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Review

A review on biochar briquetting: Common practices and recommendations to enhance mechanical properties and environmental performances

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ABSTRACT

Biochar briquettes stand as the current frontrunner for cost-effective and sustainable substitutes for fossil fuels in both energy and industrial sectors. Produced through the thermochemical conversion of biomass to biochar followed by densification, this process yields a renewable briquette that imitate coal in mechanical attributes and combustion efficiency, while maintaining a carbon-neutral profile. Findings indicates that substituting biochar briquettes for coal has the potential to reduce methane (CH₄) and carbon dioxide (CO₂) emissions by approximately 40%. The densification stage plays a crucial role in converting biochar which has low bulk density (0.2 g cm⁻³ to 0.4 g cm⁻³), into a coal-like energy product. Thus, effectively addressing concerns associated with handling, transportation, and storage. To ensure the fabrication of high-quality biochar briquettes, particular attention must be directed towards the choice of binder, compaction technology, and operational conditions. In addition, critical briquette quality parameters such as density, mechanical durability, calorific value, and volatile species are influenced by the binder. The optimal binder loading ranges from 5 to 15% depending on the feedstock and pyrolysis temperature. Biochar briquettes produced under these conditions tend to exhibit durability values ranging from approximately 70%–90%. While the existing literature offers broad insights into pyrolysis conditions for various biomass types, available densification technologies, and binder options for biochar briquetting, a more comprehensive understanding of how these factors impact the mechanical and environmental performance is lacking. This review aims to bridge this knowledge gap. By enhancing the biochar densification process to improve energy efficiency, increase mechanical strength, and reduce pollutant emissions, there is real potential for accelerating the transition away from traditional fossil fuel like coal in a variety of industrial applications where it is challenging to decarbonize the production systems.

1. Introduction

A drastic reduction in greenhouse gas emissions is necessary in the next years to meet the objectives set by the European Union under the Green Deal (2020), which aims to increase the share of renewable energy in the European energy mix from 18% in 2018 to at least 32% in 2030 (European Environment Agency, 2020). However, between 2022 and 2023, the European Union climate and energy goals for 2030 were revised to more ambitious targets within the framework of the Fit-For-55 package. As a result, the current renewable energy share stands at 42.5% by 2030, with a potential of reaching up to 45%. The urgency of the climate crisis is demonstrated by the rapid revision of the 2020 goals within only two years (European Environment Agency, 2023). In this context, carbon-intensive industrial processes, typically using fossil

fuels, should move towards the use of alternative renewable fuels. Biomass can play a role in this scenario, as a renewable carbon-rich bioresource, highly available at a low cost, generating biogenic CO₂ emissions (European Environment Agency, 2013).

Biochar, obtained from thermochemical processes, such as pyrolysis, have physical and chemical properties close to those of coal, which makes it a suitable bio-sourced alternative to fossil fuels at industrial scale (Mousa et al., 2019; Riva, 2019). However, it exhibits low bulk and energy density compared to coal, limiting its viability as a commercial alternative to fossil fuels. Densification increases the physical and energy density of solid biomass fuels and facilitates its handling, which enables it to meet the specifications of industrial processes (Kaliyan and Vance Morey, 2009). The main densification processes, initially developed for coal fine particles, were progressively adapted for biomass compaction into pellets and briquettes. Thus, enabling facile transition

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List of abbreviations

D	diameter
GHG	greenhouse gases
H	height
HHV	higher heating value
ID	inner diameter
LB	lignocellulosic biomass
LHV	lower heating value
OD	outer diameter
P	pressure
PAHs	polycyclic aromatic hydrocarbons
SRF	solid refuse fuel
T	temperature
Ti	Ignition temperature
F	force
VOCs	volatile organic compounds

of solid biomass fuels in industrial applications. The prospect of densified biomass as a sustainable biofuel is forecasted to grow by 8% annually (Bajwa et al., 2018). Certainly, there is a need to adapt the densification processes initially utilized in biomass briquetting to the production of biochar briquettes, which has properties that closely resemble those of coal. This adaptation is essential for integrating biochar briquettes seamlessly into existing industrial coal combustion processes. In general, biochar densification will be used rather biomass densification followed by pyrolysis. This ensures the achievement of suitable properties for the resulting biochar briquettes, especially in terms of mechanical resistance.

The key characteristics of biochar briquettes impacting their behavior in combustion are related to their physical stability, structural properties, hot and cold mechanical properties, moisture content, carbon content, and calorific value (Mousa et al., 2019; Nzihou, 2020). Since biochar has poor agglomeration properties, a binder is typically required in the densification process. As a result, the thermal, mechanical and environmental performances of the densified composite are analyzed to verify that it fulfills the specifications of the targeted process whether domestic or industrial.

This review aims at providing insights on current trends on biochar briquetting for fossil fuel replacement in domestic and industrial combustion processes. Furthermore, recommendations are proposed on further developments in the field by linking biochar characterization and production conditions to briquette thermal and mechanical properties, as well as environmental performances.

The need for this review arises from a variety of challenges associated with the use of fossil fuel. Firstly, its non-renewable nature, which implies an eventual depletion of resources. Secondly, the rapid degradation of the environment, notably climate change, that has been linked to emissions released during fossil fuel combustion. Given that coal usage is the primary contributor to the largest CO₂ release into the

atmosphere, the urgency to develop a sustainable substitute becomes imperative. Furthermore, finding a suitable alternative to coal requires compatibility with existing coal firing systems such as, furnaces, kiln, stoves. Therefore, to effectively integrate biochar briquettes as a substitute for coal, it is essential to optimize production conditions in order to improve key biochar briquetting aspects in line with the objective. Hence, the focus on combustion, thermal and environmental performance.

To avoid ambiguity, it is important to clarify that the term “coal” in this review refers specifically to fossil coal and not to charcoal.

2. Biochar

Biochar is the solid product obtained in biomass thermochemical conversion processes. It can serve as an alternative to fossil fuels in several industries such as cement plants, foundries and electric power, with benefits for carbon neutrality and reduction of greenhouse gases (GHG) due to its bio-based origin (F. Li et al., 2023). As a result, biochar production and processing processes has significantly gained momentum over the years.

2.1. Biochar production

2.1.1. Resource diversity for biochar production

A bulk of the resource used for biochar production are lignocellulosic biomass. It includes woods, energy crops, and agricultural residues. Amongst other applications, it is used for energy generation purposes (Barzegar et al., 2020; Hartmann and Kaltschmitt, 1999; Romero Millán et al., 2017). Lignocellulosic biomass species are characterized by a high moisture content, low calorific value, and poor grindability in their native state. Lignocellulosic biomass is mainly composed of cellulose, hemicelluloses, lignin, and, to a lesser extent, organic extractives and ash. The proportions of biomass components are mainly dependent on their biological origin, growing location, and harvesting period. In the case of woody biomass, it is composed of about 40%–44% cellulose, 20%–30% hemicelluloses, and 10%–30% lignin (Díez et al., 2020; Jung et al., 2015). While cellulose has an ordered structure, mainly constituted by glucose, hemicellulose structure can be linear or branched, mostly composed of D-xylose and L-arabinose. Lignin is a phenyl-propane-based polymer composed of monomers based on p-coumaryl, coniferyl and synapyl alcohols (Vanholme et al., 2010). The degradation pathway followed by biomass in a thermochemical conversion process such as pyrolysis is strongly dependent on its macromolecular composition, as well as on operating conditions, mainly temperature and atmosphere.

The main groups of lignocellulosic biomass used for biochar production include are shown in Table 1.

All these resources differ in their chemical and physical properties, which influences their response to carbonization and hence the optimal pyrolysis condition. Therefore, the optimal pyrolysis condition would most likely vary depending on the resource type and therefore the lignocellulose biomass group. Typically, the pyrolysis temperature for biochar briquette preparation is between 350 and 1000 °C. Although the

Table 1
Groups of lignocellulosic biomass used for biochar production.

Groups	Examples	References
Forestry residues	wood chips, sawdust, pine needles	(Riva, 2019; Riva et al., 2019; Sharma et al., 2020)
Agricultural residues	wheat straw, rice straw, rice husk, maize straw, maize husk, coffee husk, coffee ground, groundnut shells, corn cob, cotton stalk, cashew waste, palm kernel nut, sugarcane bagasse, orange bagasse	(Abakr and Abasaeed, 2006; Bazargan et al., 2014; Guo et al., 2020; Karine Zanella et al., 2016; Lubwama et al., 2022; Sawadogo et al., 2018),
Municipal solid waste and other biomass	sludge, algae, solid refuse fuel	(Asamoah et al., 2016; Li et al., 2024)

properties of biomass from various resources can be homogenized by pyrolysis, which involves the evaporation of water, the devolatilization of aliphatic groups and the aromatization of the carbonaceous substrate at elevated temperature, certain basic elements of the biomass structure are preserved after pyrolysis. The carbon structure of the biomass remains intact following pyrolysis at 700 °C, as indicated by the presence of more prominent pores in softwood compared to hardwood. This distinction is expected to influence the interaction between the biochar and the binder, ultimately impacting the mechanical properties of the resulting briquettes (Jiang et al., 2017).

2.1.2. Thermochemical conversion process

Biochar is mainly produced by pyrolysis (300–1000 °C, inert atmosphere). The heating rate of the process determines the distribution of the pyrolysis products biochar, bio-oil or biotar and gases (Mohan et al., 2006; Raza et al., 2014). Slow pyrolysis enables the maximization of biochar yield. This implies a heating rate around 0.1–1 °C s⁻¹, for a vapor residence time of around 500s and particle size between 5 and 50 mm (Rashidi et al., 2020). In these conditions, biochar yield is around 35%, while bio-oil and gas are produced in equivalent amounts. A higher heating rate would favor bio-oil and gas yield (Rashidi et al., 2020). Likewise, increasing pressure contributes to increase the char yield (Kaur et al., 2015). Furthermore, biochar structure is strongly dependent on pyrolysis operating conditions (Yuan et al., 2021). High temperature carbonization favors high carbon content, while pyrolysis duration maximizes the efficiency of biomass conversion to char. In addition, carbonization temperature and biomass conversion efficiency influence the volatile content in the resulting char. Thus, biochar exhibiting high reactivity is indicative of a biochar rich in volatile content. The increased reactivity can be attributed to the high release of volatile components during char combustion which facilitates rapid ignition and faster burn rate.

Pyrolysis induces changes in the biomass structure through mechanisms like depolymerization, fragmentation and cross-linking reactions of the macromolecular components. As the temperature rises, water is expelled from biomass structure and functional groups such as aldehydes and ketones are formed above 100 °C. From 300 to 350 °C, hemicellulose decarboxylation occurs, leading to cleavage of cellulose chains (Yaashikaa et al., 2020). Above 550 °C, the biochar structures fuses, making it more aromatic, which contributes to the formation of the solid matrix that constitutes the biochar (Zhang et al., 2020). At higher temperatures (T > 600 °C), complex lignin decomposition produces benzene ring rearrangements that promote the release of volatile compounds, non-condensable gases, and potentially phenolic compounds. In addition, secondary reactions around 800 °C may favor the formation of polycyclic structure and catalytic deposit on the substrate surface (Collard and Blin, 2014).

The macromolecular composition of lignocellulosic biomass significantly affects the distribution of volatile compounds along pyrolysis temperature/duration. Agricultural residues (corn cobs, grape seed cake) have more heterogeneous distribution of volatiles than woody biomass and forestry residues (González Martínez et al., 2019).

2.1.3. Physicochemical properties of biochar

One of the benefits of biomass carbonization is that it enables the enrichment of the physicochemical properties of the resulting char. Depending on the temperature and particle size, devolatilization ensures the reduction of polar (-O, -N) functional groups, leading to a porous and hydrophobic carbon-rich material (Masebinu et al., 2019). Subsequently, the hydrophobic structure prevent water from entering into the formed pores (Gray et al., 2014). The increase in the surface area is a secondary consequence of species devolatilization, endowing biochar with cation exchange capacity based on its active sites. As a loose fuel, biochar exhibits a low density between 0.2 g cm⁻³ to 0.4 g cm⁻³ (Bazargan et al., 2014). Notably, the inorganic salt content (alkali and alkali earth elements) favor the alkalinity and conductivity of biochar,

which become significant when acid functionalities degrade during pyrolysis (Singh et al., 2017). These properties affect biochar behavior during further processing such as densification and the binding mechanism during agglomeration (Singh Yadav et al., 2023). Therefore, considering the objective of this study, aimed at supporting efforts to improve the viability of biochar briquettes as sustainable substitutes for coal in existing combustion systems, especially in industrial settings, biochar production should prioritize the following properties:

- i. *High fixed carbon content*: Biochar with a high fixed carbon content ensures an equally higher heating value, thereby improving its efficiency as an energy source.
- ii. *Thermal stability*: A high thermal stability is a key requirement for biochar designed for certain coal replacement applications. Given that biochar exhibits lower thermal stability compared to coal, the devolatilization of char becomes imperative so as to lower the burn rate while improving the thermal stability.
- iii. *Low environmental impact*: Biochar is expected to pose minimal damage to the environment in the aspect of its production (pyrolysis) and the combustion of the final product (biochar briquettes). Oftentimes, the challenge is in controlling the release of pollutant emissions into the atmosphere during pyrolysis and combustion. In advanced technical installations where the gaseous product streams produced during pyrolysis are efficiently collected and transformed to fuel, pollution is curbed. However, potential pollution remains a possibility during combustion of the biochar if it contains substantial amounts sulfur, chlorine, and nitrogen.

Prioritizing these properties will facilitate the compatibility of biochar existing coal firing systems and accelerate the shift from coal to biomass-derived clean energy in a wider range of applications.

2.1.4. Biochar combustion

Carbonized biomass exhibits interesting thermal properties in terms of ignition and heat release, which renders it a suitable fuel. Biochar produced at low temperature burns easily due to the presence of volatile species clogging biochar pores (Shanmugam et al., 2022). This is consistent with the high reactivity observed for biochar with high volatile content. The ignition temperature (Ti) is a parameter that can be used to evaluate the ignition performance of fuels and thus the choice of biochar resource. Coal exhibits higher Ti range than biochar (Ti < 700 °C), but biochar has a higher LHV (lower heating value) compared to coal, which is a key benefit of this sustainable biofuels (Fig. 1). Some studies showed that the optimal pyrolysis range for biochar production for combustion applications is 500–600 °C due to the generally low Ti (Ti < 500 °C) (Anand et al., 2023; Chen et al., 2021; Guo et al., 2020; Ning et al., 2022; T. Wang et al., 2019). Although, a low ignition temperature (Ti) might have been proposed by some researchers as ideal for biochar produced for energy purposes, it might be viewed as disadvantageous for certain applications. This is because the high reactivity typical of biochar with low Ti, can lead to diminished thermal stability, which is an important drawback for biochar in certain applications that require a longer burn time.

In summary, biochar is a cost-effective, carbon-rich material derived from abundant, renewable biomass resources, particularly lignocellulosic biomass. Biomass originating from sources like wood or agricultural residues, exhibit distinct chemical and physical properties, influencing their behavior during carbonization and the optimal pyrolysis conditions. The conventional route involves subjecting biomass to pyrolysis within the temperature range of 350–1000 °C. While pyrolysis can harmonize properties across biomass sources by expelling water, devolatilization of aliphatic groups, and the aromatization of the carbonaceous substrate at elevated temperatures, fundamental aspects of the biomass structure (carbon skeleton) remain intact post-pyrolysis. These subtle yet vital variations in the carbon structure of resulting

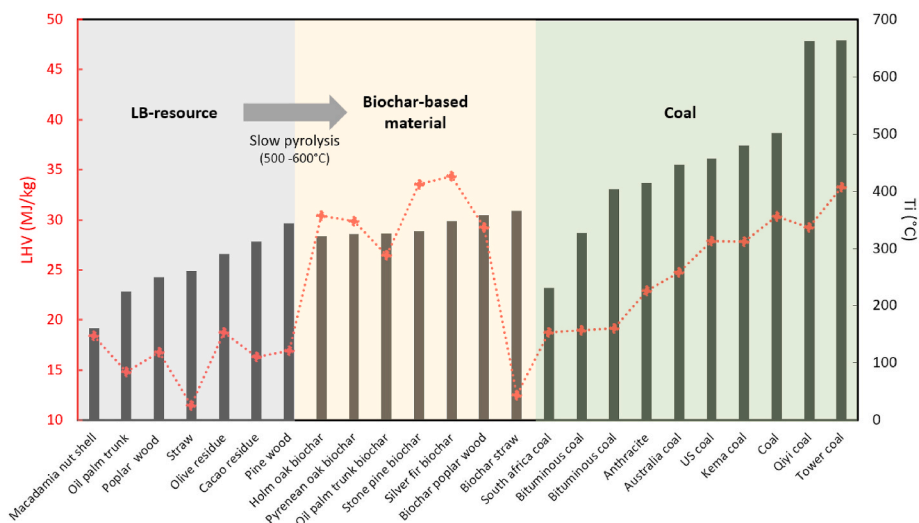


Fig. 1. Calorific value-ignition diagram (biochar versus coal; LB for lignocellulosic biomass; LHV on dry basis) (Anand et al., 2023; Bada et al., 2015; Biagini and Tognotti, 2006; Chen et al., 2020; Kongto et al., 2022; Li et al., 2018; López et al., 2013; Ning et al., 2022; Yang et al., 2022).

biochar, originating from biomass diversity, significantly impact post-processing stages like the agglomeration and densification process.

3. Bioresource densification

The low density of both biomass and biochar presents some significant challenges in handling, transportation, and storage. Furthermore, the irregular shapes and sizes of these fuels may lead to uneven combustion. Fuel densification mitigates these issues, leading to an increased energy density, mechanical strength and durability. Furthermore, it eases handling, storage, transportation, and minimizes losses.

3.1. Densification process

Densification includes any process that increases the cohesion of the material by reducing void spaces, which improves the packing efficiency of the resulting product. Examples of densification processes include agglomeration of fine particles, and compaction or compression under pressure. The process may necessitate the addition of a binder to facilitate the cohesion of the material depending on the type of material and the intended application. Both biomass and biochar can undergo densification, and the same technologies are often employed for this purpose. Fig. 2 illustrates the mechanism of densification.

The conventional form of densified bioresource used for energy purposes are pellets and briquettes. Pellets are produced in the pelletizing process, with diameter ranging from 6 to 8 mm and length from 18 to 24 mm, presenting a smooth surface and cylindrical shape. Briquettes on the other hand are obtained in the briquetting process. They

present a larger diameter (50–100 mm) and length (60–200 mm). In addition, the briquettes surface is rougher and its geometry is variable (cylinder or polygonal) (Bajwa et al., 2018). Pellets or briquettes manufactured from biomass presented a bulk density of around 450–750 kg m⁻³, which represents a considerable increase compared to raw biomass (40–200 kg m⁻³) (Kaliyan and Vance Morey, 2009). However, the bulk density of densified biochar can reach 1670 kg m⁻³ (T. Wang et al., 2019). While pellets are mainly used in primary applications (boilers) (Anukam et al., 2021), briquettes are used in large and medium industrial scale combustion processes due to their low cost (Wilson et al., 2012). Although some biomass pellets may be produced without the addition of a binding agent, binders are crucial to making briquettes.

Bio-sourced fuel briquetting and in general, densification, is impacted by feedstock characteristics (moisture content, particle size) and process parameters (type of technology, temperature, pressure, residence time, die diameter). High temperature is required to achieve high compressive strength and better bonding between briquette particles. The increase in temperature can result from feedstock preheating, with or without binder, or simultaneous heating using briquetting device. Pressure increase on the other hand ensures the filling of voids and particle contact (Dinesha et al., 2019). Thus, both increased briquetting temperature and pressure, result in improved durability of the resulting fuel.

3.2. Densification technologies

Most of the densification technologies were developed for fine coal particles. They were then adapted to biomass and more recently to

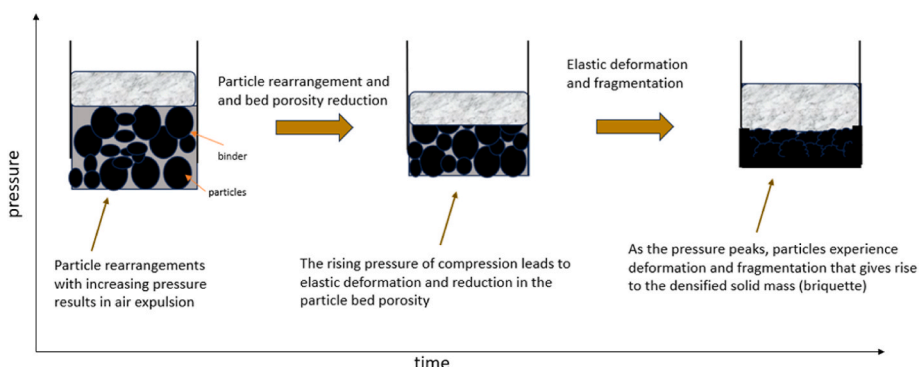


Fig. 2. Mechanism of densification.

biochar (Su et al., 2022). However, the compaction of biochar presents challenges due to its porous and hydrophobic nature, resulting from the breakdown of cellulose, hemicellulose, and lignin structures during pyrolysis. As a result, biochar typically requires a binder for its densification. In the case of biomass, briquetting can be achieved without the addition of binders because of the presence of natural binders such as lignin, hemicelluloses, and water in its structure. During compaction, binders (hemicellulose, lignin) may be expelled from the interior to the surface of the material, enabling compaction. In any case, important parameters to consider for densification include, resource type, pyrolysis conditions, and pre-densification treatments, like grinding and sifting.

Densification devices for biochar briquetting include screw press, piston press, hydraulic press, and roller press. The hydraulic press is the most commonly used device for biochar briquetting allowing for the fabrication of briquettes at room or elevated temperatures.

- **Roller press:** It consists of two counter-rotating rollers that exert pressure on the feedstock, forming briquettes. The distance from both rollers influences particle agglomeration. The bulk density of briquette ranges from 450 to 550 kg m⁻³. A manual press may also be used for briquette manufacturing with a very low production capacity (5–50 kg h⁻¹) (Kaliyan and Vance Morey, 2009).
- **Hydraulic press:** In this device, the feedstock is mechanically pressed using a hydraulic pump piston. Bulk densities of up to 1000 kg m⁻³ can be achieved (Kpalo et al., 2020a). The densification rate is higher than that of the roller press. Unfortunately, lower ram or leakage of oil limits the performance of the machine (Dinesha et al., 2019).
- **Piston press:** the feedstock is pushed from the feeding chamber into a die through the pressure of the reciprocating ram. The resulting briquette retain the die shape. The mechanical press can apply high pressure of around 196 MPa for briquettes density of >1000 kg m⁻³ (Tumuluru et al., 2011a; Kpalo et al., 2020a).
- **Screw press:** is composed of a screw extruder and a die. The feedstock fed to the hopper flows down in the conical compression zone before high-pressure compression. Nevertheless, screw presses are known for high briquette quality, with densities ranging from 1000 to 1400 kg m⁻³. Moreover, the screw press requires more energy consumption than the piston press. (Kpalo et al., 2020a).

Diagrams of the four main densification technologies are shown in Fig. 3.

3.3. Properties of densified bioresources

Densified fuel must meet logistical demands such as transport, storage, and handling during use. The main characteristics investigated are mechanical, combustion, and environmental performances. Concerning mechanical performance, a poorly formed briquette can quickly disintegrate before or during use, resulting in waste, and low energy efficiency (Kabaş et al., 2022; Liu et al., 2018). As a result, biomass is carbonized before briquetting, as the carbonization process increases thermal stability, carbon content, and thus calorific value (Guo et al., 2020). In addition, solid biofuels must meet environmental safety requirements to ensure that gas and particulate emissions are limited to acceptable standards. Controlling other sources of pollution such as ash content is beneficial for both the proper functioning of the combustion device and for the environment (Abioye et al., 2024; Niu et al., 2016). Table 2 summarizes the international standard methods that allow the determination of these properties. Acceptable values and units are indicated. Clearly, achieving high calorific value and a low ash content is essential to improve combustion efficiency.

3.4. Binders for bioresource densification

Binders are chemical or biological compounds in liquid or solid state that facilitate compaction of materials, acting as lubricants and plasticizers (Cong et al., 2021). To do this, binders interact with the substrate through chemical or physical bonds. Binders are not only viscous substances with known adhesive properties but includes water and other compounds that serve as hardeners, stabilizers, and combustion enhancers. Besides, the application of a binder improves interparticle interaction, mechanical and thermal properties of the densified fuel. Binder selection depends on factors such as availability, sustainability, adhesive and thermal attributes, and stability within the briquette formulation throughout storage and end-use applications (Nwabue et al., 2017; Obi et al., 2022; Trubetskaya et al., 2023).

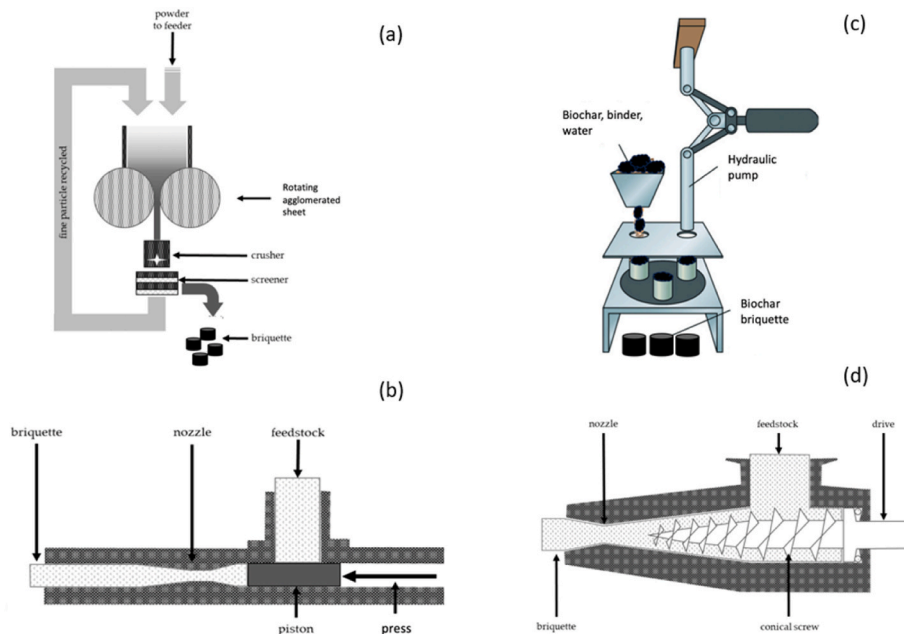


Fig. 3. Diagrams of the main densification technologies (a) Roller press (b) Piston press (c) Hydraulic press and (d) Screw press (Kpalo et al., 2020b; Tumuluru et al., 2011b).

Table 2
Summary of briquette standard test parameters.

Properties	Test parameter	Significance	Acceptable value	Unit	Standard
Mechanical properties	Shatter test	Extent of fines generation of briquettes during handling	>95	%	ISO 616
	Durability	Briquette's resistance to shock and abrasion	>95	%	ISO 17831-2
	Water immersion test	Water resistance ability of the briquettes	>50	%	–
	Humidity test	Extent of water absorption during storage	–	–	–
	Compressive strength test	Determines the force required to crush the briquettes	–	kN m ⁻²	–
	Hot compressive strength test	Determines the thermal stability of the briquettes	>500 °C	°C	–
Combustion performance	Calorific value	Thermal energy generated by fuel during combustion	>20	MJ Kg ⁻¹	ISO 18125
	Volatile matter	Volatile composition of the fuel. Volatile species are a source of heat and could be beneficial in some applications	<20	%	ISO 18123
	Moisture content	Stability of the briquette in a humid atmosphere. Moisture adsorption could affect durability	<10	%	ISO 18134-2
	Ash content	Solid residue that remains after combustion. The presence of high ash-forming components in briquettes could negatively influence the heat produced and degrade combustion performances due to fouling and/or slagging	<5	%	ISO 18122
Environmental performance	C, H, N, S	Gaseous emissions from the fuel combustion (SO ₂ and NO _x)	C > 70	%	ISO 16948, ISO 16994
Transport/storage safety measures	Self-heating substances test	Performed to determine if biofuel pellets undergo spontaneous ignition indicated by a 60° rise in temperature within 24 h	Temperature rise <60	°C	ISO 20049-1

C: carbon, H: hydrogen, N: nitrogen, S: sulfur.

Table 3
Types of binders, advantages, and drawbacks.

Binders	Properties	Inclusion range (%)	Ti (°C)	Advantages	Disadvantages	Reference
Organic binders						
Starch	Thickness, stability, and gelation	10–40	200–300	Strong adhesion	Poor waterproofing ability	(Alsaqoor et al., 2022; Lubwama et al., 2020; Pigłowska et al., 2020; Rolland-Sabaté et al., 2012)
Molasses	Rich in nutrients (proteins, sugars, and minerals)	8–30	190–200	Calorific value Bonding ability	Increases moisture absorption	(Alsaqoor et al., 2022; Baker et al., 2005; Manyuchi et al., 2018; Thabuot et al., 2015)
Arabic gum	Binder blending	10–30	300	water resistant	–	Tambuwal et al. (2023)
Lignosulfonate	Lignin derivative byproducts	–	140	High bonding ability	Expensive	(Brebú et al., 2011; Jablonský et al., 2015)
Lignin	Rich in aromatic compounds	–	175	High bonding ability	–	(Brebú et al., 2011; Kong et al., 2013)
Alkaline black Liqueur	Various composition (polysaccharides, aluminum, lignin, silicon, iron, etc.)	30	–	Good strength properties and Calorific value	Formation of insoluble complex due to Si and K content	(Cardoso et al., 2009; Tian et al., 2018)
Biotar	Complex mixture (organic compounds, ash, etc.)	6–40	–	Low-cost	Pollution (VOCs, PM, SO ₂ , NO _x)	(Cong et al., 2021; Hasanah et al., 2012; Riva, 2019)
Wood ash	Products-derived burning (fly ash, bottom ash)	30	600–900	High thermal stability	–	(Misra et al., 1993; Nath et al., 2018)
Inorganic binders						
Sodium Silicate	Main composition of sodium metasilicate (Na ₂ SiO ₃)	15–25	180	Strong adhesion and mechanical strength	–	(Liu et al., 2015; Thompson et al., 1997)
Hydrated lime	Limestone derivative	10–50	350–360	Reduced emissions (NO _x , SO ₂)	Low hydrophobicity and calorific value	(Fengmin and Mingquan, 2011; Rogalewicz et al., 2020)
Plastic waste	–	–	200–490	High density and mechanical durability	Toxic emissions (HMs, PM), high Cl and S in ash	Miandad et al. (2019)

VOCs: volatile organic compounds, PM: particulate matter, HMs: heavy metals, Cl: chlorine.

3.4.1. Main types of binders

Binders can be organic or inorganic, depending on their chemical nature. Apart from its availability and efficiency, the intended application is also considered when selecting a binder (Table 3). Nonetheless, organic and inorganic binders can be simultaneously used or combined to create composite binders with improved properties.

Binders used for compaction can be broadly grouped into five classes as defined by the authors:

- **Class 1:** Food/fuel conflicts arise as they are cultivated on arable land reserved primarily for food production purposes. This class includes native or unprocessed starch (cassava (Katimbo et al., 2014; Lubwama et al., 2020; Sawadogo et al., 2018; Ugwu and Agbo, 2011;

Ugwu and Agbo, 2013), corn (Karine Zanella et al., 2016)); processed starch (pregelatinized or modified) (Bazargan et al., 2014; Guo et al., 2020; Tian et al., 2018); Arabic gum (Tambuwal et al., 2023), and molasses (Adeleke et al., 2019; Manyuchi et al., 2018).

- **Class 2:** They are usually considered as waste or by-products of the paper mills and lignocellulosic biorefineries. These by-products include lignin (Hu et al., 2015), lignosulfonate (Jablonský et al., 2015; Riva, 2019), alkaline black liqueur (Tian et al., 2018), waste paper, and biotar (Kang et al., 2018; Riva et al., 2019; T. Zhang et al., 2019). For instance, biotar is produced in significant quantities in thermochemical processes and consist of a complex mixture of compounds difficult to isolate. Thus, the utilization of biotar as binder presents significant advantages. From an ecological and

economic standpoint, class 2 binders show promise as their use contribute to the waste management endeavor.

- **Class 3:** It includes biosolids (sludge, sewage), and seaweed/microalgae. These binders are used in biomass briquette preparation due to their adhesive properties (Davies and Davies, 2013; Muazu and Stegemann, 2017). Although they are not as efficient as binders from Classes 1 and 2 and lead to excess ash in the briquette, they make economic sense due to their low cost and low environmental impact.
- **Class 4:** This class of binders comprises inorganic materials like clay (Katimbo et al., 2014), cement (Kumain et al., 2020), sodium silicate (Sharma and Samuel, 2006), hydrated lime (Cong et al., 2021; Hu et al., 2015; Kong et al., 2013), limestone (Kozhev et al., 2022), and alumina (Olugbade et al., 2019). Although some of them are synthetically produced, they are relatively cheap and contribute in improving the thermal stability of the briquette. Their primary drawback is the high ash content that they introduce to the briquette. Inorganic binders can be used in small amounts as catalysts/additives to improve the mechanical strength and combustion behavior of the briquettes (Kong et al., 2013). They have been reported to suppress SO₂ and NO_x emissions and also bind with KCl in ash to mitigate Cl-related issues in the combustion system (Cong et al., 2021; Manyuchi et al., 2018).
- **Class 5:** These binders are from fossil origin, such as petroleum bitumen, tar pitch, asphalt, and plastic wastes. They have good combustion properties and lead to an increase in the calorific value of the formulated briquettes. However, they are associated with the production of harmful emissions and greenhouse gases (Si et al., 2017).

3.4.2. Binding mechanisms

The mechanical resistance of densified materials particularly briquettes rely on the effective interaction between the binder and the substrate. Thus, understanding the binding mechanisms operating during the compaction process is of utmost importance in selecting suitable binders for high quality briquettes.

The main binding mechanisms reported in the literature are capillary pressure and interfacial forces, interparticle attraction forces, mechanical interlocking, solid bridges and viscose adhesion (Kang et al., 2019). Prior to compaction, the loose material is composed of air spaces between particles. As densification occurs, the binder begin to fill the air

gaps, and on drying of the densified product, the volatile components of the binder evaporate, leaving behind solid bridges between adjacent particles (Manickam et al., 2006). These bridges were attributed to the action of capillary and interfacial forces. Also, the presence of moisture in the feedstock during compaction facilitates the formation of bridges between compressed particles (Manickam et al., 2006). Interestingly, lignocellulosic biomass consists of polymers such as lignin, hemicellulose, starch, wax, that soften at the high temperature and pressure associated with some compaction technologies, leaching from the fiber cells and forming linkages between the particles. These linkages harden on drying to form solid bridges (Grover and Mishra, 1996). Likewise, solid bridges can also result from the hardening of viscous binders and chemical reactions like the crystallization of dissolved substances (Tabil et al., 1997). Viscous binders are essential for briquetting as they improve the adhesion and cohesion of the particles, which is made possible by the formation of a kind of film around the particles. Thus, reducing the distance between the particles, thereby increasing the contact area between the particles during compression. Illustrations of these binding mechanisms is presented in Fig. 4.

Particle bonding can also result from interparticle attraction produced by electrostatic forces, van der Waals forces, and magnetic forces. The binding mechanism arising from interparticle attraction although weak, are relevant and contribute to the global performance of densification. Mechanical interlocking on the other hand occurs between fibrous materials or relatively large particles during compaction (Grover and Mishra, 1996; Manickam et al., 2006; Tabil et al., 1997). In fibrous materials, mechanical interlocking develops during compression due to entanglements of fibers with each other and with other particles (Gendek et al., 2018). Regardless of the binding mechanism, the overall goal of a binder is to promote volume reduction and thus increase density.

To sum up, the densification of bio-sourced fuel plays a crucial role in the production of viable bio-based alternatives to coal. Pelletizing and briquetting are the main methods used for this purpose. The selected densification technology and form (pellets or briquettes) will be dependent on the final application requirements, as well as on the characteristics of the resource to be densified.

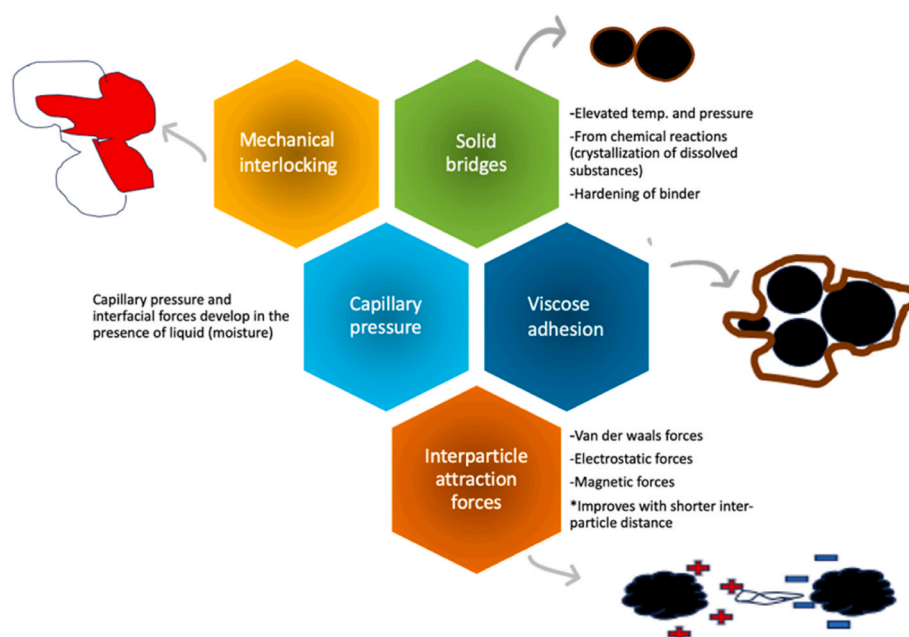


Fig. 4. Binding mechanisms.

4. Biochar briquetting

When it comes to biochar, briquetting is the preferred densification technology, especially through the hydraulic and piston press. Successful biochar briquetting involves the inclusion of a suitable binding agent and understanding the binding mechanisms is crucial when selecting the most appropriate binder. Briquetting involves the compaction of loose biochar and binder under pressure to form a densified solid mass of regular shape. Biochar briquetting allows for the increased mechanical strength and energy density of biochar, facilitating handling, transportation, and storage. As briquettes have regular shapes and sizes, briquetting promotes homogeneous combustion and longer burn time. While there are many studies in the literature on biomass and coal briquetting, biochar briquetting studies are comparatively fewer. As this application is gaining an increasing interest among the industrial community, we discuss in this section the state-of-the-art on the topic and identify the key issues for a successful biochar briquetting operation.

4.1. Common shapes and sizes

Briquettes can be prepared in several shapes depending on the desired application and available technology. **Regular briquettes** with moderate cross-sectional dimensions (45 mm × 45 mm and 50 mm high), are light in weight, weighing around 55 g, and are range in density from 620 to 950 kg m⁻³. **Cylindrical briquettes** have a diameter of 55 mm, a height of 45 mm, a mass of about 65g and a density ranging from 600 to 850 kg m⁻³. In contrast, **conical briquettes** weigh the heaviest with mass around 100–200 g. They typically measure 90 mm outer diameter and 80 mm height for the larger cone briquettes, while 70 mm outer diameter and 50 mm height for the small cone briquettes. Their densities range from 734 to 935 kg m⁻³ (Yumak et al.,

2010). Other irregular shapes potentially used could be ellipsoid, cubic, hexagonal, triangular, and spherical (Zhuo et al., 2021).

The shape and size of biochar briquettes has been shown to be as important as its volatile content in influencing the ignition, and burning times. The higher the density and the lower the porosity of the briquette (cylindrical), the longer will be the ignition (3.5 min) and burn times (20 min) of biochar briquettes (Aguko Kabok et al., 2018). Furthermore, briquette shape impacts the packing ratio in the combustion chamber (Schobing et al., 2023). This parameter is related to the volume of briquettes compared to the volume of combustion chamber, which determines the bed porosity and thus the air flow during combustion. For the same number of briquettes in a combustion chamber of a cook stove, triangular briquettes lead to a lower packing ratio and thus exhibited lower ignition (3 min) and burn time (17 min) compared to cylindrical briquettes with slightly higher packing ratio (Aguko Kabok et al., 2018).

4.2. Binders for biochar briquetting

Given that the goal of biochar briquetting is to provide a sustainable alternative to coal in industrial settings, a good binder should have all or some of the following properties: abundance (Ezéchiél et al., 2022), cheap, pollution free, good bonding ability, low ash content, good thermal stability (Mousa et al., 2019), high calorific value, low toxic emissions (Cong et al., 2021; Guo et al., 2020), and low chlorine and sulfur content. Regarding the functions of biochar binder, it is expected to increase the plasticity of the biochar, improve particle agglomeration, increase energy density of the biofuel, improve mechanical properties of briquette (Ezéchiél et al., 2022), and reduce wear of densification, and combustion device (Manyuchi et al., 2018).

Depending on the desired applications, organic binders such as starch could be used alone (Bazargan et al., 2014; Kansai et al., 2018; Karine Zanella et al., 2016) or in combination with other binders

Table 4
Examples of briquette formation with different binders and main associated properties.

Feedstock	Binder(s) inclusion (%)	Briquette technology	Densification condition	Dimensions (mm)	Findings	Reference
Coal	Starch 7%, resin 13.3%	–	–	–	No significant effect	Trubetskaya et al. (2023)
Coal fines	Pulp black liquor 30% Pre-gel starch 2%	–	P: 5 MPa, T: 25 °C	D:45, H:10	Ash contained salts of higher melting point	Tian et al. (2018)
Coal fines (67%)/sawdust (25%)	Molasses 8%	Hydraulic press	P: 5 MPa	–	Improved strength and LHV	Tian et al. (2018)
Charcoal (50%)/semi-coke (50%)	Biotar 6%, hydrated lime 3%	Customized device	P: 10 kPa, T:25 °C	H: 82–84, OD:60, ID:25	high-quality briquettes with reduced emissions	Cong et al. (2021)
Biochar (sawdust/maize husk) (60%), pyrolytic plastic (10%) waste, and (20%) carbonized sub-bituminous coal	Cassava flour 5%, limestone 2.5%, and laterite 2.5%	Hydraulic press	F: 98.1 N	–	30% of ash content	Nwabue et al. (2017)
Cashew waste biochar	Cassava starch 10%, water 35%	Screw press	–	D:55, H:100	High LHV	Sawadogo et al. (2018)
Palm kernel shell biochar	Starch thickened pyrolysis oil 25%	Hydraulic press	P: 14.7 MPa	D:19, H:50	Durability, high water resistance	Abdullahi et al. (2017)
Pine needle biochar	Lime 50%	Screw press	P: 1.5–2.5 MPa	D:65, H:25	high-strength briquettes	Kumain et al. (2020)
Biochar composite (30% coffee dusks, and 70% rice husks)	Starch 10–40%	–	P: 7 MPa	D:50, H:800	High strength-briquette with high LHV	Lubwama et al. (2020)
Orange bagasse	Corn starch 10%	Hydraulic press	F: 9.8 N	–	Good mechanical strength	(Karine Zanella et al., 2016)
Charcoal	Molasses 20%, Ca (OH) ₂ (10%) Cement (4%), SiO ₂ (4%)	Hydraulic press	P: 160 MPa	D: 40 and 70	Good cold and hot mechanical strength	Mousa et al. (2019)
Maize, wheat and rice straw biochar	Modified starch 4.32%	–	P: 25 MPa	D: 40, H: 20	Good mechanical performance and reduced emissions	Guo et al. (2020)
Peanut shells char	Cassava flour 10%	–	–	–	Improved durability	Ezéchiél et al. (2022)
Rain tree residues (50%) and coffee ground/tea wastes (50%)	Cassava flour 10%	–	–	D: 40, H: 10	Good combustion and strength properties	Kansai et al. (2018)

D: diameter, H: height, OD: outer diameter, ID: inner diameter, P: pressure, T: temperature, F: force.

(organic or inorganic) to improve briquette properties (Abdullahi et al., 2017; Nwabue et al., 2017; Tian et al., 2018). In formulations involving biotar, there are instances where heating was necessary either during binder preparation (Penmetsa and Steele, 2012; Riva, 2019; Riva et al., 2020) or during the densification process. Some studies presenting feedstock types, binders, and briquetting technologies currently used are shown in Table 4. Biochar briquettes comprised of a single feedstock have been produced with a wide range of binder ratios (4–25%) resulting in quality briquettes with improved combustion performance that meet the acceptable standards (Table 1). However, studies on feedstock blending (biomass/coal or biochar/biomass, biochar/coal, Biomass/biochar/coal) and binder blending have shown significant improvements in terms of emission reduction, energy and mechanical strength, all of which depend on the briquetting technology and binder applied. Additionally, densification studies performed on spruce wood sawdust char bounded by lignin (15%) showed that the shatter index, impact resistance, and compressive strength failed by 100% after 2 weeks in storage (Kong et al., 2013). This was attributed to the effect of moisture absorption of the densified fuel in storage, which was around 25%. The problem was mitigated by the coupling of lignin with hydrated lime in a ratio of 10:5. Another study highlighting the benefits of coupling lignin with other adhesive materials was reported (Lumadue et al., 2012).

4.3. Biochar briquette properties

The properties of the biochar briquette are directly related to biochar characteristics and to the binder(s) used in the densification process. In this section, we explore the influence of the resource type and the pyrolysis operating conditions for biochar production, as well as the effect of particle size distribution, and the binder type on the mechanical properties of biochar briquettes and their environmental performances.

4.3.1. Mechanical properties

4.3.1.1. Resource type. The resource type utilized for biochar production significantly impacts the mechanical properties of the resulting biochar briquettes. The compressive strength measured for biochar briquettes prepared under the same pyrolysis conditions (450–500 °C, 5 °C min⁻¹, N₂) from maize straw, rice straw and wheat straw were 1.1 MPa, 1.2 MPa, and 1.0 MPa, respectively (Guo et al., 2020). This result indicates that the resource type affected the mechanical properties of the briquettes despite rice and wheat straw having similar chemical composition. As a result, a combination of several biomass types pyrolyzed under the same operating conditions might improve the mechanical properties of the resulting briquette. This was shown with a blend of 70% rice husk and 30% coffee husk biochar, as the formed briquette had higher drop strength than a blend of 70% groundnut shells and 30% coffee husk biochar. In this case, despite the use of the same binder type and proportion, a 10% fall in the drop strength was observed, which could be due to the difference in resource type (Lubwama et al., 2020). Interestingly, ash content can also impact the mechanical strength of biochar briquettes. This was shown for briquettes prepared with two commercial charcoals differing in ash content (39w% and 0.7w%), using molasses as binder and compressed at 160 MPa. The results showed that the briquette with the highest ash content had a higher splitting tensile strength (625 kN m⁻²) compared to the low ash content briquette (507 kN m⁻²). The improved mechanical performance of the high ash charcoal briquette could be attributed to properties such as porosity, density, friability, particle size of the feedstock and not just the high ash content (Mousa et al., 2019).

Recently, most of the biochar briquetting studies has focused on woody biomass and agricultural residues. However, a growing interest towards municipal solid waste briquetting has emerged. This is attributed to the abundant availability of the resource and its similarity in

composition to that of conventional bioresources. Among municipal solid waste, solid refuse fuel (SRF) appears as a suitable fraction with limited valorization routes nowadays. SRF typically present a high fixed carbon content compared to the ash content, as well as limited moisture content, which is crucial for energy applications. Regarding the use of unconventional biomass for biochar briquette production, algae (Amarasekara et al., 2017) and fecal sludge (Atwijukye et al., 2018) have been reported. In addition, algae, which are mainly composed of carbohydrates and proteins, might lead to production of pollutant emissions resulting from substantial amounts of nitrogen and sulfur (Encarnação et al., 2015). Other alternative bioresources, such as sludge, may have an excessively high ash content (70%), and thus low calorific value.

4.3.1.2. Pyrolysis condition. The pyrolysis temperature is a crucial parameter impacting both physical and chemical characteristics of biochar, which affects the mechanical performances of the briquettes. The effect of pyrolysis temperature on biochar properties is dependent on the initial composition of the biomass, which is directly linked to the resource type. The optimal pyrolysis temperature for agricultural residue falls within the range of 350 °C–550 °C. Higher temperature beyond this range may result in increased ash content (Liu and Balasubramanian, 2013; Lubwama et al., 2020; Sawadogo et al., 2018; T. Wang et al., 2019). Conversely, woody biomass exhibits resilience to higher pyrolysis temperatures, typically ranging from 600 °C to 800 °C. This results in the production of biochar characterized by a satisfactory calorific value and ash content (Jiang et al., 2017; Kong et al., 2013; Riva, 2019). Therefore, the pyrolysis temperature not only alters the physical properties of biomass, it also influences the interaction between the binder and biochar particles. The extent of this interaction manifests in the mechanical performance of the briquette. T. Wang compared the mechanical strength of corn straw biochar briquettes produced at two different pyrolysis temperatures: 350 °C and 700 °C, with ash contents of around 20% and 60%, respectively. The findings revealed that, at a biochar-to-binder ratio of 50:1, the biochar briquettes pyrolyzed at 350 °C exhibited higher shatter strength (89.5%) compared to those pyrolyzed at 700 °C (64.5%). However, when the biochar-to-binder ratio was adjusted to 100:1, the biochar briquettes pyrolyzed at 700 °C demonstrated an increase in shatter strength (91.4%) as opposed to the ones pyrolyzed at 350 °C (40.9%) (T. Wang et al., 2019). This implies that the high ash content of the biochar pyrolyzed at 700 °C had a positive effect on the mechanical resistance at a low binder dosage, but had the opposite effect at high binder dosage. On the contrary, in the case of low-ash biochar produced at 350 °C, a higher binder loading was found to be advantageous for enhancing mechanical strength.

The impact of pyrolysis temperature (500 °C, 800 °C, and 1100 °C) on the durability of spruce biochar briquettes as reported, indicated that at a 10% binder loading, biochar briquettes produced at 800 °C exhibited durability of 80%, whereas those produced at 1100 °C exhibited durability values of 70%. Interestingly, increasing the binder loading to 40% did not have a significant influence on the durability of the biochar briquettes (Riva, 2019).

4.3.1.3. Particles size distribution. Biochar properties directly influence the mechanical strength of biochar briquettes. Specifically, the particle size distribution has a direct relationship with several critical aspects of the briquette's quality, including homogeneity, binder distribution, density, durability, and, ultimately, its mechanical strength. Studies indicates an inverse relationship between particle size and mechanical strength (Bazargan et al., 2014; Gill et al., 2017; Guo et al., 2020; Kaliyan and Vance Morey, 2009; Rahaman and Salam, 2017). This connection arises from the fact that smaller particles contribute to enhanced uniformity throughout the briquette's structure, thereby leading to improved durability and increased density. Furthermore, greater surface area of finer particles promotes a more consistent binder

distribution across particle surfaces. This results in particles being more tightly packed and interlocked, yielding higher mechanical resistance. Thus, biochar with large particle sizes (>2 mm) would impede mixing due to fewer contact surfaces between the binder and biochar particles (Kaliyan and Vance Morey, 2009). This will result in uneven distribution of binder on the biochar particles and ultimately, poor agglomeration. However, some drawbacks associated with the use of fine particles for biochar briquetting include, poor flowability and feeding problems, increased equipment wear due to increased friction between particles and equipment surface, slower drying rates of resulting product leading to higher energy consumption.

The porosity of particles is also important. Porous structures pose challenges for compaction because they enable the entrapment of the binder within its pores, preventing homogeneous distribution on the surface of biochar particles where they are useful for agglomeration. In addition, higher compaction pressure is required due to the presence of more void spaces, which results in lower density and poor particle interlocking.

4.3.1.4. Binding agent. In addition to the resource type, pyrolysis conditions, and particle size distribution, the selection of binder and its proportion in the briquette formulation, has substantial influence on the mechanical attributes of biochar briquettes. The binder provides cohesion between the biochar particles, making it a key component of biochar briquetting. Therefore, understanding the chemical and physical properties of the binder, along with the bonding mechanisms, is vital in determining the optimum briquette formulation. In general, an increase in binder loading results in an equivalent increase in mechanical resistance (Karine Zanella et al., 2016). A substantial rise in the stress resistance and durability of biochar briquettes made from orange bagasse and starch binder was observed when the binder ratio was increased from 5% to 15%. Likewise, the addition of 8w% molasses to a briquette formulation composed of coal fines and sawdust lead to a 50% increase in the compressive strength (Manyuchi et al., 2018). Furthermore, the effect of storage time on the compressive strength of molasses bonded briquettes showed that the briquettes absorbed moisture during 2 months of storage, resulting in a 19% decrease in compressive strength (Sharma and Samuel, 2006). In another study, it was shown that combining lignosulfonate with pyrolysis oil improved the density and mechanical durability of spruce biochar briquettes (Riva, 2019). As expected, each binder has a unique effect on the mechanical performance of the resulting briquette (Ezéchiel et al., 2022; Hu et al., 2015). Therefore, it is critical to consider the advantages and drawbacks of the binders (Table 2) during the selection process.

4.3.2. Environmental performance

Biochar briquettes must meet not only mechanical and combustion quality standards but also environmental safety requirements. Depending on the biomass feedstock, pollutants generated from biochar briquettes combustion may include gaseous emissions (SO₂, NO_x, CO, CO₂, CH₄), particulate solids, polycyclic aromatic hydrocarbons (PAH), organic carbon, toxic metal, dust, volatile organic compounds (VOCs), and chlorinated micropollutants (dioxin) (Li et al., 2019; Schobing et al., 2023). In a recent study carried out by (G. Li et al., 2023) the amount of pollutant emissions generated by the combustion of biochar briquettes and coal were compared. The results indicate a more than 40% reduction in the emissions of methane and CO₂ when compared to coal. This suggests that using biochar briquettes may not completely eliminate harmful emissions, but it can significantly mitigate their impact. Thus, by close monitoring of environmental performance indicators, it is possible to keep gaseous and particulate emissions within acceptable limits. This is critical because the utilization of biochar briquettes is not solely for industrial application as a substantial population in developing countries utilize it in satisfying their domestic energy needs. Additionally, most of the cooking and heating equipment are located

within the homes (in poorly ventilated kitchens, living room and bedrooms). Therefore, in order to prevent untimely deaths and other health-related complications associated with pollutant emissions, the environmental performance indicators of biochar briquettes must be respected. This can be achieved by carefully controlling the components of the biochar briquettes and the production aspects, including resource type, pyrolysis conditions, and binder type. Given that pollutant emissions from both household and industrial combustion significantly contribute to ambient air pollution and affect air quality, knowledge of the standards is important.

The acceptable limit of gaseous pollutants in ambient air, set by the American EPA's National Ambient Air Quality Standard (NAAQS) are presented in Table 5.

However, for industrial applications utilizing solid fuel for combustion, the acceptable limit is usually set based on the thermal rating of the installation. The acceptable limit for some pollutant emissions generated from biomass-based solid fuel combustion installation in France with thermal rating of 50–100 MW are 200 mg Nm⁻³ for SO₂, 300 mg Nm⁻³ for NO_x and 30 mg Nm⁻³ for dust. Regarding combustion installation of thermal rating between 100 and >300 MW, the acceptable limit for SO₂, NO_x, and dust are 250 mg Nm⁻³, 250 mg Nm⁻³, and 20 mg Nm⁻³ respectively. Meanwhile the dioxins and furans standards irrespective of the thermal rating is set a 0.1 ng Nm⁻³ (Directive 2010/75/EU, 2010). Apparently, smaller installations are permitted higher limits compared to large ones.

When it comes to meeting these limits, biochar briquettes are one step ahead of raw biomass briquettes. As the carbonization process effectively reduces or eliminates the volatile components which are linked to pollutant emissions. Furthermore, the boiler type and design influences the species and quantity of gaseous pollutant emitted (Du et al., 2017; Krümal et al., 2019). Nevertheless, priority should be given to operational parameters like the resources type and composition, pyrolysis conditions, particle size distribution, and binding agent for adequate control of toxic emissions in biochar briquettes.

4.3.2.1. Resource type and pyrolysis conditions. The raw biomass used to produce biochar briquettes will affect not only the mechanical strength, but also the environmental performance, in terms of the pollutant emissions generated during combustion. Biomass fuel with a high volatile matter content would likely cause high gaseous and particulate solids emissions while a biochar with a high ash content (rich in chlorides, silicates) would lead to slagging and fouling (Cong et al., 2021; Guo et al., 2020; Lubwama et al., 2020; Li et al., 2019). Key parameters of biochar, which vary depending on the resource type and pyrolysis temperature, include volatile matter content, ash content, sulfur content, chlorine content, and nitrogen content. These parameters can impact the environmental performance of biochar. However, biochar exhibits lower levels of S, and Cl (Table 6).

Thus, the selected feedstock has significantly impact on the volatile matter content, total suspended particles and ash content of the biochar briquette. Furthermore, pyrolysis temperature and heating rate will impact the proportion of solid, gaseous and condensable species produced, as well as the properties of the biochar produced. Therefore, biochar with a high volatile matter and low ash content are obtained at low pyrolysis temperature. Conversely, increasing the pyrolysis

Table 5
Acceptable limit of gaseous pollutant emissions NAAQS.

Gaseous pollutant	Averaging time	Acceptable limit	Reference
Carbon Monoxide (CO)	8 - 1 h	9–35 ppm	(US EPA, 2024)
Nitrogen Dioxide (NO ₂)	1 year–1 h	53–100 ppb	
Ozone (O ₃)	8 h	0.070 ppm	
Lead (Pb)	3 months	0.150 µg m ⁻³	
Particle Pollution (PM _{2.5})	1 year–1 h	15–35 µg m ⁻³	
Sulfur Dioxide (SO ₂)	3 h	0.5 ppm	

Table 6
Summary of biochar properties with respect to resource type and pyrolysis temperature.

Resource type (biochar)	Pyrolysis T (°C)	Volatile matter content (%)	Ash content (%)	Total suspended particles (mg g ⁻¹)	Sulfur content	Nitrogen content (%)	Chlorine content (mg g ⁻¹)	Reference
Sawdust	500	38.44	4.23	5.03 ± 0.68	–	–	–	(Li et al., 2019)
Rice straw	500	25.67	27.49	12.7 ± 0.9	–	–	–	
Maize straw	500	28.26	18.7	14.4 ± 0.5	–	–	–	
Wheat straw	500	29.99	21.79	11.4 ± 0.3	–	–	–	
Bituminous Coke	500–600	3.51	11.61	1.05 ± 0.71	–	–	–	
Lignite	500–600	11.05	28.75	1.44 ± 0.32	–	–	–	
Corn stover	600	10	31.81	–	–	–	–	Hongbin et al. (2020)
Tree branches	550–600	12.02	3.35	–	–	–	–	Cong et al. (2021)
Pine wood	600	7.55	4.22	–	–	–	–	Riva et al. (2019)
Spruce sawdust	500	13.36	6.51	–	–	–	–	Kong et al. (2013)
Spruce chips	500	17.5	2	–	–	–	–	Riva (2019)
Spruce chips	800	8.5	2	–	–	–	–	
Spruce chips	1100	6.8	2	–	–	–	–	
Oak	500	23.6	4.5	–	160 ppm	0.3	–	Cheah et al. (2014)
Oak	850	–	–	–	150 ppm	0.2	–	
Corn stover	500	14.9	38.8	–	800 ppm	0.3	–	
Corn stover	850	8.4	47.1	–	610 ppm	0.4	–	
Straw	500	25.4	52.4	–	0.5 %	1.8	2.5	(Wang et al., 2019)
Coal	–	33.7	33.4	–	0.4 %	1.0	0.6	

temperature leads to a low volatile matter content and high ash content in the biochar.

Moreover, studies on the effect of resource type and pyrolysis temperature on the concentration of polycyclic aromatic hydrocarbons (PAHs) indicated that biomass pyrolyzed between 400 °C and 500 °C exhibited higher concentrations of PAHs in contrast to those pyrolyzed at higher temperature (Brown et al., 2006; Hale et al., 2012; Keiluweit et al., 2012; Kloss et al., 2012). The variety and concentration of the PAHs at the peak temperature of abundance (400–500 °C) in biochar, is dependent on the chemical characteristics of the feedstock. For instance, the PAH concentrations (mg kg⁻¹) of three different feedstocks (straw, spruce and poplar) pyrolyzed at 400 °C and 525 °C were 5.2, 30.7, 4.3 and 33.7, 1.8 and 2.0 respectively (Kloss et al., 2012). Similarly, the evolution of PAHs concentration with temperature indicated that the PAHs begin to form at 300 °C, peaks at 500 °C and decomposes at higher temperatures (700 °C) (Keiluweit et al., 2012). Both biochar produced from grass and wood followed the same trend with the difference being in the concentration of the PAHs formed. Thus, to control the generation of polluting emissions from biochar briquettes, consideration must be given to the resource used and the pyrolysis temperature (Keiluweit et al., 2012).

4.3.2.2. Particle size distribution. With regards to combustion, the expectation is that fine particles of uniform size distribution enable enhanced mixing between the solid fuel and the oxidant (oxygen, air), similar to the behavior observed with liquid or gaseous fuels. However, it seems that when burning briquettes, the size of the briquette holds more relevance over combustion characteristics than the particle size distribution of the material itself. Consequently, larger coal lumps (8–12 cm) exhibit lower particulate matter emissions compared to small coal lumps (0.8–2 cm) (Li et al., 2016). Likewise, the ratio of CO/CO₂ is lower in large coal sizes (2.5–5 cm) than smaller lumps (0.8–1.6 cm) (Li et al., 2021). This observation was attributed to the gradual release of volatiles in larger-sized coal, which facilitates more complete combustion, in contrast to the rapid release consistent with smaller-sized coal.

4.3.2.3. Binding agent. The inclusion of a binder in biochar briquetting is almost unavoidable due to the loose, porous and hydrophobic nature of biochar. Although organic binders achieve high adhesive effect, which is key for mechanical strength, they lead to an increased content

of volatile components in the resulting briquette (Cong et al., 2021; Tian et al., 2018; T. Wang et al., 2019). On the other hand, the use of inorganic binder increases the ash content and does not contribute to the calorific value of the briquette (Kumain et al., 2020). For this reason, composite binders (mixture of organic and inorganic binders) have been proposed to balance the strong adhesive effect of the organic binder with the stabilizing effect of the inorganic binder.

The binder proportion used in the briquette formulation has far-reaching impacts on the environmental performance of the resulting briquette. A binder with high binding strength and low toxicity would promote particle agglomeration at a lower dosage (starch), thereby limiting the possibility of generating pollutant emissions. Conversely, a binder with a low binding strength would require a higher dosage, increasing the risk of pollutant emissions generation (biotar). Moreover, organic binders such as alkaline black liquor and biotar have been reported to release considerable amounts of VOCs, SO₂, and NO_x (Cong et al., 2021). In order to mitigate the problems of pollutant emissions arising from the combustion of biochar briquettes, investigations into the development of efficient and cost-effective binders for biochar briquetting must be carried out.

In summary, the production of a high-quality biochar briquette with the potential to serve as an environmentally friendly substitute for coal requires careful consideration of critical factors, such as resource type, pyrolysis conditions, particle size distribution, and the selection of binding agents. These elements not only impact the mechanical performance of the briquettes but also affect the environmental aspect, particularly emissions. Therefore, employing strategic approaches to skillfully control these factors becomes essential in achieving superior-grade biochar briquettes.

5. Recommendations and future research directions

5.1. Strategies to improve mechanical properties

Some strategies have been proposed to enhance the mechanical performance of biochar briquettes so that they can support handling, transportation, and storage while also maintaining high thermal stability. Furthermore, in the improvement of the mechanical properties of biochar briquettes, a balance must be struck between mechanical performance and other quality parameters such as combustion properties, environmental sustainability, and production costs. In this context, the

four strategies considered in this review are:

(i) Co-densification

Co-densification involves the compaction of two or more feedstocks that are essentially different in composition and structure (Kang et al., 2019; Lubwama et al., 2020; Zhu et al., 2017). This allows improving the response of the feedstock to compaction and the quality of the resulting briquette. The co-densification of biochar with other feedstock (biomass or coal) could reduce the quantity of binder required for efficient agglomeration compared to the densification of only biochar. In addition, co-densification of biochar and other feedstock activates additional bonding mechanisms that promote particle to particle interaction (Kang et al., 2018) thus, improving mechanical durability (Cong et al., 2021; Kang et al., 2018; Zhang et al., 2019). Furthermore, to achieve high mechanical and thermal efficiency, biomass-coal blends have been proposed (Kang et al., 2019). These blends (biomass-coal briquettes) result in superior mechanical properties (Manyuchi et al., 2018).

(ii) Particle size control

For superior-strength biochar briquettes, it is crucial to control the particle size distribution of the material (biochar). This is because, the optimum particle size distribution will facilitate uniform binder distribution on the biochar particle surfaces, improve homogeneous mixture of biochar/binder within the briquette to obtain consistent structure, and increase briquette density, durability, and mechanical strength.

(iii) Binder blending

This approach involves coupling two or more binders with complementary properties that stabilize the formulation. A synergistic effect is produced when different binders interact with the biochar particles. Studies show that the key mechanical challenges like water absorption during storage (Kong et al., 2013), hot mechanical resistance (Mousa et al., 2019) and abrasion are mitigated by the strategic blending of binders (Abdullahi et al., 2017).

(iv) Choice of briquetting technology

The choice of briquetting technology contributes to the mechanical performance of biochar briquettes as it determines the moisture content and binder content in the formulation. In addition, the densification conditions particularly, pressure and temperature which influence the mechanical properties of the briquette depend on the technology. High pressure compaction technology can accommodate lower binder content in the formulation and high temperature briquetting has been reported to facilitate binder activation and briquette drying. The right briquetting technology not only enhances mechanical durability, but also offers cost advantages such as reduced binder consumption and energy needed for drying.

5.2. Strategies to improve environmental performance

Biochar briquettes are considered a sustainable alternative to lump coal for both industrial and household applications. However, the generation of pollutant emissions resulting from the binder or other additives must be carefully monitored and efficiently reduced. To this end, some approaches to improve the environmental performance of biochar briquettes have been proposed.

i. Co-densification

Co-densification as previously explained involves the compaction of diverse feedstock in order to boost particles agglomeration. To further reduce volatile matter content of a biochar briquette, it can be co-

densified with coal or coke fines which is known to generate less volatiles components and produce substantial gain in calorific value (Hongbin et al., 2020). Moreover, the co-densification of high ash biochar typical of agricultural residue, with the low ash biochar from woody biomass might help in controlling the volume of ash produced and ultimately prevent ash related issues in combustion equipment. Similarly, the co-firing of coal and biomass char was reported to reduce slagging and fouling caused by biomass fuel specifically, agricultural residues (Míguez et al., 2021; Niu et al., 2016; Zhu et al., 2017), and enhance combustion efficiency (L. Chen et al., 2020; Li et al., 2018).

ii. Binder blending

Binder coupling or blending has been shown as an effective approach to reduce binder related pollutant emissions. The coupling of biotar with hydrated lime was shown to significantly reduce the volatile organic compounds (VOC) and SO₂ produced (Cong et al., 2021). In the production of biochar briquettes from palm kernel shell, the coupling of starch with pyrolysis oil resulted in durable and high water resistant briquettes (Abdullahi et al., 2017).

iii. Briquette size control

Studies on coal briquette combustion shows that larger-sized briquettes generated reduced levels of particulate matter and CO emissions in contrast to smaller-sized coal (Li et al., 2021; Li et al., 2016). This suggests that optimizing the briquette size is essential to ensuring a gradual release of volatiles during combustion, which allows for complete combustion without significant delays in the combustion process.

iv. Choice of briquetting technology

As mentioned earlier, briquetting technology could influence the amount of binder used, especially organic binders, which may be linked to the quantity of volatile species produced (Bazargan et al., 2014; Kaliyan and Vance Morey, 2009; Manyuchi et al., 2018; Mousa et al., 2019). This is so because efficient compression technology may require less binder to achieve optimum agglomeration.

6. Conclusions

This review provides a systematic overview of the various stages involved in the biochar briquette production processes, key parameters for the conversion from biomass to biochar, characteristics of a suitable binder for biochar briquetting and the standard test parameters for biochar briquettes. To address the dual challenge of mechanical and environmental sustainability that limits the potential of biochar briquettes to fully replace coal in both domestic and especially industrial applications, some critical factors identified include: resource type, pyrolysis conditions, biochar particle size distribution, densification technology, binder type and inclusion level (biochar to binder ratio). Based on extensive analysis carried out in this review, two key deductions were made:

1. The quality of biochar briquettes and its ability to fulfill the desired application requirements are assessed by the mechanical and environmental performances. The mechanical performance is related to factors affecting the durability of the biochar briquettes and the resistance to handling during utilization, transportation and storage. On the other hand, environmental performance is related to the quantity and quality of pollutant emissions produced during the combustion of the biochar briquettes, which is dependent on the composition of both biochar and binder. It was shown that the resource type, pyrolysis conditions, biochar particle size distribution, choice of binder and binder ratio had a crucial impact on briquette quality.

2. Increase in the binder load usually leads to a corresponding increase in the mechanical strength of biochar briquettes. Nonetheless, this could also lead to a decrease in the calorific value, and increase in emissions and ash content, depending on the type of binder used. Therefore, achieving optimal briquette formulation requires finding a balance between the desired mechanical strength and combustion characteristics.

Some recommendations proposed to enhance the mechanical and environmental performance of biochar briquettes are co-densification of diverse feedstocks, binder blending, and catalyst development for pollutant emissions control. The design and development of biocarbon-based catalysts that facilitate the capture and conversion of pollutant emissions and toxic metals into more environmentally friendly options (Graul et al., 2024) also appears as an interesting application for biochar related to pollutant emissions mitigation.

Finally, while biochar briquettes show promise and considerable potential as a sustainable alternative to coal in industrial processes, further research is necessary to improve its thermal stability. This improvement is crucial to facilitate utilization in a broader range of industrial applications.

CRedit authorship contribution statement

Gloria Ifunanya Ngene: Writing – review & editing, Writing – original draft, Resources, Data curation, Conceptualization. **Bénit Bouesso:** Writing – original draft, Resources, Data curation. **María González Martínez:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Ange Nzihou:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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