water or steam acts as a plasticizer and lowers the softening temperature of lignin [132], hence the specific energy requirement for densification. For instance, raising the proportion of water in woody bio-char from 20 to 40 % decreased the energy required for pelletization from 25.51 to 16.25 J/g [133].

According to ENplus standards, steam and other pellet quality enhancing additives may be used up to 2 % level [19]. Thus, production of commercial quality pellets using torrefied feedstocks would require incorporation of a binder or blending the thermally processed material with other feedstocks [134]. For example, several researchers have demonstrated that different bio-based additives such as castor bean cake [135], rapeseed cake [136], and rapeseed oil [125] as well as alkali lignin, glycerol, and L-proline [126] could be used for densification of torrefied biomass. According to Cao et al. [135] pelletization of torrefied biomass with 15 % castor bean cake produced high-quality fuel pellets without the need for high die temperature and compression pressure. Generally, incorporation of an additive in a torrefied biomass material lowers the energy requirement for densification [137].

5.2. Effect of torrefaction on physicomechanical properties

Density, compressive strength, impact resistance and resistance to water absorption are typical examples of physical and mechanical properties of briquettes/pellets. Compressive and impact resistance are taken as indicators of mechanical durability of densified product. In simple terms, mechanical durability is a quality parameter that determines the ability of densified biofuels to remain intact during handling, transportation and storage [138]. According to the ASTM D440-86 standard, the durability value of an ideal briquette must be >90 %. Generally, durability of densified torrefied biomass material depends on the feedstock characteristics, degree of torrefaction [19,21] and densification process conditions. Usually, the physicomechanical properties are affected by the degree of severity of torrefaction process [115]. For instance, the compressive strength of briquettes produced from torrefied groundnut shell mixed with cassava starch increased from 0.94 to 3.66 MPa [139]. This is consistent with the results obtained by Akogun et al. [140] for the admixture of corn husk and sawdust in which torrefaction increased the compressive strength of the densified product by 0.55 N/mm^2.

Additionally, the resistance to water absorption of briquettes has been shown to increase with increase in torrefaction severity. For example, briquetting torrefied sawdust reduced the water absorption of briquettes from 16.85 to 13.72 % [115].

Furthermore, particle density is commonly taken as a measure of durability, for example, high particle density leads to a high durability [141]. Literature has shown that briquetting torrefied biomass with a binder produces briquettes with higher density compared with their raw counterpart. For instance, torrefying corncob and sawdust at 300 °*C* and then mixing them at 90:10 proportion with 10 % deionized water and starch binder increased the density of briquettes by 83 kg/m^3 compared with raw briquettes prepared under similar conditions [140]. Similarly, torrefying groundnut shell and mixing it with cassava starch increased the density from 602 to 1450 kg/m^3 [139]. However, binderless densification of torrefied biomass materials produces densified product with lower density. For instance, densifying torrefied cassava rhizome reduced the density from 1270 to 810 kg/m^3 [142].

Generally, decrease in density increases the susceptibility of pellets/briquettes to breakage and fine generation during handling, transportation, and storage [21]. The reduction in density of torrefied biomass densified without a binder could be attributed to loss of water and thermal degradation of compositional contents, which act as plasticizers and facilitators of bond formation during compaction. Unlike raw briquettes, torrefied briquettes have superior hydrophobicity over raw ones due to loss of hydroxyl groups and formation of non-polar C–C bonds [143]. Table 4 further highlights the effect of torrefaction on physicomechanical properties of briquettes.

5.3. Effect of torrefaction on combustion properties

Torrefying biomass feedstock affects the calorific value, burning rate and energy density of the resultant briquettes. For example, densifying wheat straw torrefied at 250 °*C* increased the calorific value from 18.9 to 19.1 MJ/kg [19]. This is consistent with the results of a study by Granado et al. [142] in which torrefaction increased the calorific value of cassava rhizome briquettes from 17.8 to 19.2 MJ/kg. Furthermore, a study by Agar et al. [19] revealed that the energy density of briquetted wheat straw torrefied at 250 °*C* increased by 3.6 GJ/m^3. The heating value and energy density of biomass material increase with the degree of severity of torrefaction as more hydrogen and oxygen than carbon are lost, hence more carbon that can be oxidized to release energy is left behind [94,144]. Table 4 highlights the effect of torrefaction on properties of torrefied briquettes/pellets.

6. Quality parameters of briquettes/pellets

The quality of briquettes or pellets is a function of feedstock parameters (particle size, external additives and moisture content) as well as operating parameters (compacting pressure, residence time and temperature) [108]. Compressive strength, impact resistance, moisture absorption or adsorption, and density discussed in the subsequent subsections are the most important quality attributes of briquettes/pellets [145]. Compressive strength, impact resistance, and density are used as predictors of the effectiveness of densification process, which enables the densified product to withstand destructive forces experienced during handling, storage, and transportation [4]. Table 5 highlights the limit values for physicomechanical and chemical properties of pellets/briquettes.

6.1. Density

Density of briquettes can be expressed either as compressed or relaxed density. Compressed density is the density of briquette just after compaction while relaxed density represents the density measured after a certain period following compaction [146]. Briquettes with higher density have higher energy-to-volume ratio and are desired to reduce handling, transport and storage costs [147–149]. According to the German Standard DIN 51731, briquettes/pellets of good quality should have particle density of 1000− 1200 kg/m^3.

The density of briquettes/pellets is influenced by a number of process variables such as moisture content, particle size, type and quantity of binder, as well as compaction temperature and pressure [20,73,150]. For example, Increasing compacting pressure (20–110 MPa) increased the bulk density (589–1082 kg/m^3) of chestnut briquettes [151]. Similarly, increasing the compacting pressure from 10 to 50 MPa of hardwood species (P. Africana) of particle sizes 1–2 mm increased the relaxed density from 441 to 723 kg/m^3 [152]. The rise in density with increase in pressure can be attributed to elimination of inter-particle voids as biomass particles are forced closed to one another.

Table 4
Properties of raw/torrefied briquettes.

Biomass material	Binder	BP (%)	Density (kgm^{-3})	DU (%)	TS (Mpa)	MA (%)	CV ($MJkg^{-1}$)	BR ($gmin^{-1}$)	ED GJm^{-3}	ERD ($kWht^{-1}$)	Reference
Groundnut shell	Cassava starch		620	–	0.94**	–	25.20	0.80	–	NR	[139]
Bio-char groundnut shell	Cassava starch		1450	–	3.66**	–	45.20	1.68	–	NR	[139]
Sawdust	Steam-treated spruce sawdust	0	1044.60	–	0.31	16.85	–	–	–	NR	[115]
		10	1095.92		0.56	14.99					
		20	1114.14		0.74	14.65					
Torrefied Sawdust	Steam-treated spruce sawdust	0	1039.77	–	0.21	13.72	–	–	–	NR	[115]
		10	1035.28		0.27	14.54					
		20	1068.67		0.72	13.65					
Wheat straw	–	–	551*	93.5	–	–	18.9	–	8.3	46.6	[19]
Wheat straw torrrefied at 250 °C	–	–	671*	94.5	–	–	19.1	–	11.9	99.6	[19]
Corn cob	–	–	718*	96.9	–	–	18.5	–	11.3	63.1	[19]
Corn cob torrefied at 260 °C	–	–	662*	94.2	–	–	21.2	–	12.6	82.1	[19]
Raw CRB	–	–	1270^	99.9	–	–	17.8	–	–	NR	[142]
CRB torrefied at 250 °C	–	–	810^	99.1	–	–	19.2	–	–	NR	[142]

Note: * - Bulk density of pellets, TS-tensile strength, **- compressive strength, BP- binder proportion, DU- durability, MA - moisture absorption, CV - calorific value, BR - burn rate, ED - energy density, ERD - energy requirement for densification, ^ - relaxed density, CRB - cassava rhizome briquettes and NR - not reported.

Table 5
Limit values for physicomechanical and chemical properties of pellets/briquettes.

Quality parameter	Limit values	Test standards
Density	1000-1400 kgm^{-3}	German standard DIN 51731
Water resistance	95 %	ASTM 870-15
Shatter index	≥ 90%	ASTM D440-86
Compressive strength	>1.0 MPa	ASTM D2166-85
Durability	95 %	ISO 17831-2
Calorific value	15.5–19.50 MJ/kg	German standard DIN 51731
Moisture content	<12 %	German standard DIN 51731
Ash content	≤ 1.0%(minimum) ≤ 3.0%(maximum)	ASTM D317-12
N	<0.3 %	German standard DIN 51731
S	<0.08 %	German standard DIN 51731
Cl	<0.03 %	German standard DIN 51731

Raising the briquetting temperature of wheat straw from 77 to 150 $^{\circ}C$ increased the bulk density of the resultant briquettes from 423 to 528 kg/m^3 [135]. Similarly, increasing temperature from 90 to 120 $^{\circ}C$ increased the relaxed density of corn cob briquettes from 570 to 1300 kg/m^3 [87]. The increase in density with increasing temperature can be ascribed to thermal softening of biomass, which reduces resistance to plastic deformation when a load is applied.

Meanwhile, changing the particle size of sawdust (A. Robusta) from <1 mm to 2–3.35 mm at a pressure of 10 MPa decreased the relaxed density from 440 to 345 kg/m^3 [152]. This is consistent with the results reported by Harun and Afzal [118] in which reduction in particle size of spruce and pine sawdust from 425 to 150 μ m resulted into increase in relaxed density between 943 and 1178 kg/m^3. The increase in density with reduction in particle size of biomass feedstock could be due to the fact that smaller particle sizes unlike coarse particles have higher surface area of contact and can fill the voids between the particles much easily. This enhances inter-particle bonding and reduces volume under pressure.

Besides, increasing the holding time from 60 to 120 s for cassava rhizome waste at a pressure of 102 MPa, elevated the relaxed density from 766 to 785 kg/m^3 [21]. On the other hand, increasing holding time from 0 to 60 s of oak sawdust at 9.7 % moisture content had no significant effect on relaxed density of logs produced at a pressure of 138 MPa than at a lower pressure of 34 MPa [153]. This is also consistent with the results reported by Chin and Siddiqui [154] where increase in holding time had no proper trend in the variation of relaxed density of densified sawdust, rice husk, peanut shell, coconut shell and palm fibre.

Furthermore, increase in moisture content of oak sawdust from 8.9 to 15.1 % at a pressure of 138 MPa, decreased the relaxed density from 915 to 761 kg/m^3 [153]. Contrarily, rise in moisture content of wheat straw from 7 to 18 % at a pressure of 800 MPa increased the bulk density of briquettes from 325 to 528 kg/m^3 [155]. The decrease in density with increase in moisture content can be attributed to the moisture trapped within the particles, which may prevent complete flattening and release of natural binders owing to the incompressibility of water [56]. However, the presence of water-soluble compounds such as starch, sugar, soda ash, sodium phosphate, potassium salt, and calcium chloride could be adduced to explain the increase in density with increase in moisture content during briquetting [83]. Usually, each feedstock has its own unique set of optimum densification process conditions required for briquettes/pellets with optimum density to be produced.

6.2. Resistance to water penetration

The resistance to water penetration is particularly important to simulate the behaviour of briquettes when stored or transported in high humid environment or when exposed to rain [146]. It can be reported either descriptively in terms of tendency and time to disintegrate or as percent absorption [156]. According to Richards [156], water penetration resistance obtained from the time for disintegration of briquettes immersed in water should be > 20 min.

Factors that affect resistance to water penetration of briquettes include hydrophobicity of the binder [157], particle size, temperature and holding time [51]. For example, varying temperature of corn cob from 90 to 120 °C, increased the resistance to water penetration of briquettes from 32.6 to 94.8 %, for all particle sizes (<2.5 mm and >2.5 mm), die pressures (9–15 MPa) and holding times (7.5–15 min) [51]. Arguably, high temperatures activate the natural binding agents such as lignin, protein, starch and water soluble carbohydrates. These binders improve bonding between the particles due to better flow or plastic properties at elevated temperatures [158].

Furthermore, a study by Ref. [51] revealed that increasing the holding time from 5 to 15 min at pressures between 9 and 15 MPa had an increasing trend on the water penetration resistance of briquettes. Longer holding time allows appreciable quantity of natural binders such

as lignin to be released and coat the particles of the feedstock. As a result, the inter-particle bonding is enhanced, hence the resistance to water penetration.

Additionally, at a temperature of 120 °C and holding time of 7.5 min, increasing pressure from 9 through 12 up to 15 MPa revealed that between 9 and 12 MPa, there was an increasing trend in water penetration resistance while between 12 and 15 MPa, the water penetration resistance was nearly constant [51]. Orisaleye et al. [51] further reported that increasing the particle sizes from <2.5 to >2.5 mm had an increasing trend in the water penetration resistance of briquettes at pressures between 9 and 15 MPa, temperatures between 90 and 120 °C and holding time of 7.5 mm. Generally, larger particle sizes of feedstocks give rise to porous briquettes with poor resistance to water penetration [159].

Furthermore, raising the moisture content of biomass-bituminous blend from 0 to 5% elevated the water penetration resistance of the resultant briquettes from 84.66 to 88.33 % [160]. It can be argued that adequate amount of binding agent in the feedstock promotes interlocking of the particles thus leading to negligible pore spaces and improvement in resistance to water penetration [161].

Literature shows that water penetration resistance of briquettes is dependent on the feedstock characteristics as well as densification process variables. Therefore, careful control of feedstock characteristics and densification process variables enhances resistance to water absorption of briquettes.

6.3. Compressive strength

Compressive strength represents the maximum amount of compressive load a briquette can bear before fracturing or braking [56]. It is recommended that compressive strength ≥2.56 MPa [162] would prevent breakage of briquettes [62,122].

Compressive strength of briquettes depends on pressure, temperature, particle size, type and ratio of binder, moisture content of the feedstock and holding time. For example, increasing pressure on olive mill solid waste from 100 to 150 MPa decreased the compressive strength of briquettes produced without externally added binder from 1581 to 1557 MPa [163]. Conversely, varying the compaction pressure from 300 to 800 MPa on tea wastes at moisture content of 7.05 % increased the compressive strength of briquettes, which ranged between 8.7 and 18.8 MPa [59]. The trend of these results is consistent with that obtained by Muazu and Stegemann [149] for low rank coal and Granado et al. [21] for cassava rhizome waste. More specifically, a study by Granado et al. [21] indicated that varying pressure from 102 to 204 MPa at holding time of 60 s and moisture content of 11.8 %, enhanced the compressive strength from 0.62 to 1.10 MPa.

Application of higher pressures facilitate mechanical interlocking between the particles, thus leading to improvement in compressive strength [64,164]. It is also argued that, high pressure enhances adhesion between particles and formation of intermolecular bonds in the contact area as a result of decrease in the distance between the particles. Consequently, the van der Waals, liquid bridge and capillary forces typically increase with reduction in the distance between particles, hence leading to higher compressive strength [165]. Furthermore, increase in pressure leads to plastic and elastic deformations, molecule diffusion and closing up of void spaces between particles. All these increase the compressive strength of briquettes [149]. Typically, pressures in the range of 100–150 MPa or >150 MPa have been suggested for densification of biomass [56]. However, previous studies have shown that low compaction pressure can produce low-cost briquettes that are durable at low compaction pressure [62,166].

In addition, varying holding time from 60 to 120ressure of 204 MPa raised the compressive strength of cassava waste briquettes from 1.10 to 1.29 MPa [21]. Furthermore, increasing the moisture content of oak sawdust from 8.9 to 12.75 % decreased the compressive strength from 49 to 25 MPa [153]. Similarly, reducing the moisture content of low rank coal from 18.8 to 9.0 % increased the compressive strength from 1045.17 to 2090.34 kPa [167]. However, the compressive strength of biomass-bituminous composite briquettes increased from 0 up-to 3 % but further increase up-to 5 % caused reduction in compressive strength [160]. Arguably, right amount of moisture in the feedstock enhances adhesion of the particles, which eventually improves the compressive strength. On the other hand, high amount of moisture in the feedstock produces porous briquettes/pellets with low compressive strength.

6.4. Impact resistance

Impact resistance simulates the forces briquettes or pellets would encounter when they are being emptied from trucks onto ground, or shifting from one place to another [56,168]. It is a measure of the tendency of briquettes/pellets to resist dust production or breakage when subjected to destructive forces [108] and an indicator of mechanical strength [60].

Holding time, compaction pressure, temperature, binder and moisture content of feedstocks are typical factors that affect impact resistance of briquettes/pellets. For example, varying the holding time during densification of cassava rhizome waste from 0 to 120 s increased the durability of the briquettes from 65.3 to 78.8 % [21]. Additionally, the impact resistance index increased from 40 to 133 when pressure applied on oak sawdust increased from 34 to 38 MPa [153]. A study by Li and Liu [153] also revealed that increasing the moisture content of oak sawdust from 8.9 to 12.7 % at compaction pressure of 138 MPa and particle size <2.36 mm reduced the impact resistance index of logs from 133 to 100.

Several studies [60,169,170] have suggested that impact resistance > 80 % is required for better handling, storage and transportation. Generally, impact resistance index of densified products can be enhanced by optimising the same factors such as temperature, pressure, binder, moisture content, particle size and holding time, which affect density. However, literature on optimisation of the effect of these factors on impact resistance of raw and torrefied briquettes/pellets are scare.

7. Combustion characteristics of briquettes/pellets

Densification process conditions such as feedstock particle size, compaction pressure, temperature, binder, moisture content and holding time affect not only the physicomechanical properties but also combustion characteristics (burning rate, calorific value, and burning time and ignition time) of briquettes/pellets.

7.1. Ignition time

Ignition time is determined from the average time taken to attain a steady glowing flame [171]. A good quality briquettes for domestic use must be easy to ignite and possess low porosity index, volatile and ash contents [92]. Densification conditions may increase or decrease the ignition time of densified products depending on the nature of the feedstock. For example, a study by Aliyu et al. [172] revealed that varying compacting pressure from 420.4 to 630.4 kN/m^2 increased the ignition time of rice husk, saw dust and rice husk-saw dust composite briquettes in the range of 1.28–1.58 s. It can be argued that high compacting pressure improves the bonding between biomass particles by lowering porosity. As a result, mass transfer is hindered due to fewer free spaces for mass diffusion [114].

Furthermore, varying the concentration of plantain peels from 10 to 50 % increased the ignition time of water hyacinth briquettes from 66.61 to 107.92 s [92]. In the same way, increasing the proportion of orange peels in corn cob from 20 to 80 % raised the ignition time of the resultant briquettes from 3.58 to 5.35 min. Similar findings indicated that raising the individual concentration of molasses, clay and cow dung binders in rice husk-bagasse-charcoal composite from 10 to 25 % increased the ignition time of the resultant briquettes from 8.0 to 14.6, 15.0–24.0 and 10.0–17.0 s respectively [112]. Conversely, blending coal

with spear grass while varying its concentration from 10 to 50 % reduced ignition time from 186 to 33 s [122].

Additionally, reducing the particle sizes of cassava peels-rice husk composite from 2000 to 500 μm through 501-100 μm up to <100 μm at 70:30 proportion of cassava peels to rice husk, revealed that the optimum ignition time occurred at particle size of 501-100 μm and further reduction in particle size beyond the optimum point lead to decrease in ignition time [159]. In contrast, findings reportedy Nazari et al. [120] revealed that decrease in particle sizes of banana residue from 500 to 150 μm increased the burn rate from 4.33 to 8.30 s. Generally, for every feedstock, there in an optimum setting of the densification process conditions at which an optimum ignition time occurs.

7.2. Burnt rate

Burn rate is determined from the ratio of mass of fuel burnt to total time taken [173] or ratio of the length of briquette burnt to the total time taken. The combustion rate of the resulting briquettes/pellets is densification process conditions dependent. For instance, by increasing compaction pressure from 3 to 9 MPa decreased the burn rate of briquettes produced from rice bran and palm kernel shells from 2.3 to 1.7 g/min [174]. This is consistent with the findings reported by Aliyu et al. [172] in which varying pressure applied on rice husk, saw dust and their blend from 420.4 to 630.4 kN/m^2 decreased the burn rate. Generally, increase in compaction pressure reduces porosity of briquettes. Consequently, the rate of infiltration of oxidant and outflow of the combustion products are greatly hampered, hence the combustion rate [112].

In addition, varying the concentration of plantain peels binder from 10 to 50 % in water hyacinth decreased the burning rate of briquettes from 2.30 to 1.57 g/min [92]. Conversely, increasing the proportion of banana residues in rice husk from 0 to 40 %, increased the burn rates from 0.1476 to 0.2055 g/min [120]. Furthermore, increasing the proportion of cassava peels in rice husk blends from 10 to 90 % resulted into an increasing trend in burn rate for particle sizes of 2000-500 μm and 501-100 μm while a decreasing trend was noted for particle size <100 μm [159]. Besides, varying the particle sizes of banana residue from 500 to 150 μm increased the burn rate from 0.0011 to 0.0022 cm/s [120]. Similarly, particle size reduction of sawdust-rice husk blends from 250 to 1000 μm lead to an increasing trend in the burn rate of briquettes but between 1000 and 2000 μm, the trend was nearly constant [159].

In practice, a low burning rate is desirable as the briquettes would not burn out rapidly and therefore continues to generate useful energy for a longer period of time. Therefore, to produce densified solid biofuels with good combustion properties at minimum cost, the densification process conditions ought to be optimized. However, studies related to optimisation of densification process conditions of different biomass feedstocks with the aim of optimising combustion rate of densified raw or torrefied biomass materials are scarcely available in literature.

7.3. Calorific value

Calorific value is a measure of the total amount of heat liberated when a unit mass of fuel is completely burnt and the combustion products are cooled to 25 °C [175]. It can also be used to determine the fuel standard sale value. Additionally, calorific value of a fuel can be used in the analysis and design of bio-energy systems [176]. The calorific value of densified biomass products also depend on densification process variables. For instance, increasing the particle size of leaves mixed with 30 % cassava starch from 600 to 5000 μ m increased the calorific value from 14422 to 16718 kJ/kg [177]. Similarly, increasing the particle size of banana residue from 150 to 500 μ m increased the calorific value of briquettes from 18798 to 19491 kJ/kg [178]. However, the use of additives in densification as depicted in Table 3 may decrease or increase the calorific value of the densified products.

The few studies reported in literature did not examine the combined effect of densification process conditions on the calorific value of densified products yet these conditions when used in combination may synergize or antagonize their effect on the calorific value. Therefore, there is need to widely study the optimum densification process conditions of a variety of lignocellulosic residues. Optimisation of these conditions helps not only to increase the calorific value but also lower the cost of production.

8. Emissions from solid biomass combustion

Solid biofuel usage in combustion is associated with release of gaseous and particulate emissions, which potentially cause adverse human health effects and contribute to global warming [179]. The principal emissions released from combustion of solid biofuels in small scale heating appliances are outlined below [180,181]:

Particulate Matter (PM):

- These include salts, soot, condensable organic compounds (COCs), volatile organic compounds (VOCs) and intermediate products (tars and polycyclic aromatic hydrocarbons (PAHs), which result from low combustion temperature [182].

Oxides of Nitrogen (NO_x):

- Nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O) are typical examples of oxides of nitrogen. Unlike NO and NO_2, N_2O is less commonly produced from combustion process and is an irritant in the lungs with direct negative impacts on human respiratory. Additionally, N_2O is a greenhouse gas, which contributes directly to the impacts of climate change. Furthermore, various gaseous forms of NO_x can react with SO_2 and other substances to form acid rain, which typically not only damages vegetation and buildings, but also contributes directly to eutrophication.

Oxides of Sulphur (SO_x):

- Sulphur dioxide (SO_2) and sulphur trioxide (SO_3): Just like nitrogen oxides, sulphur oxides emissions are mainly feedstock dependent [182]. However, combustion of most bio briquettes is sulphur free unlike fossil fuels combustion, which leads to release of sulphur in from of sulfides. The sulfides react with air and water to from acid rain, which severely impacts the environment, hence leading to water, soil and air pollution [183].

Oxides of Carbon (CO_x):

- Carbon monoxide (CO) and carbon dioxide (CO_2) are oxides that result from combustion of carbonaceous substances. Unlike CO_2, CO results from low combustion temperature and poor mixing of fuel with air [182].

Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs):

- These are listed as persistent organic pollutants (POPs) and have been linked to several adverse health risks [184,185].

Particulate Matter (PM) and NO_x are considered to be the most relevant emissions when considering biomass combustion [181]. However, carbon monoxide (CO) and PM are the major pollutants emitted from incomplete combustion of household solid biofuels [23,24]. These two pollutants have the potential to cause environmental and adverse human health effects [25,26]. For example, atmospheric photochemical reactions that are associated with carbon monoxide indirectly increase greenhouse gas (GHG) levels, hence leading to global warming [27,28]. Carbon monoxide has higher global warming potential per kilogram of carbon than CO_2 [29]. Typically, PM consists of a mixture of solid and liquid particles suspended in air [186–188] and can be measured based

on mass concentration, number concentration or number size distribution. In other words, the mass concentration of $PM_{2.5}$ and PM_{10} is the commonly used exposure metric in assessing the human health effect of PM [189]. Besides, PM_{10} contains ultrafine ($PM_{0.1}$), fine ($PM_{0.1\text{-}2.5}$), and coarse ($PM_{2.5\text{–}10}$) fractions [190] while $PM_{2.5}$ comprises ultrafine particles of diameter < 0.1 μm [26]. Therefore, the aerodynamic diameter of particulate matter is used as a measure of their potential to cause human health and environmental impact. For example, fine particulate matter with an aerodynamic diameter equal or smaller than 2.5 μm ($PM_{2.5}$), is an important environmental health risk factor and contributes to the development and/or exacerbation of many diseases [191].

The indoor air quality during combustion of solid biofuels such as briquettes in an energy saving cook stove can be determined from the concentration levels of CO, fine particulate matter ($PM_{2.5}$ and PM_{10}) and CO_2 [192]. Generally, high CO and PM emissions of burning biofuels may arise from low combustion temperatures, nature of the feedstock, air speed, design of combustion system and poor mixing of fuel with air inter alia. Therefore, monitoring emission characteristics of solid biofuel such as briquettes/pellets in commonly used combustors is necessary to ensure safety of the users.

8.1. Human exposure limits for CO and PM

Human exposure to ambient $PM_{2.5}$ and PM_{10} increases the risks of respiratory illness as well as cardiovascular morbidity and mortality [81]. Consequently, the World Health Organization (WHO) has revised air quality guidelines (AQG) levels for human exposure to gaseous and particulate matter pollutants. For example, the permissible exposure limits for $PM_{2.5}$ have been revised to an annual mean of 5 μg/m^3 and 15 μg/m^3 for the 24-h mean with 3–4 exceedance days allowed per year. Similarly, the permissible exposure limits for PM_{10} have been revised to an annual mean of 15 μg/m^3 and 45 μg/m^3 for the 24-h mean with 3–4 exceedance days allowed per year [30]. In the same manner, the permissible exposure limits for CO in 24 h, 8 h, 1 h and 15 min are 4 with 3–4 exceedance days allowed per year, 10, 35 and 100 mg/m^3 respectively [30].

Although these limits exit, studies about monitoring of CO and PM emission levels from solid biofuels utilization remain poorly documented in low income countries. The emission levels of these pollutants depend on nature of biofuel, design of combustor and ventilation of the cooking area inter alia. Therefore, sensitization of the populace about the human health effects of exposure to high levels of these pollutants and implementation of mitigation strategies to minimize exposure to high dosages is critical.

8.2. Effect of pretreatment on emissions characteristics of solid biofuels

Densification, torrefaction and pyrolysis could be used to improve combustion emission characteristics of solid biofuels. For example, briquetting reduced the $PM_{2.5}$ emission factor of maize straw and wheat straw by 7.57 and 3.58 g/kg respectively [193]. Similarly, densification of corn stalk into pellets reduced PM_{10} emissions from 88.35 to 23.12 mg/Nm^3 [194]. Additionally, the $PM_{2.5}$ emission factor carbonization of maize straw, wheat straw and wood branch briquettes pyrolysed at 400 $^{\circ}C$ reduced by 7.89 g/kg, 5.14 g/kg and 0.3 g/kg respectively [193]. Furthermore, at 13 % O_2 concentration, CO emission from combustion of torrefied spruce, willow and olive briquettes reduced from 9.1 to 6.0, 7.0-6.9 and 6.6–6.0 g/m^3 respectively [26].

The emissions characteristics after pretreatment are affected not only by feedstock inherent characteristics but also pretreatment and combustions conditions. For instance, a study by Thai [195] revealed that CO emissions during combustion of paper and wood briquettes were 1162 and 957 ppm respectively. Additionally, NOx emissions level was 41 ppm for paper briquettes and 29 ppm for wood briquettes. Furthermore, $PM_{2.5}$ mass concentration during combustion of paper briquettes was 25 mg/m^3 and 43 mg/m^3 for wood briquettes [195]. Also, combustion of wood pellets at 10 vol % O_2 resulted into CO, PM, and NO emissions of 241, 39 and 152 mg/m^3 respectively. On the other hand, corn cob pellets combustion resulted into emissions levels of 2040 mg/m^3 for CO, 463 mg/m^3 for PM and 170 mg/m^3 for NO_x [196].

Study by Dragutinović et al. [196] further revealed that addition of starch binder increased emissions of CO by 394 mg/m^3 and PM by 146 mg/m^3, while NO_x emission decreased by 7 mg/m^3. On the other hand, increasing the concentration of kaolin binder in corn cob pellets reduced CO emissions from 2434 to 357 mg/m^3 and PM from 609 to 317 mg/m^3 while NO_x emissions levels exhibited intermittent trend as the concentration of kaolin increased [196].

Generally, torrefaction of biomass reduces its volatile matter and moisture contents, which are the main contributors of emissions produced during combustion. On the other hand, densification reduces the inter-particle pores in biomass feedstock and this affects mass diffusion, thus gaseous and particulate matter emissions. The gaseous and particulate matter emissions of biomass fuel are dependent on densification conditions and feedstock parameters. Additionally, combustion conditions such as design of the combustor, air to fuel mixing ratio and air flow rate also affect emissions characteristics of densified products. The main emissions associated with incomplete combustion of briquettes/pellets can be minimized through optimisation of pretreatment and combustion conditions. Further research focused on producing densified products with fewer emissions could minimize their human exposure and environmental effects. Importantly, carrying out economic feasibility of such pretreatment techniques is very crucial and this has been discussed in the next section.

9. Economic aspect of biomass briquetting

The economic feasibility and viability of a briquetting project can be evaluated through estimation of common profitability indicators such as net present value, internal rate of return, benefit cost ratio and payback period [35]. These indicators are essential in making strategic investment decision on densification project prior to its implementation in a particular location. Each of the methods is briefly described in specific subsections below.

9.1. Net present value

The net present value (NPV_i) represents the discounted value of the net cash inflows to the project [197]. This can be computed using Equation (1) as given by Adeoti et al. [198].

$$NPV_i = \sum_{t=0}^{n} \frac{(C_b - C_c)_t}{(1+i)^t} \quad (1)$$

where, C_b-C_c is the net cash flow in the tth year, C_b is cash benefit of the investment, C_c is cash cost of the investment (investment, operational and raw material costs), and i is the discount rate or the return that could be earned in an alternative investment [199]. A positive and high net present value indicates strong project profitability and is more likely to sustain the business [200] but the project is rejected by an investor if the net present value is negative. Additionally, if the net present value = 0, it means that the project is at break-even point [201].

Most of the reported studies indicated high and positive NPVs of densification projects. For instance, the net present values of briquetting groundnut shell, sawdust, sugarcane bagasse and tamarind shell were reported to be 3, 9, 31 and 245 Indian Rupees (INR) respectively [202]. Similarly, the NPV of briquetting carbonized cashew shell in Pakistan Rupees (Rs) was 1935370.8, 2256434.38 for grass and 631948.8 for rice husk [203]. The positive and high NPVs in the above study are consistent with Rs. 4,964,379.5 for sugarcane bagasse pith briquette production plant [38]. The NPV takes into account the capital value over time and has become more widespread and accepted as a measure of financial performance of projects. However, the method has the following

limitations [204]:

- It is difficult to define the real value of capital cost for an investment.
- It assumes that the discount rate or capital cost remains unchanged throughout the period the project is under review. However, the cost of capital depends on financial market behavior and risk of new developments in the analysis.
- It is difficult to compare projects in different currencies unless expressed in percentage terms.

9.2. Internal rate of return (IRR)

The IRR criterion determines the discounted rate at which the cumulative NPV of the project costs would exactly equal the cumulative NPV of all project benefits if both are discounted at the internal rate of return [205]. IRR is the cut-off discount rate (*irr*) that makes the NPV equal to zero. An IRR value >the standard financial cut-off discount rate, *i*, in financial analysis indicates that the project is profitable and can be accepted by an investor. It can be computed from Equation (2) [203].

$$\sum_{t=0}^{n} \frac{(C_b - C_c)_t}{(1+irr)^t} = 0 \tag{2}$$

Few studies have reported economic profitability of densification projects using internal rate of return. For example, an internal rate of return for briquetting cashew nut was 23.55 % [80]. Additionally, a study by Shahapur et al. [202] revealed an internal rate of return of a plant briquetting groundnut shell, sawdust, sugarcane bagasse and tamarind shell to be >30 %. Furthermore, high internal rates of return of 374.0, 428.0 and 230.0 % for carbonized cashew shell, grass, and rice husk briquettes respectively have been reported [203]. Although the method involves a lot of intuition, it has the following limitations [204]:

- Structural complexity of cash flows of a project may lead to more than one IRR which hinders clear decision making.
- Unlike NPV which more realistically assumes that cash flows are reinvested at discounted rate, the IRR implicitly assumes that all cash flows can be reinvested at the IRR.
- The approach does not take into account the different sizes of investment.

9.3. Benefit cost ratio

Benefit cost ratio is the ratio of the equivalent worth of benefits to the equivalent worth of costs [203]. This can be calculated as shown in Equation (3) [198].

$$\text{Benefit cost ratio} = \frac{\sum_{t=1}^{n} \frac{C_b}{(1+i)^t}}{\sum_{t=1}^{n} \frac{C_c}{(1+i)^t}} \tag{3}$$

Benefit cost ratio of densifying diverse lignocellulosic residues have been investigated. For example, briquetting willow, Virginia mallow, rape straw, Virginia mallow/willow (50:50), straw/willow (50:50), straw/rapeseed oilcake (75:25), straw/rapeseed oilcake (50:50) and pine sawdust in Poland in the year 2010 could generate an estimated profit of 16,444.2, 22,264.0, 37,627.4, 37,627.4, 30,412.6, −7808.8, −50,561.3 and 66,963.1 € $year^{-1}$ respectively [206]. The above set of results indicates that briquetting straw/rapeseed oilcake (75:25) and straw/rapeseed oilcake (50:50) would be at a loss. However, according to Raj and Tirkey [38] sugarcane bagasse pith briquette production plant had a profitability index of 1.98. Similarly, briquetting groundnut shell, sawdust, sugarcane bagasse and tamarind shell had benefit-cost ratio of 2.21 [202]. This is consistent with the benefit cost ratio of 2.8, 2.93 and 1.51 for briquetting carbonized cashew shell, grass and rice husk respectively [203]. This method of economic analysis can used as a selection criterion for all eligible projects that have independent cost-benefit ratio; however, it suffers from the following limitations as stated by De Oliveira and Fernandes [204]:

- It ignores non-monetary impacts.
- It is difficult to precisely define benefits and costs.
- It cannot be used to choose between mutually exclusive alternatives.

9.4. Payback period

The payback period is the length of time required before a project makes enough to recover the initial investment. It can be computed using Equation (4) [199].

$$\text{Payback period(years)} = \text{Initial investment}/\text{Annual net cash inflow} \tag{4}$$

The payback period for densification of biomass feedstock is dependent on a number of factors such as availability of the feedstock, prices of other competing fuel sources, government policy, context in which the plant is located inter alia. For example, the payback period of cashew nut bio-briquette project was 3.42 years [80]. Furthermore, the payback periods for briquetting carbonized cashew shell, grass, rice husk were 8.1, 7.56 and 29.35 months respectively [203]. Payback periods for densification of many more feedstocks have been reported for example, groundnut shell, sawdust, sugarcane bagasse and tamarind shell [202] and sawdust and wood chips [199]. However, the reported payback periods varied among the same feedstocks in different contexts. This implies that the payback period for establishing densification project is dependent on the market dynamics in a given location. Usually, investors prefer briquetting projects with short payback period as that would signify rapid briquetting return of the investment [197]. This approach is often preferred as a measure of investment merit due to its simplicity. However, its disadvantages, which limit applicability in renewable energy related business practices include [207]:

- The tendency to ignore the value of economic resources over time may be misleading.
- It ignores cash flows that occur after the recovery period. It may be that a project has shorter payback, but smaller NPV over the life of the entire project, which may lead to choice of wrong alternative by an investor.

Each of the methods of estimating economic feasibility and viability of densification projects has its own merits and disadvantages. However, literature has shown that the method of net present value is predominantly being used.

10. Future perspectives

Literature has indicated that lignocellulosic residues are ubiquitous and abundant in developing nations, but have unbefitting inherent properties when used directly for energy generation. These properties include low bulk density, heterogeneity, fibrousness, low volumetric calorific value, hygroscopicity and high moisture content. Consequently, their utilization in energy production increase storage, handling and transportation costs. Additionally, high moisture content of these residues leads to incomplete combustion, hence leading to indoor air pollution during cooking/heating, which characteristically affects human health. The above challenges can be addressed through torrefaction and briquetting.

Previous studies have shown that briquetting/pelleting improves the physical, mechanical and energy properties of raw and torrefied lignocellulosic residues. Additionally, the quality of briquettes has been shown to be dependent on the feedstock characteristics (binder, type of feedstock, moisture content and particle size) and operating process conditions like temperature, pressure, and residence time. However, scientific information on the optimum briquetting conditions of diverse raw and torrefied lignocellulosic residues is scare. Future research

should focus on optimising densification conditions for production of raw and torrefied briquettes/pellets of superior quality from various lignocellulosic residues if they are to compete favorably with fossil fuels, charcoal and firewood. Furthermore, alternative low cost organic binders that could be used in agglomeration of raw and torrefied lignocellulosic biomass should be investigated to promote production of briquettes/pellets in rural areas. This would provide employment opportunity or provide alternative means of livelihood to the local population.

Additionally, reviewed literature reaffirms biomass densification as an economically feasible and profitable enterprise provided the feedstocks are available in significant quantities, effective marketing strategies are used and technology appropriate for a particular content is chosen. However, the uptake of products of biomass densification is still sluggish in developing countries probably because of prohibitively high upfront costs, lack of enabling national legal and regulatory policy frameworks as well as long payback period inter alia. To reduce upfront costs, further studies on specific energy requirements for densification of diverse lignocellulosic wastes under different conditions ought to be conducted to aid in fabrication of cost effective densification equipment, which are adapted to local context. Furthermore, to spur briquettes/pellets production and uptake in developing nations, there is need for national and regulatory policies that provide supportive environment as well as financial support from the government or development partners to researchers and entrepreneurs involved in waste-to-energy valorization technologies. Additionally, there is need to sensitize the populace about the dire need to include briquettes/pellets in the national energy portfolio in order to mitigate greenhouse gas emissions and climate change arising from unsustainable exploitation of fossil fuels and forest.

11. Conclusions

An overview of sources of biomass, structural composition of biomass, densification of raw and torrefied biomass residues, physicomechanical, emissions and combustion characteristics of densified raw and torrrefied lignocellulosic residues have been reviewed. Furthermore, factors affecting quality of densified products and economic aspect of briquetting have also been reviewed. Previous studies have indicated that torrefied briquettes/pellets have superior energy density, calorific value, and hydrophobicity, but have low density and durability in comparison to their raw counterparts especially when no binder is applied during densification. Furthermore, densification enhances physicomechanical properties of biomass materials, hence leading to reduction in handling, storage and transportation costs of the material intended to be used for energy generation. In spite of the above merits, literature has indicated that producing mechanically durable and stable torrefied briquettes/pellets remains a critical challenge especially if no external binder or sufficiently high pressure is applied. Further research on possible low cost organic binders can help to promote production of low cost briquettes/pellets with enhanced physicomechanical and combustion characteristics.

Literature has revealed that briquetting/pelleting properties of raw and torrefied lignocellulosic biomass are dependent on feedstock characteristics and densification process parameters. However, information on optimum densification conditions of different lignocellulosic residues is scarcely available in literature. Further research on optimum feedstock characteristics, torrefaction and densification process conditions needs to be extensively conducted for different lignocellulosic residues.

Reviewed literature reaffirms densification generally as a prospective economically profitable enterprise but local scientific data on economic indicators of its feasibility and viability are limited. More research on economic analysis of biomass densification projects in different regions of developing countries ought to be carried out since different locations are endowed differently with biomass resources.

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