

BIOCHAR IN CONCRETE: A PATHWAY TO ECO-FRIENDLY BUILDING PRACTICES

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HIGHLIGHTS

- Biochar reduces the CO₂ footprint in concrete production and enhances its hydration and long-term strength.
- Incorporating biochar in concrete promotes sustainable construction practices.
- Biochar acts as a carbon sink, effectively sequestering carbon within concrete structures.
- Biochar reduces drying shrinkage, improving the durability and lifespan of concrete.
- Future research should focus on optimising biochar dosage and feedstock properties for concrete.

GRAPHICAL ABSTRACT



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ABSTRACT

The threat of global warming—driven by rising levels of atmospheric greenhouse gasses—has raised the need for a paradigm shift in the construction industry, a major contributor of CO₂ emission. Concrete, a cornerstone of modern construction is responsible for a significant portion of global CO₂ emissions due to the high carbon footprint of cement, a key ingredient. Biochar, a charcoal-like material produced from pyrolysed organic waste, offers a multifaceted approach to mitigate the environmental impact of concrete by reducing CO₂ emissions during production, sequestering carbon within the concrete structure, and potentially enhancing its properties. This paper explores the definition and production methodologies of biochar, its physical and chemical properties, and the effects of incorporating biochar into concrete mixes, including rheology, hydration, setting time, mechanical strength, shrinkage, and durability. Additionally, it discusses the substantial environmental benefits of using biochar in concrete production, particularly its role in carbon sequestration. The findings suggest that biochar holds significant potential for the construction industry to adopt more sustainable practices.

Introduction

Global warming poses a significant threat to our planet, driven by the relentless rise of atmospheric greenhouse gas (GHG) levels, primarily carbon dioxide (CO₂) (Florides & Christodoulides, 2009). This insidious issue disrupts weather patterns, causes unprecedented ice melt and inexorably raises sea levels, threatening the very fabric of our existence. These dire environmental consequences pose an immediate threat to ecosystems, livelihoods, and the future of human civilisation (Atkinson, 2014). This alarming scenario calls for immediate action and innovative solutions across all sectors, including the construction industry, which plays a crucial role in shaping our built environment.

Concrete is a universal material born from the union of cement, sand, gravel, and water; it has been the cornerstone of human progress (Ashley & Lemay, 2008). Concrete is central to every building block of modern society (Tomosawa *et al.*, 2005). It is used not only in elaborate architectural projects, but also in utilitarian construction works. From soaring skyscrapers housing businesses and communities, to sprawling bridges connecting vast expanses and mighty dams supplying water and electricity, concrete is the main component of these megastructures besides steel. This versatile material offers an excellent combination of properties, being incomparably strong and durable with a long lifespan. Concrete can effectively resist aggressive environments such as exposure to freezing and thawing, and external elements like ions (chloride and sulphate), gases (CO₂), and water (Li *et al.*, 2023). Its relative affordability also makes concrete an accessible building material for all sorts of projects. However, the environmental cost associated with concrete production, particularly the carbon footprint of cement as its key ingredient, casts a long shadow over its otherwise impressive application (Mostert *et al.*, 2022).

Concrete production is one of the largest sources of GHG emissions, which is central to global warming. GHG emissions from

the cement industry are significant (0.8-1.3 tonnes of CO₂ per tonne of cement) (Andrew, 2018), accounting for about 8% of global annual CO₂ emissions (Glenk *et al.*, 2023). The process is inherently energy-intensive, with primary energy demand supplied through the combustion of fossil fuels to heat limestone (a critical raw material) to high temperatures for calcination, releasing large amounts of CO₂ into the atmosphere (Hasanbeigi *et al.*, 2012). Other hazardous emissions also contribute to air pollution through the calcination decomposition process of limestone (Karstensen *et al.*, 2016). The ecological footprint of concrete extends beyond production, with large resource demands in concrete manufacture through aggregate material quarrying. The immense volume of concrete required for mega projects further exacerbates resource demand.

In view of the environmental concerns, researchers and industrialists have been striving to reduce the adverse impacts of cement manufacture and concrete consumption. An obvious pathway forward involves addressing inefficiencies in the manufacturing process itself. Shifting to energy-efficient technologies and alternative fuels for calcination can drastically reduce CO₂ emissions (Naqi & Jang, 2019). Efficiency improvements can be achieved through advanced design methodologies for the concrete value chain (Habert *et al.*, 2020) such as minimising waste, maximising efficiency, and recycling concrete waste to reduce its carbon footprint (Ho *et al.*, 2021). Additionally, adopting prefabrication increases the likelihood of controlled production environments and reduces the environmental impact associated with on-site activities (Lu & Yuan, 2013). Another promising approach is using alternative materials with lower embodied carbon contents such as supplementary cementitious materials (SCMs). Many SCMs are byproducts of other industrial processes and can partially replace cement in concrete mixes, contributing to a greener production chain (Lothenbach *et al.*, 2011).

SCMs can be sourced from several avenues. One effective method is recycling construction and demolition waste, which mitigates the negative environmental impact of these materials. These recycled and waste materials can be used to partially or completely replace the binder and/or aggregate components in cementitious composites. Additionally, waste materials from other industries such as fly ash can serve as SCMs (Juenger & Siddique, 2015). Fly ash, a byproduct of coal combustion in power plants, acts as a pozzolanic material, reacting with calcium hydroxide (a byproduct of Portland cement hydration) in the presence of moisture to form calcium silicate hydrate (C-S-H). This strong binding gel enhances the strength and durability of concrete (Giergiczny, 2019).

Another valuable SCM is ground granulated blast-furnace slag, which is used as a partial replacement for Portland cement in concrete. This SCM improves concrete strength over time and enhances resistance to cracking, chloride penetration and sulphate attack, making the concrete more durable. It also reduces the heat of hydration, minimising the risk of cracking, and lowers shrinkage and creep, thereby reducing permeability (Qu *et al.*, 2022). Waste glass powder and red mud are other industrial wastes that have been beneficially utilised in geopolymers to improve concrete microstructure and strength. Overall, the use of such materials reduces the negative impact of cementitious composites and decreases GHG emissions by lowering cement consumption in concrete production (Hu *et al.*, 2020).

In addition to industrial waste or recycled materials, other SCMs derived from biomass sources are also being studied for integration into concrete production. Agricultural waste, such as wheat straw ash, sugar cane ash, and corn cob ash have been explored due to their increased pozzolanic activity from amorphous SiO₂ (Tayeh *et al.*, 2021). Beyond agricultural waste ash, biomass-origin materials like biochar—produced by heating organic waste in an oxygen-limited environment—are

emerging as revolutionary components with the potential to transform concrete production. This charcoal-like substance offers a three-fold benefit: Reducing the environmental footprint of concrete, improving its properties, and an effective tactic for CO₂ sequestration when mixed into the concrete (Buss *et al.*, 2019).

The undeniable reality of climate change brought on by global warming necessitates a paradigm shift in the construction industry, which is a significant contributor of GHG emissions. Concrete, a cornerstone of modern infrastructure, offers immense strength and durability, but carries a significant environmental burden due to the carbon footprint associated with cement production. This paper explores the promising solution of biochar, covering its definition and production methodologies. In the following sections, the application of biochar in concrete production is discussed, detailing how it can be incorporated into concrete mixes either as a partial replacement for cement or as a lightweight aggregate. Additionally, the paper examines the positive effects of biochar in improving concrete properties, including strength, workability, and durability, and its potential to produce self-healing concrete with an extended lifespan and reduced maintenance requirements. Finally, the impact of biochar use in lessening the carbon footprint and enhancing carbon sequestration in concrete production is analysed.

Biochar Definition and Methodologies of Production

Biochar is defined as the solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment. Various feedstocks can be used for biochar production, resulting in a stable material that does not readily decompose, and can store carbon for thousands of years, making it an effective method for carbon sequestration (Leng *et al.*, 2019). Several conventional practices are employed to produce biochar, with the most well-known thermochemical conversion methodologies being pyrolysis, gasification, and hydrothermal

carbonisation (HTC). During these conversion processes, biochar is produced either as the main product or byproduct (Emenike *et al.*, 2024).

Pyrolysis is a thermochemical conversion technique that breaks down organic materials using high heat in an oxygen-limited environment. Unlike burning, which requires oxygen and produces energy, ash and CO₂, pyrolysis decomposes the material into new products, including solid biochar, condensable liquids (bio-oil) and non-condensable gases (a mixture of combustible gases like methane and hydrogen) known as syngas. The outputs of pyrolysis depend on the feedstock composition and operational parameters such as temperature,

heating rate, residence time, and presence of catalysts (Figure 1) (Kan *et al.*, 2016). Pyrolysis can be categorised into three main types: Slow, fast, and flash pyrolysis. Slow pyrolysis occurs at the lowest heating rate (around 10°C/minutes), moderate temperatures (400-600°C), and the longest residence time (hours to days), primarily producing biochar with minimal bio-oil and syngas (Waheed *et al.*, 2013). In contrast, fast and flash pyrolysis occur at higher heating rates and temperatures, with significantly shorter residence times (minutes to seconds or milliseconds), resulting in bio-oil and syngas as the main products, with significantly less biochar (Ighalo *et al.*, 2022).

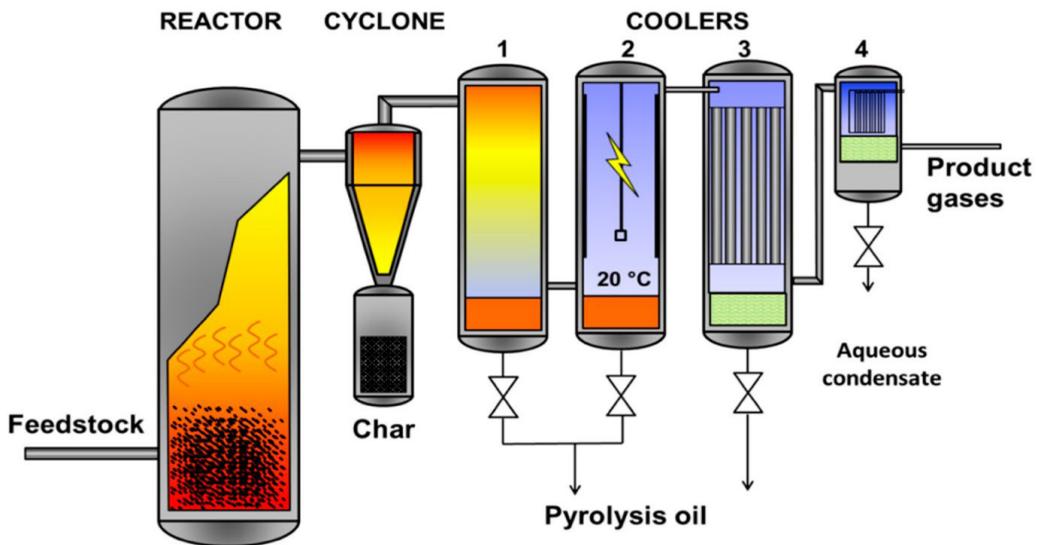


Figure 1: Biomass pyrolysis equipment line and resulting products (Pandey *et al.*, 2019)

Gasification is another thermochemical process that transforms feedstock into carbonaceous materials. Like pyrolysis, gasification occurs in a controlled environment with limited oxygen, but it uses higher temperatures, close to 1,000°C (Molino *et al.*, 2016; Sikarwar *et al.*, 2016). In this process, the feedstock characteristics and operational parameters—including temperature, equivalence ratio, steam-to-biomass ratio, system pressure, and the type and amount of catalyst (if used)—are crucial factors that determine the yield and

proportion of the main product and byproducts (Sikarwar *et al.*, 2016).

HTC is an exothermic process facilitated by subjecting a suspension of biomass and water to temperatures ranging from 180°C to 220°C under saturated pressure for several hours (Pavkov *et al.*, 2022). During HTC, the levels of both oxygen and hydrogen within the feed material are reduced, while several reaction mechanisms, including hydrolysis, dehydration, decarboxylation, polymerisation, and aromatisation, occur. The most important

factors determining the product yield and quality in this technique are temperature, residence time, pressure, heating rate, reactant concentration, and aqueous quality (Wang *et al.*, 2018). The products of HTC include a solid phase of biochar that can be easily isolated from the liquid phase. The biochar produced typically retains approximately 75% to 80% of the carbon input (Oliveira *et al.*, 2013).

Physical and Chemical Properties of Biochar

One of the notable physical properties of biochar is its large surface area. The release of volatile matter during the thermochemical conversion process leads to the formation of pores of various sizes. The pore structure, quantity, arrangement, compactness, and porosity of biochar will change with increasing pyrolysis temperature (Leng *et al.*, 2021). Additionally, the source of biochar also significantly influences the pore structure and surface area (Muzyka *et al.*, 2023). For instance, biomass from softwood displays elongated and fibrillar structures (Ghani *et al.*, 2013), while biochar derived from cork exhibits ridges and honeycomb pores (Wang *et al.*, 2022). Biochar particles can range from 5 μm to 5,000 μm , covering a wide range of pore sizes: Micropores (less than 2 nm), mesopores (between 2-50 nm), and macropores (more than 50 nm) (He *et al.*, 2018; Pastor-Villegas *et al.*, 2010). This property means a significant fraction of biochar particles is within the range of cement particles (less than 50 μm) and grinding can further enhance the compatibility of biochar with cement particles (Gupta *et al.*, 2020b).

Chemically, biochar is composed of carbon, hydrogen, and nitrogen, besides small amounts of heavy metals and inorganic minerals like calcium and magnesium (Giri *et al.*, 2020). The carbon content contributes to the hardness and toughness of biochar, which is important when mixing into cement mortar (Maljaee *et al.*, 2021a). The pH of biochar can vary depending on feedstock and production conditions, ranging from slightly acidic to slightly alkaline (Bopp *et al.*, 2016). Additionally, biochar can act like a sponge for cations (positively charged ions)

like calcium, magnesium and potassium due to its cation-exchange capacity. A higher C/O ratio in biochar implies the presence of oxygenated functional groups such as hydroxyl (OH), carboxyl (COOH), and carbonyl (C=O), which may explain its high cation-exchange capacity values, indicating a more negatively charged surface (Kamini *et al.*, 2023). Moreover, the surface of biochar is also adorned with other carbon-based functional groups like carboxyl (Tan *et al.*, 2021).

Effects of Biochar Mixing on Concrete Properties

The addition of biochar to cement mortar can significantly influence the properties of concrete. Mixing biochar with concrete impacts the rheological properties of cement mortar, including static stress (the minimum stress required to initiate flow), dynamic yield stress (the stress needed to maintain continuous flow), plastic viscosity (the internal resistance to flow), stability (the resistance of mortar to separation and settling of its components), and compatibility (Petit *et al.*, 2009; Libre *et al.*, 2010; Rubio-Hernández *et al.*, 2020; Gupta *et al.*, 2022; Moeini *et al.*, 2022). These parameters can vary based on the particle size, dosage, and porosity of the biochar used in the mortar mixture.

The physical properties of biochar such as surface area, density, porosity, morphology, and pore volume also influence cement mortar characteristics (Gupta & Kua, 2019). Due to the complex interplay of these factors, identifying optimal conditions for combining biochar and cement is challenging. Generally, fine particles of biochar in cement can improve hydration, pore filling and consequently, the strength and durability of cement-based materials. However, fine biochar particles may also increase viscosity and affect workability, with added consideration that the production of finer biochar particles requires more energy, potentially offsetting its environmental benefits (Zhou *et al.*, 2023).

The blending ratio of biochar to cement is another critical factor. Maintaining the correct

blending ratio is essential as it impacts the rheological characteristics of the mixture, directly influencing bonding and strength (Mensah *et al.*, 2021). Workability decreases in samples with higher levels of biochar due to its filler effect and higher water absorption capacity. Consequently, significant amounts of biochar can disrupt the flow of cement paste (Maljaee *et al.*, 2021b). The rheological properties of biochar-incorporated cementitious mixtures are influenced by biochar particle size, with micro-sized particles being more effective than nano-sized ones due to superior water absorption, reduced water-to-cement ratio and densification effects (Wei *et al.*, 2002). Additionally, the higher surface area per unit volume of nano-sized biochar particles suggests a greater presence of atoms and molecules on the surface, enhancing contact and adhesion between the cement matrix and biochar particles.

Besides particle size, the shape of biochar also significantly affects the properties of cementitious composites. Angular biochar particles will hinder the movement of infused cement paste, resulting in reduced spread diameter in flow table tests. The coarse texture of biochar particles promotes adhesion with the cement paste (Danish *et al.*, 2021). Adding porous biochar particles to the mortar mixture can enhance the hydration process and contribute to a more durable final product. Biochar particles retain significant water in their pores, which is not chemically bonded to the biochar, making it readily available for the anhydrous cement, particularly in the early stages of concrete production (Gupta & Kua, 2018). This reservoir effect continues to be beneficial as the concrete cures, maintaining internal moisture crucial for ongoing hydration reactions, and preventing shrinkage cracks (Muthukrishnan *et al.*, 2019). Therefore, biochar acts as a built-in reservoir, slowly releasing its absorbed water to maintain a favourable moisture environment, which promotes better long-term strength and durability of the concrete.

The addition of biochar to cement mortar influences the setting time of concrete. The

setting time of cement composites includes the initial and final setting times. The initial setting time marks when the cement mixture starts losing plasticity and transforms into paste upon addition of water (Ting *et al.*, 2019). The final setting time represents the time when the material achieves a certain strength after completely losing plasticity (Guo *et al.*, 2020). Biochar particles create a micro-filler effect, speeding up the hydration of cement by providing extra surface area for the formation and growth of hydration products. Consequently, both the initial and final setting times of mortar paste containing saturated and unsaturated biochar are decreased (Gupta *et al.*, 2018). Higher dosages or more porous biochar, which absorb more water are likely to slow down the initial and final setting times compared with smaller dosages due to delayed water availability for cement hydration (Jia *et al.*, 2023).

In general, incorporating biochar into cement mortar mixtures offers both challenges and benefits. While the addition of biochar can improve hydration, strength, and durability, it also requires careful consideration of particle size, blending ratios, and the physical and chemical properties of the biochar. Understanding these factors and their interactions is essential for optimising the use of biochar in concrete production, ultimately contributing to more sustainable construction practices and reducing the environmental impact of cement-based materials.

One of the most important phenomena in concrete production is the hydration process, which plays a crucial role in determining its properties. When biochar is added, it significantly influences the hydration kinetics based on factors such as particle size, feedstock, and preparation conditions (Senadheera *et al.*, 2023). Studies have shown that the inclusion of low-ash biochar causes a slight acceleration in cement hydration and an increase in peak heat associated with tricalcium silicate hydration. This effect is attributed to the nucleation impact of biochar, which provides a surface area for the precipitation of hydration products (Guo *et al.*,

2012). The hydration level can be increased by ensuring a continuous water supply to the cement paste, a process known as internal curing. This process requires using a water-saturated material such as biochar that can retain moisture for an extended period. As mentioned previously, the material used serves as a reservoir from which the hydrating cement paste can draw water as needed (Sirico *et al.*, 2021). Additionally, due to their smaller size compared with cement particles, biochar granules can fill the gaps between the cement particles and other solid grains (Gupta & Kua, 2019). Moreover, the negative charges on the biochar particle surfaces will attract positively charged clinker grains, resulting in the formation of nucleation clusters and ultimately enhancing cement hydration (Gupta *et al.*, 2021).

In contrast, a high ash content and presence of phosphorus in biochar will result in a significant decrease in peak heat and hinder the hydration process. Phosphorus can dissolve and form an insoluble layer of calcium phosphate on clinker grains. This layer acts as a barrier to moisture, restricting its interaction with the anhydrite clinker and consequently reducing the rate of hydration kinetics. During the early stages of hydration, the insulating properties of biochar can trap heat within the concrete, which might, in some cases, lead to a slight delay in peak heat dissipation (Guo *et al.*, 2012). Preparing a mixture of biochar and mortar cement affects not only the concrete properties during the initial hours, but also its long-term mechanical characteristics. The incorporation of

biochar from lignocellulosic sources into mortar mixtures was found to increase compressive strength when Portland cement was replaced with biochar in small dosages (Qing *et al.*, 2023). The increase in strength with the incorporation of biochar is connected to its higher absorption capacity, resulting in a lower binder ratio and a corresponding densified microstructure. The pore-filling ability of biochar particles also leads to a refinement of the microstructure, contributing to the higher strength observed (Qin *et al.*, 2021).

However, when biochar is incorporated at higher dosages, the compressive strength is reduced. This reduction in compressive strength is attributed to the significant decrease in cement content, resulting in reduced product formation. It may also be due to the different particle sizes and internal pore sizes of biochar particles in the Portland cement mixture, which limits the production of calcium silicate hydrate. Nevertheless, as biochar possesses pozzolanic capabilities, further enhancements in compressive strength are expected in the long term (Yang & Wang, 2021). The decrease in compressive strength becomes more significant as the size of biochar particles is increased. However, as depicted in Figure 2, the compressive strength of all mixtures under 10% blending ratio remains above 20 MPa, irrespective of the type or content of biochar. These findings suggest that structural-grade concrete incorporating biochar remains suitable for structural applications (Sirico *et al.*, 2022).

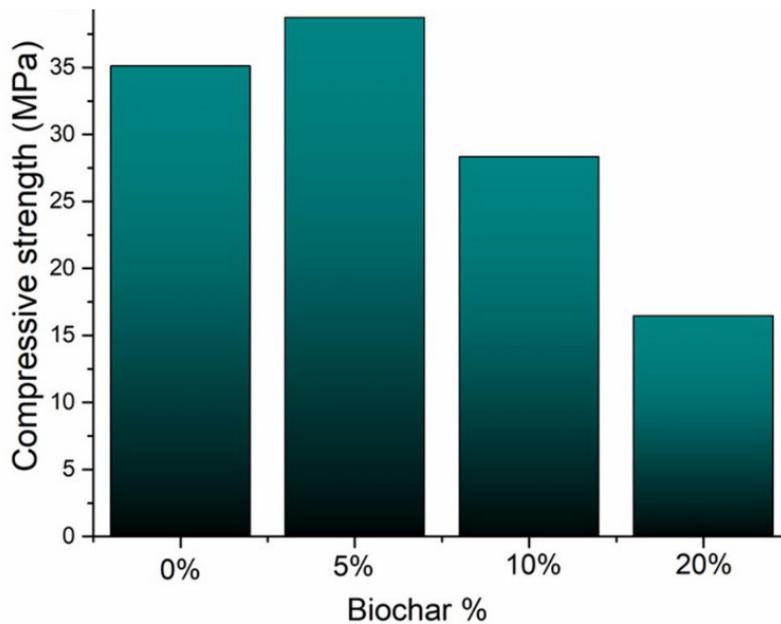


Figure 2: Average compressive strength for different biochar and cement mortar blending (Mensah *et al.*, 2021)

The effect of biochar on the tensile strength of concrete is a complex issue with ongoing research. A very small dosage of biochar with a specific surface chemistry that promotes good adhesion with the cement paste might have a minimal impact or even a slight positive effect on tensile strength (Zeidabadi *et al.*, 2018). Unlike compressive strength, which often benefits from biochar incorporation, the impact on tensile strength can be negative or minimal (Li *et al.*, 2023). This difference underscores the need for careful consideration of biochar dosage and properties when aiming to improve tensile strength. Another important parameter for concrete quality control is shrinkage properties. Concrete with a high amount of shrinkage is prone to cracks, which are unfavourable in concrete production. The addition of a small percentage of biochar has been observed to decrease the drying shrinkage of mortar while simultaneously increasing the plastic and dynamic viscosity of concrete due to the porosity of biochar (Gupta *et al.*, 2020a). This characteristic makes biochar a beneficial additive for controlling shrinkage in cementitious composites.

The stable porous structure of biochar enables it to be utilised as an internal curing agent, effectively lowering the shrinkage of cementitious composites. The decrease in autogenous shrinkage resulting from the addition of biochar can be attributed to two potential mechanisms. First, the retention of water in the pores of biochar reduces the proportion of capillary pores filled with water. Second, the extraction of moisture from the pores of biochar helps alleviate the capillary stress induced in the cementitious matrix compared with pure cement mortar (Gupta & Kashani, 2021). These mechanisms highlight the dual role of biochar in enhancing the hydration process and reducing shrinkage, contributing to the overall durability and performance of concrete. By acting as a reservoir for water, biochar ensures a more consistent and prolonged hydration process, which is crucial for developing strength and minimising defects in the concrete structure.

In general, while the addition of biochar to concrete presents challenges and requires precise optimisation, its benefits in terms of

compressive strength, shrinkage reduction and internal curing make it a promising material for sustainable concrete production. Ongoing research is essential to fully understand the complex interactions between biochar and cementitious materials, and to maximise the advantages of incorporating biochar into concrete mixes.

Environmental Effects of Using Biochar in Concrete Production

Biochar, as a negative emission technology, can significantly reduce the environmental impact of the construction industry when used in concrete. The carbon present in biomass can be transformed into a more stable form in biochar, which persists one to two orders of magnitude longer than its biomass precursor, resulting in long-term carbon sequestration (Arif *et al.*, 2020). Biochar acts as a carbon sink, trapping the carbon it absorbed during its creation within the concrete structure. This captured carbon remains locked away for a very long time, potentially for centuries. By replacing a portion of cement with biochar, concrete manufacturers can effectively reduce the overall CO₂ emissions associated with concrete production (Kharissova *et al.*, 2024). The rate at which CO₂ diffuses through the pore solution of the cement matrix is vital for carbonation reactions, and the high surface area and porosity of the raw materials are essential for effective carbonation.

Studies have shown a 20% reduction in net CO₂ emissions for cement mortar, where 40% of biochar was used to replace sand, compared with mortar without biochar (Gupta *et al.*, 2018). The replacement of sand or cement with biochar in cementitious composites is also important due to the shortage of natural aggregates and the need to reduce cement production, which is one of the largest sources of anthropogenic CO₂ emissions. Therefore, incorporating biochar not only addresses material scarcity, but also mitigates the carbon footprint in concrete production.

The high surface porosity of biochar and its ability to attract non-polar compounds enable it to efficiently store and adsorb CO₂ within the

cement matrix. This capability enhances the rate of CO₂ diffusion and promotes the development of hydration products. The synergistic mechanisms of carbon sequestration involve the contribution of biochar to both improving the physical properties of concrete and enhancing its capacity for CO₂ capture and storage (Zaid *et al.*, 2024). Generally, the use of biochar in concrete not only helps in reducing the environmental impact of the construction industry but also contributes to long-term carbon sequestration. This dual benefit of improving concrete properties while capturing and immobilising carbon in building structures makes biochar an essential component in the move towards sustainable construction practices.

Conclusions

Biochar, a substance resembling charcoal produced through the pyrolysis of organic waste, represents a promising solution to reduce the environmental impact of concrete production. This review delves into the physical and chemical properties of biochar, as well as the traditional thermal methods used to convert biomass into biochar, including pyrolysis, gasification, and HTC.

Many studies have examined the positive effects of incorporating biochar into concrete production, such as its ability to promote hydration, potentially enhance long-term strength, and reduce drying shrinkage. Their findings underscore the significant potential of biochar to facilitate the shift of the construction industry towards more sustainable practices. Furthermore, the study considers the positive environmental contributions of biochar in the construction industry.

Utilising biochar as a filling material can yield substantial environmental benefits, including reduced CO₂ emissions during production and enhanced carbon sequestration within the concrete structure. The partial replacement of cement with biochar is shown to significantly decrease the overall CO₂ footprint. Biochar also acts as a carbon sink, effectively sequestering captured carbon for centuries.

However, optimising the use of biochar use in concrete requires further investigation. Future research should focus on identifying ideal dosage levels for various applications, tailoring biochar properties through different feedstocks and production methods, and conducting comprehensive life cycle assessments to understand its environmental impact throughout its lifespan. By addressing these areas, biochar can revolutionise concrete production, paving the way for a more sustainable and environmentally conscious construction industry.

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Conflict of Interest Statement

The author declares no conflict of interest.

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