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REVIEW ARTICLE

Reducing the carbon footprint of buildings using biochar-based bricks and insulating materials: a review

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Abstract

The rapid growth of global industrialization and urbanization has led to the excessive use of non-renewable energy sources and the alarming release of greenhouse gases within the construction industry. In response, adopting sustainable and environmentally friendly building materials has emerged as a vital solution for achieving the international sustainable development goals set by the United Nations. This review discusses the potential benefits of incorporating biochar-based bricks and insulation materials, focusing on their preparation methods, material properties, emission reduction capabilities, effectiveness in reducing carbon emissions, enhancing thermal insulation, and promising economic prospects. The major points are: (1) Biochar-based materials offer significant potential for reducing the carbon footprint of buildings and enhancing their thermal insulation properties. (2) With a thermal conductivity ranging from 0.08 to 0.2 W/(m·K), biochar insulation materials contribute to reduced energy consumption and greenhouse gas emissions. (3) Replacing one ton of cement with biochar in brick production can substantially reduce 1351–1505 kg CO_2-eq over the entire life cycle. (4) Using biochar as part of concrete insulation saves about 59–65 kg of carbon dioxide per ton while offering clear economic benefits. Although biochar insulation is comparatively more expensive than traditional insulation materials like fiberglass and foam, its energy-saving advantages can balance the extra cost. (5) Biochar insulation is derived from organic waste, contributing to improved recyclability, environmental sustainability, and cost-effectiveness.

Keywords Biochar · Insulation material · Sustainable building · Brick · Emission reduction · Carbon neutrality

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Introduction

The global expansion of industries and cities has led to widespread reliance on non-renewable energy sources, causing significant environmental problems, notably a substantial increase in global temperatures (Farghali et al. 2022a; Farghali et al. 2023; Sarwer et al. 2022). Furthermore, data revealed a substantial rise in the average carbon dioxide concentration in the earth's atmosphere, climbing from 285 to 419 parts per million between 1850 and 2023 (Liu et al. 2020). The rise is mainly attributed to the use of non-renewable energy sources, with predictions showing a 50% increase by 2050 (Osman et al. 2022a; Rabaey and Ragauskas 2014). Notably, buildings play a significant role in global climate change, contributing to 39% of worldwide carbon dioxide emissions (Adams et al. 2019; Chen et al. 2022a; Liu et al. 2022; Ji et al. 2022). This underscores the importance of construction decisions in achieving the United Nations' Sustainable Development Goals (SDGs) (Omer and Noguchi 2020; Orsini and Marrone 2019; Sabnis and Pranesh 2017).

To genuinely commit to sustainable development, there is an urgent need to prioritize eco-friendly and recyclable building materials, such as biochar-based sustainable bricks and insulation materials (Pandey et al. 2022). Biochar, derived from biomass pyrolysis, has versatile applications across various sectors, including heat production and building materials (Osman et al. 2022b). Importantly, it serves as a substitute for fossil carbon sources, and its exceptional properties, such as high porosity and low thermal conductivity, make it effective in emissions reduction (Osman et al. 2023; Weber and Quicker 2018). Moreover, incorporating biochar in cement-based materials not only reduces thermal conductivity but also enhances insulation and enables carbon storage within the building material, thus reducing energy consumption (Minunno et al. 2021). By doing so, biochar greatly enhances buildings' sustainability (Cuthbertson et al. 2019; Lee et al. 2019), and this review explores critical aspects related to biochar-based bricks and insulating materials, such as preparation methods, emissions reduction potential, insulation benefits, and economic assessment, as shown in Fig. 1.

Biochar-based sustainable bricks

Preparation and formulation of biochar-sustainable bricks

The production of biochar-based sustainable bricks involves several steps, including biochar production, selection of suitable binding materials, and mixing and molding of the final product. Biochar is obtained through pyrolysis, where raw materials are exposed to high temperatures of 500–800 ℃ in an oxygen-free environment. Various biomass-based waste materials like wood chips, crop and forest residues, municipal solid waste, sunflower husk, and pelletized grape wine pressings can be used to produce biochar (Colantoni et al. 2016; Lehmann et al. 2006). Various techniques are available for biochar production, with pyrolysis, hydrothermal carbonization, and microwave carbonization commonly utilized (Chhimwal et al. 2022). Pyrolysis can be categorized into two main types: fast and slow pyrolysis, which differ in operating conditions. Fast pyrolysis involves around 500 ℃ for approximately two seconds, with a high heat transfer rate of 300 ℃/min. This process yields approximately 75% bio-oil, while char and gas outputs are around 12 and 13%, respectively. On the other hand, slow pyrolysis occurs over longer periods, typically at 300–500 ℃ for 5–30 min, with a slower heat transfer rate of approximately 5–20 °C/min. Slow pyrolysis results in a lower bio-oil yield of 30–50%, with 25–30% biochar output and 35% gas output (Osman et al. 2023; Ramola et al. 2020).

Apart from traditional fast and slow pyrolysis methods, newer techniques have emerged, including hydrothermal carbonization and microwave pyrolysis. Hydrothermal carbonization is a process where biomass undergoes conversion through the use of water at high pressure and temperature (Farghali et al. 2022b; Regmi et al. 2012; Zhang et al. 2013). This technique presents benefits, including efficient conversion, decreased operating temperature, and omitting supplementary energy for drying (Farghali et al. 2022a; Sabio et al. 2016). On the other hand, microwave pyrolysis is a modern technique that offers benefits like precise process control, cost savings, and reduced raw material preparation requirements (Mašek et al. 2013a; Morgan et al. 2017). Moreover, microwave pyrolysis allows for more uniform temperature distribution during the process, resulting in biochar with enhanced properties, including greater surface area and higher concentrations of functional groups compared to traditional pyrolysis methods (Wang et al. 2009). These advantages make microwave pyrolysis an appealing choice for biomass conversion. Detailed characteristics of specific biochar production methods are presented in Table 1.

Over recent years, there has been an increasing inclination toward leveraging engineered biochar in construction materials. The engineering community has pioneered an innovative strategy of integrating biochar into cementitious blends either as a substitute or an additive (Restuccia et al. 2020). Integrating engineered biochar into construction materials offers multiple benefits, including enhanced structural strength and improved permeability, providing an advantage over pristine biochar. These results carry profound

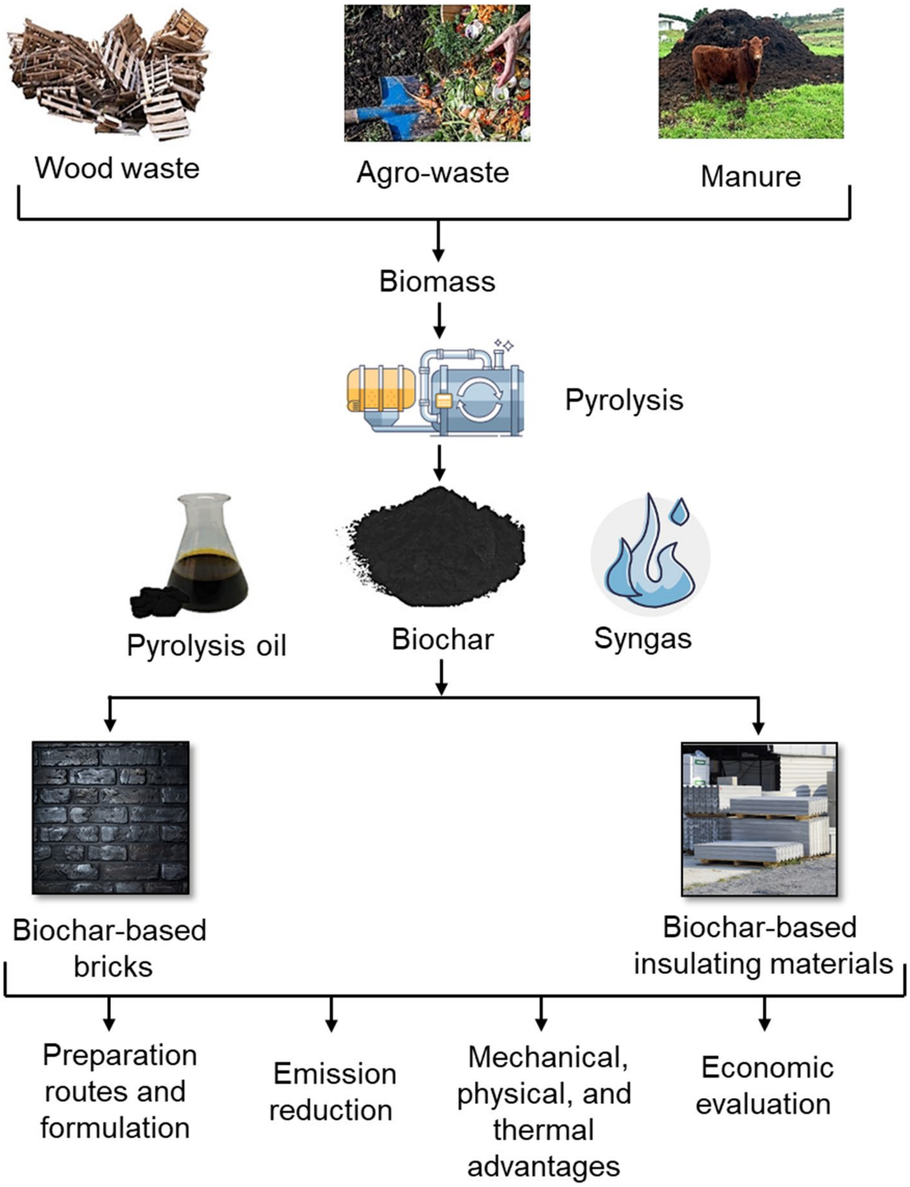

Fig. 1 The conversion process of biomass feedstocks into biochar-based bricks or insulating materials. The process begins with the preparation of biochar, utilizing various well-known pyrolysis techniques. The subsequent focus is on preparing biochar bricks and insulation materials, considering four key aspects, namely the methods and formulations used in their preparation, their potential for reducing emissions, their mechanical, physical, and thermal properties, and an economic evaluation of their viability

implications for applying engineered biochar as a carbon-capturing component in building materials and waste-repurposing strategies (Gupta et al. 2018a). In engineering, bricks are commonly classified into stone, fired clay, and concrete bricks. Biochar is a material from biomass thermal decomposition, so it is not readily suitable for high-temperature firing processes. Therefore, it is typically used as an additive or substitute for concrete bricks. Recent research indicates that bricks made from a mix of 50% biochar and 50% high-density polyethylene display enhanced compressive strength relative to other substances. Additionally, bricks composed of biochar and cement surpass traditional bricks in terms of insulation, rigidity, and water absorption capabilities (Maxwell et al. 2020).

Researchers have investigated using biochar as an aggregate substitute in lightweight concrete. Previous studies have explored lightweight aggregates such as hollow cenospheres, wood, reed fibers, and milled fibers to produce high-performance concrete with reduced weight (Lu et al. 2021; Shon et al. 2019; Wang et al. 2016). Biochar exhibits promise as a porous and lightweight substitute for fine aggregate in concrete formulations (Schmidt 2014). Recent investigations underscore the feasibility of using biochar instead of sand for concrete manufacturing. Studies reveal that the substitution of sand by biochar in a 20% volume ratio, with an average granule dimension of 26 µm, results in a decline in bulk density by 10% and a boost in bending strength by 26% (Praneeth et al. 2021; Ramola et al. 2022; Schmidt 2014). In a separate exploration, biochar nano-aggregates sourced

Table 1 Biochar production methods and characteristics

Production method	Heating rate	Residence time	Suitable feedstock	Heating method	Production efficiency	Production scale	Typical designs	References
Slow pyrolysis	Very low, around 100 °C/h or even lower	Long, from hours or even days	Lump wood and similar biomass	External or internal	Relatively low and labor-intensive	Flame-curtain pyrolysis or flaming pyrolysis, used for small-scale production	Brick kilns, steel retorts, or earth mounds	Cornelissen et al. (2016), Emrich (1985), Mašek (2022), Ramola et al. (2020)
Intermediate pyrolysis	Comparatively elevated, on the magnitude of 100 °C/min or more	Relatively short, in the order of minutes to ten minutes	Biomass reduced in size to allow fast heating	External or internal	Relatively higher efficiency than slow pyrolysis	From small to medium scale	Rotary kilns, auger reactors, and vertical moving bed reactors	Boateng (2015), Mašek (2022), Zhang et al. (2018)
Fast pyrolysis	Several hundred °C/s, the temperature range between 400 and 600 °C	Relatively short, typically in the range of seconds to a few minutes	The size of the lignocellulosic biomass particles is smaller than 2 mm	Fast heating is attained by intimately exposing small biomass particles to a heat carrier, like heated sand or a heated metal surface	Fast pyrolysis with high heating rates, namely several hundred °C/s, and quick removal of released volatiles, resulting in high liquid product yields, i.e., 40–75 wt.%, and lower biochar yields, i.e., 10–25 wt.%	Not reported	Fluidized bed reactors, screw reactors, ablative reactors	Bridgwater (2012), Mašek (2022), Ramola et al. (2020)
Microwave pyrolysis	Dependent on reactor design, feedstock characteristics, and processing conditions	Dependent on reactor design, feedstock characteristics, and processing conditions	Any biomass material with high-moisture content that can absorb microwave radiation, such as municipal solid waste, sewage sludge, and agricultural waste	Microwave radiation, electricity is the primary source of energy	Microwave pyrolysis reduced secondary reactions and potentially higher product yields, making it easier to control the thermal decomposition process, with the microwave intensity adjusted based on the specific decomposition conditions	Ranging from small-scale laboratory units to commercial-scale units	Microwave pyrolysis reactors—batch and continuous processing units	Mašek (2022), Mašek et al. (2013a), Mašek et al. (2013b), Morgan et al. (2017), Wang et al. (2009)

Table 1 (continued)

Production method	Heating rate	Residence time	Suitable feedstock	Heating method	Production efficiency	Production scale	Typical designs	References
Biomass hydrothermal carbonization	Around 200–400 ℃, the pressure is much higher due to water being in a critical state, which makes it more reactive	Dependent on reactor design, feedstock characteristics, and processing conditions	Wet organic matter, sludges, and slurries, including biomass with high-moisture content	Water in a critical or supercritical state is the reactive medium, making pre-drying of biomass unnecessary and enabling high-moisture feedstocks	The process involves hydrothermal processing at high pressure but lower temperatures, namely 200–400 ℃, resulting in high yields of solid carbon products commonly known as hydrochar	Ranging from small-scale laboratory units to pilot-scale and commercial-scale units	Hydrothermal reactors with different designs, including batch and continuous flow reactors	Liu et al. (2018), Mašek (2022)
Biomass gasification	High heating rates due to high temperatures, namely above 1000 ℃	Short residence time, typically several minutes	Any biomass type	High temperatures, namely above 1000 ℃, with a gasification agent, such as carbon dioxide or water	High efficiency in producing gas rich in combustible gases, with a typical yield of solid carbonaceous residues from a few percent to over ten wt.%	Downdraft and updraft gasifiers for small-to-medium-scale plants and fluidized bed gasifiers for large-scale plants	Updraft gasifier, downdraft gasifier, and fluidized bed gasifier	Mašek (2022), Sikarwar et al. (2016)

The table compares six biomass pyrolysis methods, including their typical designs, production scale, production efficiency, heating method, suitable feedstock, residence time, and production process. The methods examined are slow pyrolysis, intermediate pyrolysis, fast pyrolysis, microwave pyrolysis, biomass hydrothermal carbonization, and biomass gasification. By evaluating factors such as production efficiency, feedstock suitability, and processing time, this table offers a comprehensive overview of the various options available for biomass pyrolysis from hazelnut shells and coffee residue, with particle dimensions spanning 10–15 μm, were employed. The inclusion of these biochar nano-aggregates notably amplified the specimen's modulus of rupture and fracture energy, experiencing increases of 22 and 61%, respectively (Restuccia and Ferro 2016b). Table 2 provides a summary of biochar-based sustainable brick formulations and their characteristics.

In conclusion, the use of biochar-based sustainable bricks offers opportunities for effective waste recycling and carbon sequestration. Biochar production involves different methods, including pyrolysis, hydrothermal carbonization, and microwave carbonization, each contributing unique characteristics. By incorporating engineered biochar into construction materials, we can achieve not only enhanced structural strength but also better-controlled permeability. This integration holds significant promise for developing sustainable and more resilient infrastructure in the future.

Emission reduction of biochar-based bricks

Addressing carbon neutrality necessitates reducing greenhouse gas emissions and capturing atmospheric carbon dioxide (Osman et al. 2020; Wang et al. 2021; Yang et al. 2023). A prominent approach gaining attention is the utilization of biochar as a soil amendment, which has been extensively studied for almost 15 years since its initial proposal (He et al. 2022; Wang et al. 2021). Biochar has shown potential in mitigating carbon dioxide emissions and facilitating carbon sequestration in soil. Research has highlighted the positive impact of biochar production in reducing net carbon dioxide emissions and global warming potential. Pyrolysis is preferred over incineration as it reduces emissions like methane, carbon monoxide, nitrogen oxide, and sulfur oxide (Gupta et al. 2018b). Various kinds of biochar have demonstrated adverse greenhouse gas emissions, estimated at approximately − 0.90, − 0.864, and − 0.885 kg of CO_2-eq/kg (kilogram carbon dioxide equivalent) for biochar derived from barley straw, biochar produced from corn stove residue, and biochar originating from yard waste, respectively (Alhashimi and Aktas 2017; Roberts et al. 2010). Recently, there has been a notable surge of interest in utilizing biochar as a carbon-negative material in the construction industry. Incorporating biochar into building materials offers the potential for buildings to serve as carbon sinks, contributing to the achievement of carbon neutrality goals. Various research studies have investigated using biochar in construction materials, yielding promising results and indicating a viable pathway toward meeting carbon neutrality targets (Alhashimi and Aktas 2017; Gupta et al. 2018b).

As a product of thermally decomposing biomass waste, biochar offers a sustainable approach to waste reuse and mitigates pollution that typically arises from waste incineration or landfill methods (Peng et al. 2023). Unlike traditional cement brick manufacturing, which consumes substantial energy in cement clinker, producing biochar-based bricks necessitates a lower heat source or electricity for thermal decomposition. However, it is worth noting that cement in its final lifecycle stage is challenging to reuse. Utilizing biochar as a filler in cement bricks or as the primary material alongside waste plastic can significantly reduce emissions while maintaining structural integrity. This approach presents a promising solution for achieving environmental sustainability and waste management in brick manufacturing. Table 3 lists some life cycle assessments for certain biochar products.

Analyzing the data outlined in Table 3 reveals a notable impact of the biochar production technique on its global warming potential. Nonetheless, considering its capacity for carbon sequestration, the global warming potential of biochar is predominantly situated in the negative spectrum, thus holding a pivotal role in environmental enhancement and climate change mitigation. On average, the life cycle global warming potential of one metric ton of biochar is roughly between −987.6 and −834.2 kg of CO_2-eq (Llorach-Massana et al. 2017; Muñoz et al. 2017; Puettmann et al. 2020; Robb and Dargusch 2018). Using a calcined clay and limestone solution for cement production can achieve a better global warming potential impact, with an average of 517 kg CO_2-eq/ton of cement. (Rhaouti et al. 2023). This implies that by substituting one ton of cement with biochar in brick-making, a reduction of 1351.2–1504.6 kg of CO_2-eq global warming potential can be achieved over the entire lifecycle. The use of biochar holds great potential in terms of environmental impact and shows promising prospects for development.

To conclude, the utilization of biochar as a carbon-negative substance within the realm of construction shows great potential in advancing the objectives of achieving carbon neutrality. By incorporating biochar into building materials, global warming potential can be reduced, and waste can be effectively reused. While biochar production demands energy, its ecological footprint is still superior to traditional cement brick fabrication. Persistent exploration and advancement within this domain have the potential to chart a path toward a more sustainable future within the construction sector.

Advantages of biochar-based sustainable bricks

Thermal insulation performance

Insulation tests play a crucial role in determining a material's insulation value. The insulation value quantifies an insulating material's capacity to resist heat flow. It is an essential metric for assessing insulation's effectiveness in separating a building's external and internal environments. The porosity

Table 2 Formulations and properties of biochar-based sustainable bricks

Formulation	Types of biochar materials	Brick making process	Characteristics	References
Biochar: high-density polyethylene = 1:1	Softwood biochar: the maximum diameter shall not exceed 3.18 mm	A high-density polyethylene and biochar mixture is prepared in a 1:1 ratio to create biochar-based bricks. The dried mixture is poured into a mold cavity and compressed using a C-shaped clamp. Subsequently, the mold containing the mixture is heated in an oven at 220 ℃ for 2.5–2.75 h. Afterward, the bricks are left to cool overnight in a well-ventilated hood	Plastic-biochar bricks offer several advantages over traditional concrete bricks. They exhibit a higher compressive strength while being affordable and lightweight. Additionally, these bricks possess excellent insulation properties. The simple manufacturing process makes them easy to produce and work. Biochar bricks are also sustainable and environmentally friendly, making them an ideal choice for impoverished countries seeking to improve their local economy and environment	Ithaka-institute-for-carbon-strategies (2019), Maxwell et al. (2020)
Biochar: Portland cement: water = 3:1:1	Softwood biochar: the maximum diameter shall not exceed 3.18 mm	To create biochar–concrete, blend water, Portland cement, and biochar. Pour the mixture into greased molds, level the surface, and cover with moist burlap after 24 h. After 48 h, remove the bricks from the molds and soak them in water for two days. Finally, allow the bricks to air dry for 27 days. The outcome is a durable and environmentally friendly material	Bricks made from biochar and cement are comparatively affordable and offer environmental benefits. They exhibit excellent fire resistance and insulation properties with high water absorption capacity. However, they do have lower compressive strength	Biochar (2019), Maxwell et al. (2020)
Cement: sand: water = 2:5:1 biochar is used as a substitute for sand, with substitution levels ranging from 10–40%	Poultry litter biochar: the average particle size is 26 µm	The composites were prepared by dry mixing the crushed biochar, cement, and sand for one minute, then water was incorporated, and the mixture was blended for three additional minutes. Extra water was infused into the biochar blends to achieve the targeted workability. After 24 h, the mortars were shaped and subsequently submerged in water to continue the curing process	Substituting 20% of the sand with biochar resulted in a 26% enhancement in flexural strength. Incorporating 10% biochar led to a 26% reduction in thermal conductivity, and adding 40% biochar reduced density by 20%. Furthermore, there was a noteworthy 20% decrease in net carbon dioxide emissions	Praneeth et al. (2021), Ramola et al. (2022), Schmidt (2014)

Table 2 (continued)

Formulation	Types of biochar materials	Brick making process	Characteristics	References
Cement: water = 2.86:1 two additional types of biochar were added at 0.5, 0.8, and 1%, respectively	Pyrolyzed hazelnut shells and coffee ground biochar: the particle size range is 10–15 µm	Begin by measuring the thermally decomposed nanoparticles and combining them with water and a water-reducing agent. Apply ultrasound treatment for 15 min. Next, slowly introduce cement to the solution while utilizing a homogenizer for mixing. Transfer the mixture into acrylic molds and place them in sealed containers for 24 h at room temperature with 90% humidity for curing. After the initial curing, remove the samples and continue curing them in water for 7–28 days	Pyrolyzed hazelnut shells have a high carbon content and low impurities, making them an ideal aggregate that is easy to disperse and durable. The pyrolyzed coffee powder contains potassium and calcium salts and lower carbon content but still improves the composites' properties. Both can significantly increase composites' flexural strength, compressive strength, and toughness, modify crack paths, increase fracture surface areas, and consume more energy. Furthermore, these biomass particles' porous and irregular shape can improve the cement paste's ability to generate the calcium–silicate–hydrates (C-S–H) phase, nucleation sites, and toughening mechanisms	Restuccia and Ferro (2016b)

The table presented below compares various biochar materials and their characteristics for brick-making. It highlights that plastic-biochar bricks exhibit the highest compressive strength, while biochar–cement bricks are relatively cost-effective and provide environmental advantages. Additionally, using pyrolyzed hazelnut shells and coffee powder biochar significantly enhances the strength and toughness of the composites. The table also includes information on the manufacturing processes employed for each type of biochar brick. Overall, this table is a valuable resource for selecting appropriate biochar materials for brick production

Table 3 Global warming potential of the biochar life cycle

Biochar production method	Raw substrates	Functional unit	Lifecycle global warming potential per functional unit	References
Pyrolysis reactor	Empty fruit bunch	One-ton biochar	−691 kg CO_2-eq	Robb and Dargusch (2018)
Pilot-scale	Tomato plant residue	One-ton biochar	21–155 kg CO_2-eq	Llorach-Massana et al. (2017)
Pilot-scale pyrolyzer	Oat hulls	One-ton biochar	−2590 to −2700 kg CO_2-eq	Muñoz et al. (2017)
Diesel power pyrolysis reactor (Biochar Solutions Inc.)	Forest residues such as pulpwood	One-ton biochar	−1.900 to −2.200 kg CO_2-eq	Puettmann et al. (2020)
Biomass gasifier power pyrolysis reactor (Biochar Solutions Inc.)	Forest residues such as pulpwood	One-ton biochar	−2300 to −2850 kg CO_2-eq	Puettmann et al. (2020)

The table compares various biochar production methods and their corresponding global warming potentials per functional unit. The methods examined include pyrolysis reactor, pilot-scale, diesel power pyrolysis reactor, and biomass gasifier power pyrolysis reactor. Different raw materials are utilized in biochar production, such as empty fruit bunch, tomato plant residue, and forest residues. The global warming potential varies, ranging from a minimum of − 2850 kg CO_2-eq (kilogram carbon dioxide equivalent) to a maximum of 155 kg CO_2-eq

of biochar is generally high, but it can vary depending on factors such as the raw material used and the pyrolysis process parameters, including temperature and residence time. When the temperature exceeds 500 ℃, the degree of porosity can differ significantly among raw materials. Recent studies have shown that biochar produced at 350 ℃ typically has an average porosity of ≤ ten μm (Weber and Quicker 2018). This high porosity contributes to its low thermal conductivity and excellent insulation properties. By incorporating uniformly distributed porous biochar into construction materials, the propagation of heat is disrupted in multiple directions, impeding unidirectional heat transfer (Jiang et al. 2022; Wu et al. 2022). This phenomenon effectively slows the expected heat flow and enhances biochar–cement composites' thermal insulation capabilities.

Several studies have reported that adding biochar can decrease the thermal conductivity of biochar–cement composites by 25% and biochar–clay composites by up to 67% (Lee et al. 2019; Radlinski and Olek 2012). For instance, the inclusion of a two-weight percent of biochar in composites resulted in a low thermal conductivity of 0.19 W/(m·K), accompanied by an enhanced acoustic performance within the frequency range of 200–2000 Hz (Cuthbertson et al. 2019). In the case of biochar and cement bricks, the earlier mentioned formulation exhibits a thermal conductivity of 0.18 W/(m·K), which is 50% lower than that of concrete bricks measuring 0.34 W/(m·K). Moreover, biochar bricks and high-density plastic demonstrate a low thermal conductivity of 0.192 W/(m·K) (Maxwell et al. 2020). Another study found that replacing 10% of sand with biochar in concrete bricks significantly enhances their insulation performance, reducing the thermal conductivity from 0.64 W/(m·K) to 0.47 W/(m·K) (Praneeth et al. 2021). These findings indicate that incorporating biochar into construction materials can decrease thermal conductivity and improve insulation properties.

The direction of heat flow affects the thermal conductivity of biomass. When heat flows parallel to the grain direction, its conductivity is at its maximum, roughly 1.5–2.7 times higher than when the heat flows at right angles to the grain. In general, a denser structure correlates with improved conductivity of heat. Conversely, when a porous structure is created in biochar, it reduces heat conductivity compared to the unaltered biomass. This variation based on grain direction is also noticeable in biochars, although less markedly than in raw wood. As biomass fibers break down and lose structural intricacy through carbonization, the conductivities in the various directions tend to equalize as the pyrolysis temperature increases. For example, above 400 ℃ in the pyrolysis process, the conductivity measurements of pine chars taken longitudinally and radially are not markedly different, even though there is more than a two-fold disparity in the raw state. Moreover, the temperature at which conductivity is measured can affect the result, with higher temperatures leading to higher readings. This should be taken into account when making comparisons between different measurements. The thermal conductivity of untreated biomass in the longitudinal direction ranges between 0.2 and 0.45 W/(m·K), and it diminishes after pyrolysis. The conductivity of charcoal at 500 ℃ is roughly 0.08 W/(m·K) (Hankalin et al. 2009).

Biohar created at extremely elevated temperatures might display less porosity and greater density than char formed at more moderate temperatures. Within this spectrum of temperatures, there could be a chance that the thermal conductivity might rise once again. However, this supposition is not currently supported by evidence. Regarding thermal conductivity, the values measured for heat capacity are affected by the temperature at which these measurements are made. This correlation has been shown by Dupont et al. (2014), who calculated that the heat capacity of woody biomass at ambient temperature was around 1300 J/(kg·K). Conversely, the heat capacity of the identical char, but produced at 500 ℃, was about 1000 J/(kg·K).

Water absorption

Studying water absorption is crucial for assessing the durability of bricks in humid or high rainfall conditions and understanding the material's permeability. The water absorption characteristics of bricks can provide valuable insights into how the material interacts with moisture. By measuring the amount of water a brick absorbs, we can evaluate its ability to resist water penetration and the potential for moisture-related issues such as deterioration, swelling, or cracking. Researchers have expressed concern about the moisture absorption capacity of cementitious materials modified with biochar due to their porous structure. When biochar is present in these materials, two distinct phases of water absorption can be observed within the first 24 h and between 24 and 144 h. These phases can be categorized as a rapid phase and a slow phase. The initial rapid phase occurs because the biochar in the material's matrix promotes enlarged capillary absorption, facilitated by capillary and fine gel pores. Subsequently, during the slow absorption phase, the absorption is solely driven by weak capillary forces generated by air voids and macropores in the biochar-modified cementitious material (Radlinski and Olek 2012).

Contrarily, multiple research works have demonstrated that the incorporation of biochar into mortar tends to decrease water absorption, independent of the quantity or nature of precursor substances involved. This evidence suggests that although biochar particles contain pores that act as a barrier to water absorption and retention, they do not invariably create an unbroken capillary network within the mortar (Akhtar and Sarmah 2018). However, an opposing study has found that exceeding a 4% by weight biochar dosage might augment the empty spaces within the mortar, ultimately resulting in increased water absorption (Gupta et al. 2020). In line with this, Praneeth et al. (2021) observed that a higher biochar percentage contributes to enhanced water absorption and porosity in experimental trials. Such an occurrence might be ascribed to the hindrance effect of porous biochar particles on the formation of more compact surfaces, causing an escalation in capillary pores and, consequently, elevated water absorption (Akhtar and Sarmah 2018). Nevertheless, in mixtures of mortar containing 1 and 2% waste wood biochar, the water penetration depth is markedly less than that in standard cement alone, with 64 and 57% declines, respectively (Gupta et al. 2018a). This reduction may be linked to the lessened biochar integration and the resulting lower porosity of the cement-biochar composite. It is significant to note that biochar macropores with dimensions ranging from 5 to 30 µm play a crucial role in the absorption and retention of water (Kloss et al., 2012), thus affecting the transport and permeability properties of the cement-biochar composite. On the other hand, pores within the 10–30 µm range can absorb and hold some of the water introduced during the cement-biochar composite's initial setting stage (Wen et al. 2023).

As evident from the information mentioned above, there is no consensus regarding the impact of biochar on water absorption. It is crucial to consider various factors, including production time and the quantity of biochar added. Incorporating a modest amount of biochar into concrete typically reduces its water absorption capabilities. However, when the biochar content surpasses 4% by weight, the concrete absorbs more water, counteracting the initial benefits.

Flowability

The term flowability in the context of biochar-based bricks and cement pertains to the ease with which these materials can be mixed and shaped during construction activities. This quality significantly influences the materials' manageability and ease of handling. The integration of biochar into bricks or cement formulations may alter their flowability, owing to the biochar's pronounced porosity and ability to absorb water. When biochar, specifically engineered from food and wood waste, is incorporated into mortar combinations, it affects their manageability. Biochar's advantageous pore configuration and broad specific surface area facilitate the formation of a layer capable of storing and retaining water. Consequently, the composite of biochar and cement demonstrates improved water-holding properties, thus fulfilling the required flowability standards (Wen et al. 2023).

In research conducted by Gupta and Kua (2018), pre-immersion was utilized to amplify the water-holding abilities of biochar pores. They found that by allowing water to form films encompassing biochar and cement particles, the cement particles underwent hydration, boosting flowability while keeping the water-to-cement ratio constant. However, when 3% of biochar derived from wood and food waste was introduced into the mixtures, there was a reduction in mortar flow by 13 and 10%, respectively (Pandey et al. 2022). This diminished workability can be linked to biochar's augmented ability to absorb water, functioning as a replacement for Portland cement. As a result, biochar's water absorption can lower the quantity of water accessible for mixing, thereby causing a decline in flowability (Gupta et al. 2018a, b, 2020). This aspect is also connected to the water absorption characteristics of biochar cementitious substances at varying stages, with notable water absorption in the initial 24 h, which stands as the primary cause for workability reduction (Radlinski and Olek 2012). Therefore, careful management of either the quantity of biochar included or the water-to-cement ratio is vital. The impact of granularity and pore architecture on the ease of handling biochar–cement composites is mainly discernible in the early phases of the mixing process between biochar and cement (Gupta and Mahmood 2022).

In the realm of engineering, there is typically a favoring of reduced porosity and more diminutive pore sizes, specifically less than 100 nm, to harmonize workability with material efficacy (Zhang and Zhou 2020). Biochar particles of a finer grain can attain a greater packing density within cementitious structures. Furthermore, given the same quantity of water, any surplus free water exceeding the amount needed for filling the pores may augment the mixture's flowability (Xu et al. 2019). The need for water to preserve the workability of the concrete sample was found to rise with the increment in biochar content. This occurrence can be attributed to biochar's ability to soak up water beyond the conventional water-to-cement ratio of 0.5. A specific experiment performed with cement revealed that 650 mL of water per kg of biochar was necessary for free water to be discernible or to create a paste. Conversely, a water-to-cement ratio of 0.4 was required to detect free water when only cement was used. These observations are consistent with prior studies, suggesting that a water-to-cement ratio ranging from 0.36 to 0.42 suffices for hydration, whereas a greater ratio between 0.45 and 0.5 is essential for ensuring workability (Li 2011). When a minor quantity of biochar, precisely 1.5 g, was combined with 10 g of cement, the water-to-cement ratio demanded for the emergence of free water grew to 0.48. This evidence illustrates that even a small addition of biochar can notably elevate the water requirement in the composite.

In contrast, the excess water-to-biochar ratio was marginally lower than that used in regular concrete production. This variance might be explained by a lack of sand and aggregate during the experiment, leading to diminished available water. The density that was attained with biochar in the mix was 1454 kg/m^3, a notable result because it indicates that biochar may be utilized to fabricate lightweight concrete with densities in the range of 1200–1800 kg/m^3 (Li 2011). This discovery further hints that alternative fillers could be exchanged without considerably altering the density, thereby providing flexibility in refining concrete formulations while still attaining the targeted density effect. It should be emphasized that when the biochar concentration neared or surpassed 10%, the concrete started to exhibit brittleness as the biochar began to take up a substantial volume of the material. Conversely, incorporating activated carbon at even higher levels, specifically up to 30%, was possible within the concrete, though the rationale for this remains unclear. Despite these elevated concentrations, there was no significant further reduction in the concrete's density beyond the minimum level observed with biochar.

In conclusion, incorporating biochar into construction materials offers potential benefits for sustainability and carbon emission reduction. However, it is crucial to acknowledge the drawbacks associated with water absorption and workability. Future research endeavors should focus on exploring the effects of biochar on cementitious materials in greater detail. Various strategies can be employed to optimize the flowability of biochar-based bricks and cement, such as adjusting the water-to-material ratio, incorporating flow-enhancing additives, or optimizing the particle size distribution of the mixture. By carefully managing these factors, it is possible to improve the flowability of biochar-based materials, facilitating their efficient and effective use in construction applications. Additionally, developing strategies to address workability concerns is necessary to fully harness the advantages of biochar in construction applications. By addressing these challenges, biochar can be utilized more effectively and contribute to sustainable practices in the construction industry.

Compressive strength

The compressive strength of biochar-based bricks refers to their ability to withstand applied compressive forces without breaking or deforming. Compressive strength is essential in assessing these bricks' structural integrity and load-bearing capacity. Compressive strength, measured in MPa or crushing strength in kg/m^2, provides the most accurate assessment of a material's ability to withstand a load. Both terms describe resistance to compression and can be converted into one another using gravitational acceleration. When biochar is incorporated into brick formulations, it can influence the compressive strength of the resulting bricks. Adding pyrolyzed hazelnut shells and coffee grounds to concrete blocks at a low percentage, namely 0.5%, increases compressive strength. This improvement can be attributed to the porous nature of these materials, which serve as sites for the rapid formation of the calcium–silicate–hydrate phase in the cement paste (Jo et al. 2007; Lin et al. 2008). Hence, biochar's porosity and physical properties can impact the brick matrix's interparticle bonding and overall strength.

It is essential to recognize, however, that an increase in the amount of biochar introduced may accentuate inherent shortcomings in the materials, such as diminished strength and increased porosity. These factors can result in a reduction in the density of the bricks and a corresponding decrease in compressive strength. An investigation into the compressive strength of concrete with added biochar examined this by pyrolyzing dry distiller grains from the bio-ethanol industry at temperatures of 500 and 600 ℃. The biochar was incorporated at levels of 1.2 and 3% by weight, substituting for sand and aggregate. Although the results did not show a significant trend, there was a minor enhancement in strength after the biochar was incorporated. Specifically, when 3% biochar pyrolyzed at 500 ℃ was employed in place of sand and aggregate, peak strengths of 21 and 22 MPa were attained, respectively (Cuthbertson et al. 2019).

Further annealing of the biochar can result in a higher degree of graphitization and carbonization of bamboo particles, reducing their amorphous nature. This aspect offers a new perspective on how biochar characteristics impact compressive strength (Gupta et al. 2018c). The study found that the optimal addition of biochar for enhancing the compressive strength of cement mortar was 1 and 2% by weight. After seven days of curing, the mortar with biochar pyrolyzed at 500 ℃ exhibited a significant increase in strength of 22 and 27% compared to the mortar without biochar. However, adding more than 2% biochar resulted in a decrease in strength.

Conversely, research by Asadi Zeidabadi et al. (2018) found that concrete containing five wt.% of bagasse biochar displayed the maximum strength. Further, a study led by Ahmad et al. (2015) revealed that the compressive strength of bamboo biochar–cement composite was enhanced by adding a smaller percentage of biochar. For this composite, three varying levels of biochar content were experimented with: 0.05, 0.08, and 0.2%. In this research, the biochar was subjected to pyrolysis at a temperature of 850 ℃, followed by annealing with sodium hydroxide-treated biomass at an identical temperature. Of all the blends of biochar and cement tested, the one containing 0.08% biochar demonstrated the most substantial increase in strength. The compressive strengths for this combination of 0.08% biochar–cement varied between 85 and 100 MPa. This notable strength enhancement is believed to result from the treatment process, which eradicated volatile substances and allowed for the creation of more extensive pores within the biochar.

Alternative materials also have shown positive effects on compressive strength. In a study conducted by Maxwell et al. (2020), the combination of 50% high-density plastic and 50% biochar in brick production resulted in a compressive strength of 20.68 MPa, surpassing the range of 9–20 days compressive strength, namely 16.54–17.24 MPa, observed in concrete bricks. The higher compressive strength, in this case, could be attributed to the substantial amount of plastic, or binder, present in the bricks. In a study conducted by Restuccia and Ferro (2016b), two materials, namely pyrolyzed hazelnut shells and pyrolyzed coffee grounds, were added separately to concrete blocks at different weight percentages, namely 0.5, 0.8, and 1%. The results show that the highest compressive strength of 57.79 MPa was achieved when 0.5% of pyrolyzed coffee grounds were added, followed by 55.09 MPa when 0.5% of pyrolyzed hazelnut shells were added. These results indicate a considerable improvement in the compressive strength of bricks compared to that of pure concrete bricks, namely 33.59 MPa. However, the compressive strength of the bricks decreased significantly as the amount of both biochar materials added increased (Restuccia and Ferro 2016b).

In a noteworthy study, Navaratnam et al. (2021) probed into the compressive strength of biochar mortar after subjecting it to pyrolysis at three distinct temperatures: 200, 450, and 700 ℃. The research employed three quantities of biochar, representing 5, 10, and 20% of the cement's weight. At ambient temperature, the compressive strengths recorded for the biochar mortars were 35, 39, 28, and 16 MPa for biochar additions of 0, 5, 10, and 20%, respectively. A decline in strength was noted when the mortars were assessed at higher temperatures. Figure 2 provides a visual representation of the impact of temperature variations on the compressive strength of biochar–concrete.

Chin et al. (2020) conducted a separate study exploring the effect of activated biochar on the compressive strength of concrete. The biochar in question was created by pyrolyzing oil palm kernel shells at a temperature of 500 ℃, followed by activation utilizing steam at a rate of 150 m^3/min and a temperature of 900 ℃ for two hours. Upon completing a 28-day curing process, the activated biochar–concrete attained its peak strength of 50 MPa. These observations correspond with the findings reported by Wu et al. (2018), who thermally decomposed peach and apricot shells at 200 ℃ for an hour, followed by additional decomposition at 550 ℃ for 4 h.

The compressive strength (ASTM-C109/C109M-20b, 2020) and flexural strength (ASTM-C348-21, 2021) of hardened mortar samples were assessed using INSTRON 1000 KN and INSTRON 100 KN instruments. Each mix design was tested with a minimum of three samples. The device recorded the breaking load, and the compressive strength was calculated using the breaking load and surface area. A three-point bending mechanism was used for flexural strength, and the breaking load determined the results. The statistical analysis of the findings employed a one-way analysis of variance and Tukey's multiple comparison tests. The main conclusion of the studies is that incorporating biochar into concrete does not harm its compressive strength. This means that the positive benefits associated with biochar can be pursued without compromising the concrete's overall strength. However, it was observed that adding biochar increased the water requirement for a workable paste. More than 1 L of extra water per kg of biochar was needed to achieve the desired workability, indicating that additional water is necessary for properly mixing and handling the concrete when biochar is included.

In summary, the enhanced strength can be ascribed to the increased absorption capacity of biochar obtained from wood and mortar waste. This increase leads to a lowered binder ratio and a more compact microstructure. The augmentation in strength is also associated with the ability of biochar particles to occupy pore spaces, consequently

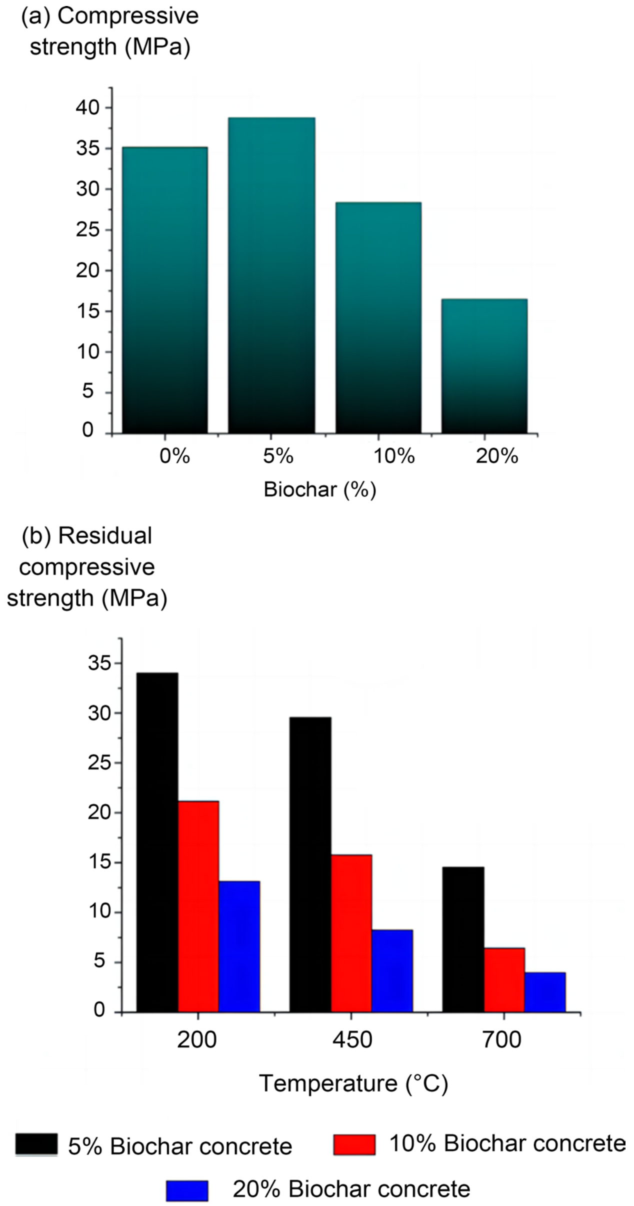

Fig. 2 Effect of temperature on biochar–cement compressive strength. **a** The effect at room temperature compressive strength; **b** increased temperature residual compressive strength up to 700 ℃ high temperatures. When 5% biochar is included, there is a marked augmentation in strength along with a decrease in residual compressive strength. Consequently, concrete containing 5% biochar can effectively enhance strength for applications involving elevated temperatures while minimizing the loss of residual compressive strength. However, compared to room temperature evaluations, mortar containing 20% biochar reduced strength by 19% at 200 ℃ and 75% at 700 ℃. These decreases were ascribed to the emergence of both internal and external microcracks, resulting from the dehydration-induced disintegration of the calcium–silicate–hydrate gel structure and calcium hydroxide within the cement matrix (modified from Navaratnam et al. (2021)

refining the microstructure (Restuccia and Ferro 2016b). Moreover, the compressive strength of mortar mixes containing biochar has been found to grow over time, a sign that the inclusion of biochar does not hinder the progression of the hydration reaction. However, it is crucial to recognize that the compressive strength of biochar is inversely related to the particle size, with strength decreasing as particle size enlarges (Odimegwu et al. 2018).

In contrast, other studies such as Asadi Zeidabadi et al. (2018) and Mrad and Chehab (2019) observed a reduction in compressive strength when higher percentages of biochar, namely 5, 10, 15, 25, and 40% by weight, were added. When comparing mortar with and without biochar, a significant decrease in compressive strength of 20–98% was noted in the biochar-containing mortar. The authors attributed this decline to the high water retention capacity of biochar, which affects the properties of the mortar and reduces strength. According to the research conducted by Maxwell et al. (2020), the experimental results indicated that the compressive strength of biochar and cement-based bricks ranges from 10.34 to 13.79 MPa after 9–20 days of curing. Concrete bricks typically exhibit higher compressive strength, ranging from 16.54–17.24 MPa. This difference in strength can be attributed to biochar being softer than gravel and sand typically used in concrete mixtures. The compressive strength of a brick is directly related to its structural strength, and the presence of “hard” materials in the composition plays a critical role in determining its strength. The study’s authors also observed that the results of concrete bricks, in which a portion of sand was replaced with biochar, were not promising. Specifically, samples with 10% weight replacement exhibited a 28-day compressive strength decrease from 42 to 34 MPa, samples with 20% weight replacement decreased to 30 MPa, and samples with 40% weight replacement only showed a compressive strength of 25 MPa (Praneeth et al. 2021). Thus, replacing a significant proportion of cementitious materials in concrete bricks with biochar did not increase their compressive strength. This outcome could be attributed to biochar’s relatively lower hardness or excessive biochar’s tendency to increase the material’s porosity. Increased porosity ultimately leads to decreased internal density, reducing compressive strength.

The impact of biochar on recycled aggregate concrete was investigated by Akhtar and Sarmah (2018). Rice husk biochar and poultry litter biochar were used, with additions ranging from 0.1 to 0.75% of the total cement volume. After seven days, 14, and 28 days of curing, no significant strength gain was observed in the biochar-added concrete compared to the control. All samples showed a 16% reduction in strength, with a 0.1% addition of poultry litter biochar resulting in an 8% decrease in strength. However, it is worth noting that all composites exhibited higher strength with increased curing time, suggesting that long-term curing may lead to greater strength. Further research is needed to validate this claim. In a study by Dixit et al. (2021), ultra-high-performance concrete was produced by partially replacing quartz powder with biochar. The biochar used in this study was derived from sawdust through pyrolysis at 500 ℃. Biochar was added to the concrete samples at 2 and 5% by weight of cement.

In addition, Dixit et al. (2021) formulated ultra-high-performance concrete by supplanting a portion of the quartz powder with biochar derived from sawdust via pyrolysis at 500 ℃. The biochar was integrated into the concrete samples at concentrations of 2 and 5% by weight of the cement. Intriguingly, the inclusion of 2 and 5% biochar in the concrete mix negatively influenced its compressive strength. After 28 days of curing, the compressive strength of the concrete with these biochar additions had decreased by roughly 13 and 14%, respectively, compared to the concrete without biochar. This decline in strength was ascribed to the substandard properties of biochar in comparison with other constituents of ultra-high-performance concrete, including silica fume, silica sand, and quartz powder. The biochar's presence essentially created a fragile zone within the cement matrix, consequently reducing the compression strength. Nonetheless, the author has indicated the potential value of conducting further experiments with varying types of biochar feedstocks to fully understand their impact on the material's strength. In another study conducted by Mo et al. (2019), the synergistic effect of biochar and magnesium oxide on the compressive strength of concrete was explored. Biochar produced from pyrolyzing weed trees at 600 ℃ was used, with an incorporation rate of 2%. Magnesium oxide was added at concentrations of 4 and 8%. The inclusion of magnesium oxide resulted in a decrease in strength, and as the amount of magnesium oxide increased, the reduction in strength became more pronounced. However, the addition of biochar to magnesium oxide enhanced its strength. After 98 days, the combination of biochar and 8% magnesium oxide in the concrete increased its strength by 6% compared to the reference concrete. This improvement was attributed to the internal curing effect of biochar, which aided in cement hydration.

In a research undertaken by Praneeth et al. (2021), the effects of substituting sand with biochar sourced from chicken litter on the compressive strength of concrete were explored, with substitutions ranging from 10 to 40%. Their findings revealed a marked decline in compressive strength upon the inclusion of biochar. Specifically, a 21% reduction was observed when 10% biochar was incorporated. The decrement in strength between 10 and 30% biochar addition was roughly 12%, with the weakest compressive strength detected at a 40% biochar inclusion. This decline is largely due to biochar's superior water retention capabilities compared to cement and sand. Water predominantly occupies the biochar pores at lower biochar concentrations, yielding denser composites. Nevertheless, as the biochar ratio escalates, there is a diminished volume of water relative to the pore count, which escalates porosity in the biochar–concrete blend, leading to a consequential dip in compressive strength, as depicted in Fig. 3. Gupta and Kua (2018) have also recorded analogous observations.

These findings suggest that the choice of biochar feedstock can influence the structure of the biochar, ultimately impacting the compressive strength of the concrete. According to Sirico et al. (2020), the physical and chemical characteristics of the feedstock material play a significant role in determining compressive strength. The highest compressive strength values for biochar-based cementitious materials are presented in Table 4. In summary, using biochar in brick production shows potential for reducing environmental impact and achieving sustainability goals. However, the quantity and type of biochar added to the brick composition can significantly affect its compressive strength. Further studies are needed to determine the optimum amount and type of biochar that can be added to brick production without compromising its strength and durability.

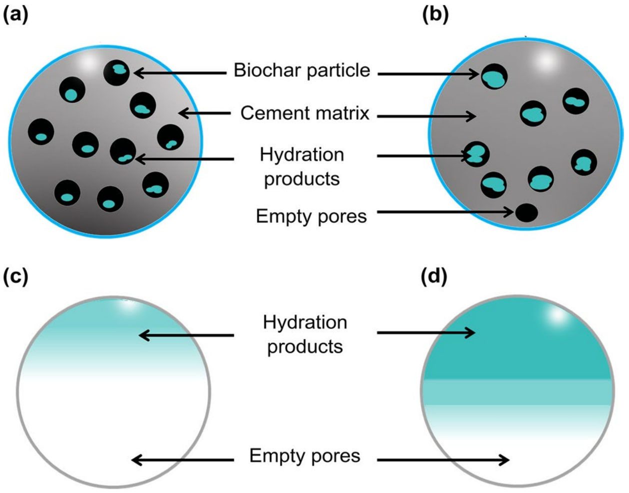

Fig. 3 Processes engaged in the cement–biochar–sand mortar structure. **a** Mortars with high biochar content in the cement, **b** mortars with low biochar content in the cement, and **c**, **d** the presence of hydration products and vacant pores in each instance indicates pore volume. The reduction in compressive strength may be traced to the introduction of water during the composite formation. When water was infused into the biochar composites, biochar's superior water-holding ability compared to cement and sand led it to absorb the majority of the water. As a result, the water contained in the biochar's pores could act as initiation points for the formation of hydration products, thereby yielding denser composites with smaller biochar inclusions. Conversely, once the percentage of biochar incorporated surpassed a certain limit, the space taken up by hydration products within the pores became inadequate relative to the biochar's pore dimensions. This discrepancy might culminate in a more porous composite instead of a denser structure, causing a decline in strength across the different blends. Modified from Praneeth et al. (2021)

Table 4 Compressive strength of several biochar/cementitious compounds

Building materials	Source of biochar	Size and content of biochar	Conditions for pyrolysis	Compressive strength (MPa) 1- or 3-day curing	Compressive strength (MPa) 7-day curing	Compressive strength (MPa) 14-day curing	Compressive strength (MPa) 28-day curing	References
Cement mortar	Rice husk	8% and 2–7 µm	The temperature of pyrolysis is 500 ℃ at a rate of 1 ℃/s	–	55*	–	65*	Muthukrishnan et al. (2019)
Ordinary Portland cement	Poultry litter	0.1%	Slow pyrolysis at 450 ℃ with a 20-min residence time	–	21*	27*	33*	Akhtar and Sarmah (2018)
Ordinary Portland cement	Pulp and paper mill biochar	0.1%	Pyrolysis at 500 ℃ using a high-temperature gasifier	–	27*	31*	36*	Akhtar and Sarmah (2018)
Ordinary Portland cement	Rice husk	0.1%	Slow pyrolysis at 500 ℃ with a 20-min residence time	–	26*	30*	35*	Akhtar and Sarmah (2018)
Cement mortar	Mixed wood	1% and 5–200 µm	Pyrolysis at 500 ℃ with a residence duration of 45–60 min. The heating rate is 10 ℃ /min	–	40*	–	58*	Gupta et al. (2018a)
Cement mortar	Food waste	1% and 5–200 µm	Pyrolysis at 500 ℃ for 45–60 min. The heating rate is 10 ℃/min	–	36*	–	54*	Gupta et al. (2018a)
Cement mortar	Rice waste	2% and 5–200 µm	Pyrolysis at 500 ℃ with a residence duration of 45–60 min. The heating rate is 10 ℃/min	–	36*	–	45*	Gupta et al. (2018a)
Cement mortar	Saw dust	1% and 0.92–100 µm	The pyrolysis temperature is 500 ℃, and the heating rate is 10 ℃/min	40.97 (1-day curing)	–	–	70.54 (for moist curing) and 66 (for air curing)	Gupta and Kua (2019)
Magnesium phosphate cement	Wheat straw	1.5% and 2.05 µm	Temperature of pyrolysis at 650 ℃ and heating rate of 18 ℃/min	75* (1-day curing)	–	–	92* (30-day curing)	Ahmad et al. (2020)

Table 4 (continued)

Building materials	Source of biochar	Size and content of biochar	Conditions for pyrolysis	Compressive strength (MPa) 1- or 3-day curing	Compressive strength (MPa) 7-day curing	Compressive strength (MPa) 14-day curing	Compressive strength (MPa) 28-day curing	References
Ordinary Portland cement	Chemically treated, pyrolyzed, and annealed bamboo	0.08% and 1–2 µm	The pyrolysis temperature is 850 ℃, and the heating rate is 1 ℃/min	–	–	–	97*	(Ahmad et al. 2015)
Ordinary cement	Shellfish biowaste	0.1%	The pyrolysis temperature is 800 ℃, with a heating rate of 5 ℃/min	21.11 (1-day curing)	–	–	–	Nisticò et al. (2020)
Cement mortar	Mixed sawdust	2 wt.% and 5–500 µm	Pyrolysis at temperatures ranging from 300 to 500 ℃ and at a rate of 10 ℃/min	–	67*	70*	73*	Gupta and Kua (2018)
Ordinary Portland cement	Pre-treated bagasse and rice husk	5 wt.%	A pyrolysis temperature of 700 ℃ was maintained for two hours using a heating rate of 10 ℃/min	–	–	–	50 MPa pre-treated rice husk. Bagasse pre-treatment-55 MPa	Asadi Zeidabadi et al. (2018)
Cement and fly ash	Corn stover	4 wt.% and 4.65–144 µm	The pyrolysis temperature is 550 ℃, with a heating rate of 15 ℃/min	40* (3-day curing)	–	38*	–	Praneeth et al. (2020)
Cement Mortar	Wood chips	1 wt.% and 38 µm	The temperature of pyrolysis ranges between 200 ℃ and 500 ℃, while the temperature of gasification reaches 900 ℃	79* (3-day curing)	–	90*	–	Sirico et al. (2020)

Considering the findings from various studies, it can be inferred that the choice of feedstock, pyrolysis temperature, characteristics of the resulting biochar, and particle size all substantially impact the compressive strength of biochar cementitious materials, irrespective of the biochar concentration. However, there has been little investigation into the synergistic effects of biochar with other concrete elements.

*Values with a star are taken from the authors' graph

"–" Indicates not mentioned

Flexural strength

Flexural strength is an important mechanical property in engineering materials such as cement and bricks. It assesses a material's capacity to resist bending or deformation when exposed to a bending force. Higher flexural strength indicates greater resistance to bending and cracking, making the material more durable and suitable for construction purposes. Unlike the compressive strength data, the impact of biochar on flexural strength can produce varying outcomes. In a study by Praneeth et al. (2021), concrete bricks were created by substituting sand with different percentages of biochar, namely 10, 20, and 40%. The results revealed a distinct trend in flexural strength after 28 days of curing. Pure concrete bricks exhibited a flexural strength of 5 MPa. However, bricks with 10% replacement increased to 5.8 MPa, followed by a further rise to 6.4 MPa with 20% replacement. Conversely, when the replacement reached 40%, a decline in flexural strength was observed. Similar findings have been reported in various other studies, where flexural strength initially increases with the biochar replacement amount but eventually decreases after reaching a certain threshold, typically around 20% (Akhtar and Sarmah 2018; Gupta and Kua 2018).

When a small amount of biochar is used to replace sand in building materials, it requires more energy than crushed cement and sand particles. This is because biochar exhibits better ductility, which means it undergoes ductile failure instead of sudden failure. Ductile failure results in volume rather than surface fracture, and the energy absorbed during this process contributes to increased flexural strength (Khushnood et al. 2016; Restuccia and Ferro 2016b). However, as the proportion of biochar increases, it can introduce excessive porosity due to the higher number of biochar particles. This excessive porosity can weaken the tensile plane of the composite material, ultimately leading to a decrease in flexural strength (Muthukrishnan et al. 2019).

In a study by Cosentino et al. (2019), the impacts of various biochar processing variables, including production method, heating velocity, temperature, and pressure, on the bending strength of biochar–concrete composites were assessed. Biochar derived from softwood was integrated at distinct ratios: 0.8, 1, and 2% relative to the cement's weight. The bending strength of the biochar-infused concrete was gauged against a standard concrete, with evaluations performed post 7 and 28 days of setting. The data revealed that the biochar-augmented concrete displayed superior bending strength in contrast to the standard variant. Nonetheless, the distinction in strength between 0.8 and 1% biochar mixtures was inconsequential. After a curing duration of 28 days, the bending strengths for the 0.8 and 1% biochar–concretes stood at 2.48 and 2.49 MPa, respectively. Following a 7-day curing interval, these values were registered as 2.16 and 2.24 MPa, respectively. The researchers inferred that the noted upswing in bending strength mainly stemmed from biochar's expansive specific surface area, which boosted its interaction with the concrete blend.

In another study by Restuccia and Ferro (2016b, 2018), the flexural characteristics of biochar–concrete made from hazelnut shells were investigated. Restuccia and Ferro (2018) discovered that employing coarse-sized biochar particles increased composite flexural strength. In their investigation, they used hazelnut shell biochar at 800 ℃ with particle sizes of 140 µm, and they made concrete with concentrations of 0.5, 0.8, and 1% biochar. The maximum strength of the 0.5% biochar–concrete was tested after seven days of curing, and it was 3.34 MPa, 51% greater than the reference concrete. The flexural strength was recorded as 2.72 and 2.65 MPa for the 0.8 and 1% biochar mixtures, respectively. The authors noted that the flexural strength of the reference concrete stood at 2.25 MPa. After a curing period of 28 days, the highest strength was observed in the 0.5% biochar–concrete, registering a value of 3.58 MPa. This was in comparison with the strengths of 3.14 MPa for the 0.8% and 3.30 MPa for the 1% biochar mixtures. Meanwhile, the reference concrete presented a flexural strength of 2.92 MPa.

Restuccia and Ferro (2016b) conducted a study comparing the flexural strengths of biochar–concrete with different concentrations after seven and 28 days of curing. The results showed that the 0.8% biochar–concrete exhibited the highest flexural strength, measuring 3.14 MPa after seven days and 4.02 MPa after 28 days. In comparison, the reference concrete had a flexural strength of 2.12 MPa. After seven days of curing, the flexural strengths for the 0.5 and 1% biochar concentrations were 3.04 and 2.73 MPa, respectively. After 28 days, the strengths were 3.96 MPa for 0.5% and 2.85 MPa for 1% biochar concentrations.

The reference concrete had a flexural strength of 2.74 MPa after 28 days. The same authors also investigated the effect of pyrolyzed coffee powder on flexural strength. At seven days of curing, the flexural strengths were reported as 3.40, 3.72, 2.80, and 2.12 MPa for 0.8, 0.5, 1, and 0% biochar concentrations, respectively. At the same curing period, the flexural strengths for the corresponding concentrations were 3.57, 3.71, 2.73, and 2.74 MPa. They determined that employing a finer size of biochar at a lower proportion produced greater mechanical strength.

Moreover, the studies indicated that the biochar-added concrete exhibited a higher peak load at 0.5–0.8%. This suggests that biochar can influence the fracture behavior of the concrete. The intense interaction between biochar and cement improved fracture resistance in the material. Additionally, the increase in fracture energy can be attributed to an enhancement in concrete toughness. They supported their findings by comparing them with other studies in the literature (Lian et al. 2011; Restuccia and Ferro 2016a) and suggested that even at low percentages, the coarse-sized biochar particles could fill larger holes in the cement mixture, potentially enhancing its strength. This finding is significant as it indicates that these particles can have a positive impact at very low dosages. Consequently, they have the potential to contribute to the production of building materials more sustainably by reducing the reliance on raw resources and enhancing cement and concrete technology.

Additionally, a study by Ferro et al. (2014) supported this conclusion, indicating that adding irregular-sized biochar particles significantly influenced fracture courses by increasing their tortuosity. The authors used carbonized hemp hurds with a mean particle dimension of 14 µm to study the influence of biochar on composite flexural strength. The study examined four different proportions of biochar, namely 0.08, 0.20, 1, and 3% by weight in cement. It was found that the modulus of rupture increased by 7% when 0.08% biochar was added to the cement. However, reductions in flexural strength were observed at higher biochar concentrations, namely 0.2, 1.0, and 3.0% by weight. The inclusion of biochar particles, however, enhanced the flexural toughness of the cement.

Incorporating biochar into concrete composites has been found to have several effects on flexural strength and fracture energy. Cosentino et al. (2019) observed that adding biochar formed impermeable barriers that altered crack direction, increasing fracture energy. Falliano et al. (2019) evaluated a biochar–concrete composite's flexural strength and fracture energy with varying biochar concentrations, namely 2 and 4%, and curing processes. They found that flexural strengths were highest in the air-cured sample without biochar. Adding 2% biochar retained part of the flexural strength, but increasing the biochar level to 4% reduced the strength by 10%. Fracture energies showed no significant difference between the control sample and the 4% biochar–concrete composite, but the 2% biochar water-cured sample exhibited a 50% decrease. The decrease in fracture energy in the water-cured sample was attributed to sample orientation during testing, leading to premature sample degradation. Furthermore, adding biochar significantly negatively impacted the compressive strength of the foamed concrete, which further deteriorated with higher biochar concentrations. Overall, these studies highlight the influence of biochar on flexural strength and fracture energy in concrete composites, emphasizing the importance of selecting appropriate biochar proportions, particle sizes, and curing processes to optimize the mechanical properties of the resulting materials.

In research spearheaded by Gupta and Kua (2019), the influence of the particle size of wood sawdust biochar on the flexural strength of cement mortar was scrutinized. They incorporated coarse biochar particles of sizes between 2 and 100 µm and fine particles ranging from 0.1 to 2 µm into a cement and sand blend at a 1:2.5 proportion. Biochar was introduced at varying concentrations: 0.25, 0.5, 1, and 2%, adding water at 0.4% of the total weight. From the perspective of flexural strength, a decline was noted with the incorporation of 0.25% fine biochar particles. Conversely, upon escalating the biochar concentration to 1%, there was a notable uptick in flexural strength by as much as 21%. The inclusion of 2% of both fine and coarse biochar particles appeared to have a neutral impact on flexural strength. These insights hint that biochar's effect on flexural strength is contingent upon its particle size, and varying biochar concentrations might be required to fine-tune specific mechanical attributes. Notably, the biochar concentration also plays a pivotal role in dictating the water quantity essential to ameliorate the efficacy of the concrete mix. The concrete variants enriched with biochar and their corresponding flexural strengths are tabulated in Table 5.

In conclusion, the use of biochar in cementitious materials, such as concrete and cement mortar, has been extensively studied to assess its impact on flexural strength. Various factors have been investigated, including biochar concentration, particle size, curing processes, and manufacturing methods. Including biochar in these materials has shown promising results in enhancing flexural strength. Studies have revealed that adding biochar, particularly at lower percentages, can lead to increased flexural strength compared to reference materials. The biochar's interaction with the cement matrix and its ability to form impermeable barriers have been identified as key factors contributing to the composites' improved fracture energy and toughness. Furthermore, the particle size of biochar has been found to play a significant role in its effectiveness. Fine biochar particles, at appropriate concentrations, have positively affected flexural strength. However, excessive concentrations or certain particle sizes may not significantly improve or reduce strength.

Additionally, the choice of curing processes and the water content in the mixture have been observed to influence the performance of biochar-added cementitious materials. Optimal combinations of biochar concentration, particle size, and water content must be carefully considered to achieve the desired mechanical characteristics. Overall, using biochar in cementitious materials presents opportunities for sustainable building methods by lessening the dependence on conventional raw materials. However, further research is needed to optimize the biochar dosage, particle size, and manufacturing methods to ensure consistent and reliable flexural strength enhancement in various applications.

Fire properties

According to studies on its fire performance, concrete has the best fire resistance compared to other construction materials, such as steel and wool (Drzymała et al. 2018).

Table 5 Flexural strength of several biochar or cementitious compounds

Building materials	Biochar source	Biochar size and concentration	Pyrolysis conditions	Flexural strength (MPa) 1-day curing	Flexural strength (MPa) 7-day curing	Flexural strength (MPa) 14-day curing	Flexural strength (MPa) 28-day curing	Flexural strength (MPa) 30-day curing	References
Normal Portland cement	Poultry litter	0.1%	Slow pyrolysis at 450 ℃ and a residence time of 20 min	–	–	5*	–	–	Akhtar and Sarmah (2018)
Normal Portland cement	Pulp and paper mill biochar	0.1%	Pyrolysis at 500 ℃ using a high-temperature gasifier	–	–	4*	–	–	Akhtar and Sarmah (2018)
Normal Portland cement	Rice husk	0.1%	Slow pyrolysis at 500 ℃ with a 20-min residence time	–	–	5*	–	–	Akhtar and Sarmah (2018)
Cement mortar	Mixed wood	1% and 5–200 µm	Pyrolysis at 500 ℃ with a residence duration of 45–60 min. The heating rate is 10 ℃ / min	–	–	13*	–	–	Gupta et al. (2018a)
Cement mortar	Food waste	1% and 5–200 µm	Pyrolysis at 500 ℃ for 45–60 min. The heating rate is 10 ℃/min	–	–	13*	–	–	Gupta et al. (2018a)
Cement mortar	Rice waste	2% and 5–200 µm	Pyrolysis at 500 ℃ with a residence duration of 45–60 min. The heating rate is 10 ℃/ min	–	–	11*	–	–	Gupta et al. (2018a)
Cement mortar	Sawdust	1% and 0.92–100 µm	The pyrolysis temperature is 500 ℃, and the heating rate is 10 ℃/min	–	–	11 (moist curing) 10 (air curing)	–	–	Gupta and Kua (2019)
Magnesium phosphate cement	Wheat straw	1.5% and 2.05 µm	Pyrolysis at 650 ℃ and heating rate of 18 ℃ / min	10*	10*	–	12*	13*	Gupta et al. (2018c)

Table 5 (continued)

Building materials	Biochar source	Biochar size and concentration	Pyrolysis conditions	Flexural strength (MPa) 1-day curing	Flexural strength (MPa) 7-day curing	Flexural strength (MPa) 14-day curing	Flexural strength (MPa) 28-day curing	Flexural strength (MPa) 30-day curing	References
Normal Portland cement	Softwood	1% and < 6 µm	Pyrolysis at 680 ℃, and the residence lasts 12 min	–	–	2*	–	–	Praneeth et al. (2020)
Normal Portland cement	Chemically treated, pyrolyzed, and annealed bamboo	0.08% and 1–2 µm	Pyrolysis at 850 ℃, and the heating rate is 1 ℃ /min	–	–	4*	–	–	Cuthbertson et al. (2019)
Normal cement	Shellfish bio-waste	0.1%	Pyrolysis at 800 ℃, with a heating rate of 5 ℃ /min	2	2	–	–	–	Praneeth et al. (2020)
Cement mortar	Mixed sawdust	2 wt.% and 5–500 µm	Pyrolysis at 300–500 ℃ and at a rate of 10 ℃/min	–	–	Moist curing-13* Air curing-11*	–	–	Wang et al. (2020a)
Normal Portland cement	Hazelnut shells	0%, 0.5%, 0.8%, and 1%, 140 µm,	Pyrolysis at 800 ℃ and a rate of 6 ℃/min	–	2.25, 3.34, 2.72, 2.65	–	2.92, 3.58, 3.14, 3.30	–	Restuccia and Ferro (2018)
Normal Portland cement	Hazelnut shells	0%, 0.5%, 0.8%, and 1%, 140 µm,	Pyrolysis at 800 ℃ and a rate of 6 ℃/min	–	2.12, 3.04, 3.14, 2.73	–	2.74, 3.96, 4.02, 2.85	–	Restuccia and Ferro (2016b)
Normal Portland cement	Coffee powder	0%, 0.5%, 0.8%, and 1%, 140 µm,	Pyrolysis at 800 ℃ and a rate of 6 ℃/min	–	2.12, 3.72, 3.40, 2.80	–	2.74, 3.71, 3.57, 2.73	–	Restuccia and Ferro (2016b)
Normal Portland cement	Wood chips	1 wt.% and 38 µm	Pyrolysis at 200–500 ℃, whereas the gasification temperature reaches 900 ℃	–	–	6*	–	–	Mrad and Chehab (2019)

Incorporating biochar in concrete bricks notably influences their flexural strength. A moderate replacement percentage can enhance strength by promoting ductility, while excessive biochar content can introduce excessive porosity and weaken the material, reducing strength. Hence, it is crucial to carefully consider and determine the optimal proportions of biochar during the production of concrete bricks to ensure optimal flexural strength.

*Values with a star are taken from the authors' graph

"–" Means not mentioned

Reinforcements can further enhance the thermal stability of concrete, although the reinforcements' size and shape may not significantly impact thermal stability. Reinforced concrete demonstrates increased strength up to approximately 450 ℃, but its strength declines when temperatures exceed 600 ℃ (Jackiewicz-Rek et al. 2016). This suggests that concrete may experience performance limitations in high-temperature fire scenarios. However, biochar-infused concrete constructions' fire behavior has received limited research attention. It is anticipated that adding biochar to concrete could potentially offer benefits due to the formation of strong C–C covalent bonds at high temperatures, namely > 700 ℃. These bonds could contribute to the material's resistance against fire-induced damage. Indeed, some studies have indicated that biochar exhibits nonflammable properties. Zhao et al. (2014) reported biochar as being nonflammable, suggesting that its inclusion in concrete mixtures can enhance the material's fire resistance. The incorporation of biochar has been shown to enhance the stiffness and water resistance of cement-based mixtures, particularly at elevated temperatures. This, in turn, enhances their ability to withstand fires and provide effective heat insulation (Gupta and Kua 2020).

Fire damage in concrete can occur through two main mechanisms. Firstly, as the temperature increases, moisture within the concrete pores evaporates, causing drying of the concrete paste. This leads to a weakening of the bond between the paste and aggregate, compromising the structural integrity of the concrete as layers may disintegrate. Secondly, rapid temperature increases can cause moisture to expand rapidly, generating high pressure within the concrete. This pressure creates tensile stresses that exceed the concrete's strength, resulting in severe spalling. To address these challenges, biochar can be utilized as a replacement for some of the aggregate or cement in concrete mixtures. This introduces a new avenue for further research in the field. Developing fire-resistant concrete structures is of utmost importance, especially in settings like mines and tunnels, where protecting human lives and preventing property damage are crucial considerations. Additionally, there is a growing emphasis on using low-carbon emission materials in construction to mitigate greenhouse gas emissions associated with manufacturing building materials. Adopting sustainable practices in the construction industry is gaining traction (Das et al. 2018; Shanmugam et al. 2021a). As a result, incorporating bio-based resources like biochar becomes imperative in striving for a more sustainable future (Babu et al. 2021).

Lightweight

The use of biochar as a replacement for sand in concrete bricks at a ratio of 40% resulted in a significant decrease in the stacking density from 1990 kg/m^3 for pure concrete bricks to 1600 kg/m^3 (Praneeth et al. 2021). This reduction in density has essential implications for the construction industry, as the weight of structures is correlated with the density of building components. The decrease in density, in this case, is because the bulk density of biochar falls between 0.25 and 0.60 g/m^3, which is lower than that of cement, namely 1.44 g/m^3 and sand (Brewer et al. 2014). As a result, the overall stacking density of the composite material is lowered. Additionally, when mixed with cement, the porosity of biochar leads to a porous structure forming around the particles, further reducing stacking density.

The presence of pores in biochar, with a wide range of sizes, allows for water absorption and retention. This characteristic makes biochar suitable for use as a soil enhancer (Downie et al. 2009). This water-holding capacity of biochar pores can also be harnessed to provide an internal curing effect in cement mortar. Incorporating biochar particles that have absorbed water into the mortar mix can act as an internal curing agent. This concept is similar to using porous lightweight aggregates in concrete mixtures, as explored in some studies (Castro et al. 2010; Henkensiefken et al. 2009). However, biochar particles offer the advantage of being finer in size compared to lightweight aggregates. By utilizing the absorbed water within biochar particles, the internal curing effect can mitigate issues related to moisture loss during the hydration process of cement. This can result in improved hydration kinetics, reduced shrinkage, enhanced durability, and potentially increased strength of the cementitious material.

Biochar-based sustainable insulating materials

Preparation and formulation of sustainable biochar-based insulating materials

In the preparation of biochar insulation materials, it is a common practice to incorporate biochar as a partial replacement for clay, cement, or concrete components (Cuthbertson et al. 2019; Jiang et al. 2020; Lee et al. 2019; Rodier et al. 2019). Biochar possesses evenly distributed pores throughout the building materials, facilitating heat dispersion and propagation. As a result, heat transfer occurs in multiple directions, enhancing the overall thermal insulation effect (Jiang et al. 2022; Xiong et al. 2022; Zhang et al. 2022). Figure 4 presents the primary preparation process for biochar insulation materials. Rodier et al. (2019) developed a biochar–cement composite material using sugarcane straw and cement. Sugarcane bagasse, the fibrous waste obtained from juice extraction from sugarcane straw, was collected from the Montebello vineyard. The raw bagasse was dried and ground to a diameter smaller than 0.6 µm. Subsequently, it was filtered using a horizontal sieve shaker. To produce

Fig. 4 Preparation routes and formulation of sustainable biochar-based insulating materials. Biochar-insulating materials are usually composite materials combined with traditional building materials. Biochar is produced after undergoing a series of treatments, including high-temperature treatment, through pyrolysis. This biochar is combined with cement or concrete to create a composite material known as biochar–cement or biochar–concrete. This composite material exhibits favorable thermal insulation properties, contributing to its effectiveness as an insulation material

larger quantities of biochar, the researchers employed the method of slow pyrolysis. The cement utilized in this study was CEM II 32.5N commercial cement, which contained 17% natural volcanic ash by mass. The biochar–cement composite was obtained by mixing the cement, biochar, and water for 5 min, maintaining an initial water/cement ratio of 0.8.

In the study by Lee et al. (2019), a composite material was developed using biochar derived from rice husk and coconut husk combined with natural inorganic clay. This composite material was designed to provide insulation to the exteriors of buildings. The raw materials were cleaned with deionized water to eliminate contaminants and subsequently dried. Steam treatment was applied to the prepared raw materials, and subsequently, biochar was obtained. The biochar was mixed with 10% of natural inorganic clay by weight. Additionally, the inherent inorganic clay component of the biocomposite accounted for 45% of its total weight, including water. As the ratio of biochar in the mixture increased, the mass ratio of injected water during the process reached less than 7%. The research findings indicate that the incorporation of biochar in building materials leads to a significant reduction in thermal conductivity. The maximum decrease in thermal conductivity observed was 67.2% when biochar was added to the materials. This reduction in thermal conductivity implies that biochar has a lower sensitivity to changes in temperature, contributing to improved thermal stability. Moreover, the presence of biochar in the materials increased the water vapor resistance factor by up to 22.6%. This indicates that biochar can effectively reduce the permeability of water vapor. This characteristic is valuable for building materials with enhanced moisture resistance and durability.

In the study conducted by Cuthbertson et al. (2019), concrete thermal conductivity was analyzed with biochar at different temperatures. The thermal conductivity of standard concrete typically falls within the range of 0.62–3.3 W/(m·K). However, Yun et al. (2013) demonstrated that incorporating 1 and 2% by weight of biochar significantly improved thermal conductivity. Specifically, the thermal conductivity decreased to 0.19 W/(m·K) when biochar was added to the concrete mixture. This reduction indicates that including biochar can effectively enhance the insulation properties of concrete and improve its thermal conductivity performance.

In the research conducted by Jiang et al. (2020), wheat straw was collected from Hebei, while rice straw was obtained from Anhui. The collected rice and wheat straws were loaded into a crucible and sealed before being placed in a muffle furnace. Cement from Jin Yu Company PSA42.5 slag Portland cement in Hebei's Taihang Mountains region was used. The preparation process for biochar–cement composite materials in this study was similar to that in other experiments. The rice straw and wheat straw were subjected to pyrolysis to produce biochar cracking products, which were then cooled and ground to room temperature. The straw biochar was added to the cement at a ratio of 2%. The resulting biochar–cement composite demonstrated good thermal insulation performance.

In conclusion, biochar stands out as a green and energy-saving component for construction materials, primarily due to its remarkable reduction in thermal conductivity and bolstered insulation capabilities. Its integration into the building sector can pave the way for more sustainable infrastructural developments. By optimizing a structure's thermal performance through biochar, there is a notable decline in energy demands, especially for temperature regulation. Consequently, this not only leads to a considerable decrease in energy bills but also plays a pivotal role in minimizing the environmental impact of buildings.

Emission reduction of biochar-based insulating materials

Biochar, derived from the pyrolysis of organic residues, presents innovative avenues for curbing carbon emissions within the construction domain. Evidence suggests that thermal insulation materials infused with biochar can significantly mitigate carbon footprints (Osman et al. 2022b; Zhang et al. 2022). As a steadfast carbon reservoir, biochar ensures long-term carbon capture and diminishes carbon outflows (Farghali et al. 2022a; Osman et al. 2023; Zhang et al. 2022). Projections estimate that by generating 373 million tons of biochar from agricultural discards annually, we could potentially offset around 500 million tons of carbon dioxide. This is tantamount to curtailing 1.5% of the worldwide carbon dioxide release (Windeatt et al. 2014; Yang et al. 2019; Zhang et al. 2022). The integration of biochar into novel construction materials not only bolsters waste containment but also slashes the carbon dioxide discharges linked with these materials, thereby fostering a holistic decrease in the construction industry's carbon emissions (Wang et al. 2021). Furthermore, advancements in biochar methodologies could lead to a global reduction in greenhouse gases by 3.4–6.4 pg CO_2-eq, of which 1.7–3.7 pg CO_2-eq (equivalent to 49–59%) is ascribed to the removal of carbon dioxide from the ambient air (Lehmann et al. 2021).

The degree of carbon reduction achieved through the application of biochar in construction substances depends on the specific production conditions of biochar and the application environment it is used in, as these factors influence the carbon dioxide emissions throughout its life cycle (Lehmann et al. 2021; Puettmann et al. 2020; Yang et al. 2021). The carbon reduction capacity of biochar insulation can be attributed to several factors. Firstly, the biochar production process captures and sequesters carbon dioxide that would otherwise be released into the atmosphere by decomposing organic waste (Yang et al. 2021). The decarbonization intensity of the pyrolysis system, including fossil fuel offsetting, can vary depending on the specific production process and application of biochar, ranging from 37 g CO_2-eq/MJ to 137 g CO_2-eq/MJ (Peters et al. 2015; Zhang et al. 2022). Secondly, the life cycle of biochar includes processes such as transport and storage, which can contribute to carbon dioxide emissions. Effective control of carbon emissions during these processes can minimize their marginal contribution to biochar emissions (Matuštík et al. 2020). Thirdly, replacing concrete or cement with a certain amount of biochar can enhance wall insulation, effectively reducing carbon dioxide emissions associated with the walls (Chen et al. 2023). Concrete and cement production contributes significantly to carbon dioxide emissions in new buildings, with concrete accounting for at least 40% and cement for 70% of these emissions, along with emissions from raw material transportation and aggregate production (Habert et al. 2020). The elevated carbon dioxide levels released during cement and concrete fabrication in construction contribute to approximately 8% of total man-made carbon dioxide emissions (Miller et al. 2018; Zou et al. 2018). Thus, substituting a portion of concrete or cement with biochar achieves wall insulation and helps reduce carbon emissions.

Studies have shown that incorporating alternative materials such as limestone, silica fume, or biochar in cement systems can significantly reduce carbon dioxide emissions. For example, a cement system mixed with 10% limestone and 5% silica fume as fillers can reduce carbon dioxide emissions by more than 13% while maintaining comparable mechanical strength to ordinary cement (Li et al. 2019). Additionally, using 5% biochar in ultra-high-performance concrete contributes to carbon sequestration, with approximately 115 kg of carbon dioxide solid phase captured per cubic meter of concrete (Dixit et al. 2021). Biochar pores can also interconnect with pores in the cement system, promoting carbon dioxide diffusion and dissolution, thereby facilitating carbonation. Incorporating biochar as an aggregate in concrete can sequester 59–65 kg of carbon dioxide per ton of concrete, offering significant economic and environmental benefits (Chen et al. 2022b). Life cycle analyses have demonstrated that biochar incorporation effectively reduces carbon dioxide emissions, and concrete reinforced with 30% biochar can even achieve negative carbon emissions. However, it is important to note that increasing the dosage of biochar beyond certain limits may lead to a loss of strength (Maljaee et al. 2021).

Finally, using biochar insulation in building and construction applications can reduce energy consumption and emissions related to heating and cooling systems, as shown in Fig. 5. Adding biochar to concrete disrupts thermal bridges within the material, enhancing the insulation of building walls and reducing energy consumption (Gupta et al. 2017). The thermal performance improvement achieved by biochar insulation significantly reduces energy consumption, greenhouse gas emissions, and costs for building owners and occupants. Additionally, the simultaneous use of biochar and carbon dioxide curing techniques can enhance building material performance and achieve deeper carbon sequestration compared to single technologies (Zhang et al. 2022). Biochar insulation aligns with the sustainable development goals for the building and construction sectors, particularly in reducing the carbon footprint of buildings and communities through decreased energy consumption and emissions associated with heating and cooling systems.

In conclusion, the capacity of biochar insulation to reduce carbon emissions makes it a promising alternative for the building and construction sector. Utilizing biochar insulation in construction signifies a strategic shift toward advanced sustainable building methodologies. Given its intrinsic properties, biochar demonstrates unparalleled efficacy in reducing thermal transmittance. As the architectural industry moves toward higher performance benchmarks, the integration of biochar becomes paramount in achieving rigorous environmental and energy efficiency standards.

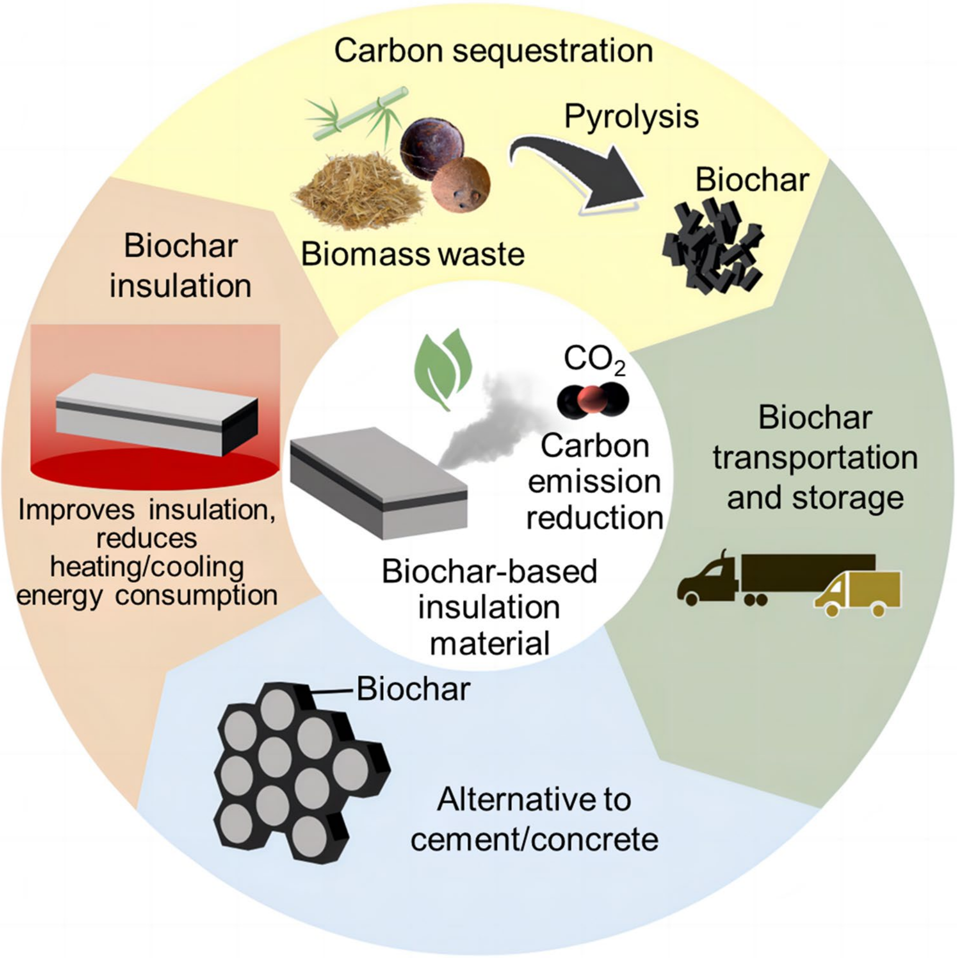

Fig. 5 Emission reduction of biochar-based insulating materials. The emission reduction of biochar-insulating materials encompasses the entire life cycle process. It involves various stages, such as producing and transporting biochar, substituting cement or concrete with biochar, and improving wall insulation performance using biochar insulation materials. These measures collectively contribute to reducing energy consumption for air conditioning, thereby effectively reducing emissions. The holistic approach of emission reduction in biochar-insulating materials addresses multiple stages of the product's life cycle. It underscores their significant role in mitigating environmental impact and promoting sustainable practices. CO_2 is the carbon dioxide

Insulation advantages of biochar-based insulating materials

Biochar offers numerous advantageous properties, such as a high surface area and abundant tiny pores, contributing to its wide range of applications. In biochar–cement composites, these properties enhance water absorption/retention, reduce weight, improve mechanical and thermal properties, and regulate temperature (Dong et al. 2023; Rodier et al. 2019; Zhang et al. 2022). To enhance the performance of biochar composites in civil structures, additional components like plant, carbon, glass, or steel fibers are incorporated to reinforce the inorganic substrates, typically cement (Da Costa et al. 2014).

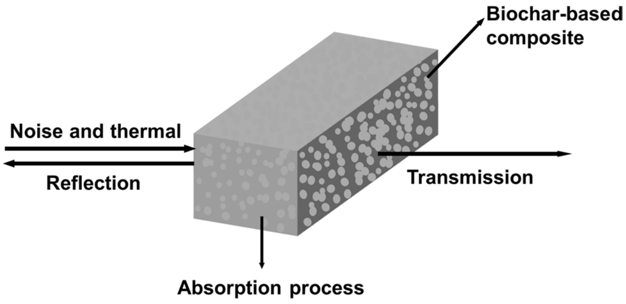

Fig. 6 Thermal insulation and noise reduction properties of biochar thermal insulation materials. The incorporation of biochar in cement or concrete composites leads to the destruction of thermal bridges within the material, resulting in reduced thermal conductivity and improved thermal insulation performance. Porous biochar in the composite promotes heat diffusion, effectively blocking one-way heat transfer and enhancing the overall heat insulation effect. By evenly distributing porous biochar in cement or concrete, the thermal insulation capabilities of the material are significantly enhanced. Modified from Zhang et al. (2022)

The uniform distribution of porous biochar within cement or concrete disrupts heat diffusion and impedes one-way heat transfer, providing adequate thermal insulation (Jiang et al. 2022; Xiong et al. 2022; Zhang et al. 2022). Custom-made biochar exhibits a three-dimensional porous structure and a two-dimensional fake structure, creating additional heat transfer pathways within the composite (Xiong et al. 2022). The presence of pores in biochar disrupts thermal bridges within the composite, resulting in reduced thermal conductivity and improved thermal insulation performance. Consequently, biochar with a higher pore density in insulation walls can enhance building materials' heat insulation and contribute to sound insulation (Zhang et al. 2022). Figure 6 presents the thermal and noise insulation advantages of biochar-loaded materials. Biochar in cement or concrete disrupts heat diffusion, hinders one-way heat transfer, improves thermal insulation, and contributes to sound insulation.

Recent studies have focused on exploring biochar-based insulation materials and determining the optimal ratio for achieving optimal insulation performance, as listed in Table 6. Cuthbertson et al. (2019) investigated using biochar as an inert filler in concrete, replacing traditional components such as sand or coarse aggregate. The study evaluated the potential performance enhancements and carbon sequestration opportunities associated with incorporating biochar into concrete. They found that increasing the biochar content in concrete decreases the density of the material. Incorporating 15% biochar by weight resulted in lightweight concrete with a 1454 kg/m^3 density, although it also increased brittleness. It was determined that the highest proportion of biochar that can be incorporated without compromising the

Table 6 Thermal conductivity of biochar-insulating materials

Biochar raw material	Combination types	Combination ratio (biochar)	Thermal conductivity coefficient W/(m·K)	References
Dried distillers' grains	Biochar–concrete	2%	0.19	Cuthbertson et al. (2019)
Rice shell, coconut shell, and bamboo	Biochar–natural inorganic clay	10%	0.10	Lee et al. (2019)
Bagasse	Biochar–cement	4%	0.21	Rodier et al. (2019)
Rape straw	Biochar–concrete	Not reported	0.095	Zhang et al. (2021)
Rice husk	Geopolymer foam	Rice husk or geopolymer mass ratio: 0–0.64	0.09–0.14	Wang et al. (2020b)
		Foaming agent or geopolymer mass ratio: 0–0.02	0.08–0.18	
		Prewetting water or rice husk mass ratio: 0–3.5	0.107–0.112	
Wheat straw	Biochar–cement	2%	0.76	Jiang et al. (2020)

This table summarizes recent research on biochar insulation materials, covering the biomass type used for biochar preparation, biochar reference ratio, thermal conductivity, and other relevant information. Notably, the thermal conductivity of biomass insulation materials can reach levels as low as approximately 0.08 W/(m·K) concrete's structural integrity is 12% by weight. Additionally, including activated carbon at up to 30% by weight had a limited impact on density, only reducing it to 1370 kg/m^3. However, adding biochar and activated carbon improved sound absorption coefficients across the 200–2000 Hz frequency range. The concentration of carbon compounds did not significantly affect the coefficient. Moreover, concrete containing 10 and 15% biochar exhibited a noise reduction coefficient of 0.45, indicating strong sound absorption capabilities.

Regarding thermal insulation, biochar enhances the material's thermal properties compared to regular concrete. The most significant reduction in thermal conductivity was achieved with 1 and 2% biochar by weight, resulting in temperature-dependent conductivities ranging from 0.21 to 0.23 W/(m·K) and 0.192–0.197 W/(m·K), respectively. Despite not being classified strictly as a building insulation substance, the material undoubtedly elevates the concrete's thermal protective traits and raises the energy competency of structures built from it. While there was no apparent trend in compressive strength with varying biochar content, a modest improvement in compressive strength was observed compared to ordinary concrete. Adding biochar did not negatively impact the concrete's compressive strength, allowing the pursuit of other associated benefits without compromising its structural integrity. However, one drawback noted in the studies was the additional water required for the concrete when incorporating biochar, with over 1 L of extra water needed per kg of biochar to achieve a workable paste.

Using plasticizers in conjunction with biochar during the addition process can be advantageous for improving water efficiency. Various concrete tests have shown that incorporating modest amounts of biochar into the mixture can produce desirable material qualities. Optimal heat conductivity in the concrete was observed when the biochar concentration ranged from 1 to 2% by weight while maintaining minimal water usage. Adding up to 3% biochar by weight did not compromise the compressive strength of the concrete. Furthermore, increasing the carbon concentration beyond 7% did not impact the sound absorption coefficient (Cuthbertson et al. 2019). Lee et al. (2019) experimented with biocomposite materials by blending rice shells, coconut shells, and bamboo biochar with natural inorganic clay. The study revealed that when the biochar to natural inorganic clay ratio reached 10%, the thermal conductivity of the biochar–clay composites decreased by 67.2%, dropping from 0.308 to 0.101 W/(m·K).

Rodier et al. (2019) combined biochar with cement to investigate its thermal insulation properties. They produced hemicellulose-free biochar by subjecting bagasse to thermochemical conversion. The results demonstrated that incorporating 4% biochar by weight reduced the thermal conductivity of cement-based composites by 25%, namely 0.21 W/(m·K). Additionally, a 2% biochar content improved the hydration properties of the cement slurry. Zhang et al. (2021) explored thermal insulation in concrete by incorporating concrete and rape straw. Their research indicated that the material's thermal conductivity was 0.095 W/(m·K). Moreover, this approach facilitated better temperature and relative humidity regulation, enhancing indoor comfort.

Furthermore, adding raw rice husk or straw to cement improved the cement's thermal insulation, toughness, and water retention properties. Wang et al. (2020b) experimentally investigated a composite material composed of rice husk and geopolymer foam for building energy conservation and insulation. They found that the composite material exhibited satisfactory performance. When the rice husk or geopolymer mass ratio ranged from 0 to 0.64, the thermal conductivity was between 0.09 and 0.14 W/(m·K). Similarly, when the foaming agent or geopolymer mass ratio ranged from 0 to 0.02, the thermal conductivity ranged from 0.08 to 0.18 W/(m·K). Additionally, when the prewetting water/rice husk mass ratio ranged from 0 to 3.5, the thermal conductivity ranged from 0.107 to 0.112 W/(m·K).

Additionally, Jiang et al. (2020) investigated the compressive strength and thermal conductivity of wheat straw biochar and rice straw biochar by substituting 2% of cement. The experimental findings indicated a significant improvement in thermal insulation performance and decreased thermal conductivity for both biochar types. The rice straw biochar–cement composites exhibited the lowest thermal conductivity at 700 ℃, with a reduction of 2%, namely 0.76 W/(m·K). In comparison, the wheat straw biochar–cement composites demonstrated the lowest heat diffusion rate at 700 ℃, also reduced by 2%. Therefore, future studies should focus on ensuring that walls can bear weight according to standards while increasing the amount of biochar replacement, effectively enhancing wall insulation performance and maximizing carbon storage in building materials (Dixit et al. 2021; Maljaee et al. 2021). Furthermore, the properties of engineered biochar need to be improved to enhance recombination properties (Zhang et al. 2022).

In summary, the principle behind biochar thermal insulation materials lies in the porous structure of biochar, which disrupts thermal bridges within composite materials, reduces their thermal conductivity, and enhances thermal insulation performance. When porous biochar is uniformly distributed in cement or concrete, it induces heat diffusion and impedes one-way heat transfer, thereby providing insulation. Biochar insulation materials are typically produced by replacing a portion of cement or concrete with biochar, and their thermal conductivity generally falls within the range of 0.08–0.2 W/(m·K).

Life cycle assessment of biochar-modified concrete or bricks

There is potential for biochar to strengthen concrete's mechanical features and cut down on the necessary cement volume, resulting in decreased carbon dioxide emissions during production. This makes biochar a promising candidate for being a key component in sustainable building practices. To ensure the environmental sustainability of incorporating biochar into concrete, conducting a thorough life cycle assessment is crucial before commercialization. Life cycle assessment is a comprehensive method that evaluates the environmental impact of a product throughout its entire life cycle, from manufacturing to disposal or recycling (Matuštík et al. 2020; Shanmugam et al. 2021b). The life cycle assessment approach encompasses several core procedures, including cradle-to-grave, cradle-to-cradle, and life cycle energy assessments. The cradle-to-grave study evaluates the complete life cycle of a product, while the cradle-to-gate examination focuses on raw material extraction for industrial processes. The cradle-to-cradle study assesses recyclability, and the life cycle energy analysis evaluates energy consumption from manufacturing to disposal stages (Campos et al. 2020; Guinée et al. 2011).

This section discusses the environmental implications of biochar and concrete mixtures utilizing various procedures. In a study by Campos et al. (2020), the cradle-to-gate analytical technique was employed to assess the environmental impact of rice husk biochar or concrete materials. The investigation considered various biochar loading quantities ranging from 0 to 20% and cement contents ranging from 0.15 to 0.19 kg. The analysis revealed that augmenting biochar quantities led to a decline in ozone thinning, pollution across air, water, and land, and hazardous waste production. Simultaneously, it bolstered ozone generation. The adverse environmental outcomes, like global temperature rise, making soils and waters more acidic, and boosting nutrient levels in both terrestrial and aquatic systems, were markedly lessened. Based on these positive findings, the authors suggested using biochar to replace fly ash. Another comprehensive study by Gupta et al. (2018b) investigated biochar generated from mixed wood sawdust as a carbon-capturing additive in concrete. A portion of the biochar was impregnated with carbon dioxide before being incorporated into the concrete mixture. The study examined the effects of saturated and unsaturated biochar on greenhouse gas emissions and global warming potential. The results indicated that biochar reduced carbon dioxide emissions and decreased methane, nitrogen oxide, and sulfur emissions during manufacturing.

Incorporating biochar in concrete has shown significant potential for reducing the environmental impact, particularly regarding global warming potential. In the case of saturated and unsaturated biochar or concrete mixtures, the net global warming potentials were measured at 6.7 and 6.63 kg CO_2-eq, respectively, compared to 7.8 kg CO_2-eq for concrete without biochar (Gupta and Kashani 2021). These findings indicate that biochar can effectively mitigate the environmental impact of concrete. Those researchers utilized leftover peanut shell biochar to elevate the attributes of cement mortar and its fly ash variant. A significant reduction in carbon dioxide emissions was observed by substituting just 3% of cement with biochar. This underscores the environmental benefits associated with incorporating biochar into the mix. Di Tommaso and Bordonzotti (2016) also found that using 1% biochar-based activated carbon in high-performance concrete led to a reduction of 0.5 gigatons in carbon dioxide emissions.

Similarly, Suarez (2018) reported that replacing 2% of cement with biochar in producing 1 m^3 of cement paste decreased 67 kg of atmospheric carbon dioxide. Furthermore, including activated charcoals and carbons, which are excellent industrial adsorbents, in concrete has demonstrated improved absorption of nitrous oxide by the hardened product (Horgnies et al. 2012; Krou et al. 2015). These studies highlight the environmental benefits of incorporating biochar into concrete mixtures. Biochar can help mitigate several environmental impacts associated with traditional concrete production, including ozone depletion, toxicity, hazardous waste generation, greenhouse gas emissions, and global warming potential. These findings support biochar as a sustainable alternative in concrete production and emphasize the potential for environmental improvement through its implementation.

In summary, biochar-based insulating materials offer a promising solution for reducing carbon dioxide emissions in the building and construction industry. Their ability to capture and sequester carbon, replace high-emission components, enhance thermal performance, and contribute to sustainable development goals make them valuable in mitigating climate change and promoting environmentally friendly building practices. Further research and development in this field are essential to unlock the full potential of biochar as a sustainable and effective solution for emission reduction in the construction sector.

Economics of biochar-based bricks and insulating materials

Using biochar building materials holds the potential to contribute to developing a carbon–neutral circular economy and sustainable waste management practices (Zhang et al. 2022). Various aspects are typically considered when assessing the economic viability of sustainable bricks made with biochar. These include raw materials, labor, energy consumption, and transportation expenses. Potential advantages such as decreased greenhouse gas emissions, enhanced soil quality, and potential income from carbon credit sales are also considered. A valuable approach for economic analysis is conducting a cost–benefit analysis. This method evaluates all the costs associated with a project or product and compares them to the anticipated benefits within a specific timeframe. Alternative economic evaluation techniques, such as life cycle analysis or net present value analysis, could also be employed.

Recent reports indicate that the price of biochar is approximately $318 per cubic meter, which is indeed higher than the price range of cement, which typically falls between $130 and $160 per cubic meter (Ltd 2023; Raju and Brooke 2021). However, previous studies have demonstrated that incorporating a small quantity of biochar, namely around 0.5%, can greatly enhance the strength of bricks (Restuccia and Ferro 2016b). Since the amount of biochar added is minimal, its impact on overall costs can be considered negligible. Nonetheless, the significant performance improvement justifies its cost-effectiveness when used as an additive in small quantities.

Conversely, other studies have used substantial biochar to replace sand or cement components (Maxwell et al. 2020; Praneeth et al. 2021). Undoubtedly, the cost of biochar is significantly higher than that of concrete. While the short-term cost benefits may not be substantial, its ability to provide low density and excellent insulation could have implications for transportation costs and savings in heating and ventilation expenses throughout the lifespan of the building (Brewer et al. 2014; Maxwell et al. 2020; Praneeth et al. 2021). Buildings are intended to operate for several decades or centuries, meaning that biochar's long-term insulation advantages may lead to remarkable cost-effectiveness over time. Hence, it is critical to examine these variables when appraising the economic feasibility of employing biochar-based sustainable bricks.

The cost of biochar is influenced by aspects like its type, the quality of its feedstock, and the magnitude of its production. In a study by Huang et al. (2015), an economic analysis was carried out on producing biochar from poultry litter waste. Based on the researchers' findings, the expense of producing a ton of poultry litter biochar stood at $266. However, when the sale of electricity and heat generated during the production process was considered, the cost was reduced to $217. It is important to note that the market price of biochar at that time was $184 per ton. In a separate study by Shackley et al. (2011), additional costs such as transportation and application were considered. The price per ton of biochar varied between $222 and $584, depending on the pyrolysis scale and feedstock. Akhtar and Sarmah (2018) undertook studies where they introduced biochar into concrete, varying its presence from 0.1 up to 1% of the complete concrete volume. The raw materials used for this purpose were derivatives of rice husks, paper industry waste, and chicken waste. Subsequently, the researchers evaluated the financial aspects of crafting mid-sized biochar-infused concrete, juxtaposing it with its conventional counterpart. They observed that for every 0.25% increase in biochar content, production cost was reduced by approximately one dollar. This indicated that increasing the amount of biochar in the concrete mixture led to cost savings. However, the decline in expense was negligible, given the limited volume of biochar used. The study's authors believed that mass-producing biochar–concrete could lead to notable economic gains.

The economic viability of biochar insulation is influenced by its cost compared to conventional insulating materials such as glass fiber and foam. Biochar insulation is generally more expensive, with the increased cost of hollow beads, silica fume, and nanoparticles impacting the production cost of biochar composites (Cao et al. 2013; Zhang et al. 2022). Integrating biochar with cement in construction engineering can enhance structures' compactness and thermal insulation performance, leading to cement conservation, reduced environmental pollution, and resource savings, thereby contributing to economic development (Danish et al. 2021).

However, the additional cost of biochar insulation can be offset by the reduced energy consumption it offers. Well-insulated structures utilizing biochar insulation experience significant reductions in heating and cooling expenditures. Moreover, when biomass pyrolysis is adequately defined to produce biochar, it can serve as a valuable green building material, promoting waste reuse and ultimately saving energy in the long run (Restuccia and Ferro 2016b). An important aspect to consider is the environmental impact of biochar insulation. Biochar insulation is derived from organic waste and uses a readily available renewable resource. Compared to conventional insulation, it exhibits significantly lower greenhouse gas emissions. This means that biochar insulation can reduce carbon emissions and mitigate the environmental effects associated with the construction industry's carbon dioxide emissions (Maljaee et al. 2021; Zhang et al. 2022). By reusing biomass waste and incorporating biochar into building materials, the construction industry can effectively work toward long-term decarbonization and developing a circular economy (Zhang et al. 2022).

Considering the economic aspects and the life cycle process of using biochar in cement, one strategy to minimize costs is choosing local raw materials for biochar production. This approach helps reduce transportation and processing costs associated with sourcing materials from distant locations. Additionally, local biochar production in cement manufacturing saves transportation fees and reduces waste disposal costs and the expenses related to conventional cement material. Furthermore, implementing climate policies has significantly increased carbon pricing, ranging from $40–80 per ton (Wen et al. 2023; World-Bank 2020). This creates an opportunity for biochar-based cement products to generate additional economic income through carbon credits. Cement manufacturers can benefit from the financial incentives associated with reducing carbon emissions by sequestering carbon in biochar. To further reduce costs, it is crucial to recover and utilize the by-products of the pyrolysis process, namely syngas and bio-oil. These by-products can be harnessed and used as alternative fuel sources, offsetting the need for other costly fuels. This approach contributes to overall cost reduction and enhances the economic viability of biochar-based cement production.

In conclusion, the economic evaluation of biochar-based sustainable bricks involves considering cost, environmental benefits, and long-term cost-effectiveness. Incorporating small amounts of biochar can significantly enhance the strength of bricks without significant cost implications. Moreover, using larger proportions of biochar as a replacement for sand or cement can result in excellent insulation and substantial cost savings in heating energy over the building's lifespan. Careful assessment of these variables is crucial for determining the economic viability of utilizing biochar-based sustainable bricks. Overall, incorporating biochar in construction materials promotes improved energy efficiency, environmental sustainability, and the advancement of a circular economy.

Conclusion

Rising energy use and emissions from global industrialization and urbanization lead to environmental problems and higher temperatures. To combat this, lowering carbon emissions from building materials is vital. Biochar-based materials offer a solution by cutting carbon dioxide emissions and costs. Adding biochar to products like bricks boosts their strength and insulation, reducing reliance on materials like cement. This decreases carbon emissions and achieves deeper carbon sequestration. The incorporation of different types of biochar has shown negative greenhouse gas emissions, improving the environment. Effective carbon emissions control during transport and storage further minimizes their overall impact. Substituting one ton of cement with biochar in brick production can reduce global warming potential to 1351.2–1504.6 kg of CO_2-eq. Biochar bricks offer good thermal insulation, water absorption, workability, and lightweight properties. However, their compressive strength is lower due to biochar's softer nature. The flexural strength of biochar bricks can be enhanced by partial replacement with biochar. Biochar bricks' lighter weight and lower density require better water absorption and retention. Although biochar insulation is costlier than materials like fiberglass and foam, reduced energy consumption offsets this cost. Biochar insulation also leads to lower long-term greenhouse gas emissions, aiding carbon reduction in the construction industry. Future research on biochar building materials should adjust engineered biochar's kinetics for optimal carbon dioxide diffusion control and performance. Striking a balance between reduced emissions and biochar insulation without compromising the structural strength is crucial. Additionally, addressing the impact of biochar on the compressive strength of building materials and exploring ways to mitigate this effect are key research directions.

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