Emerging biochar construction materials towards carbon neutrality

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Abstract
Biochar, a carbon-negative waste biomass-derived material, is demonstrating its tremendous promise for applications in carbon-neutral/negative construction materials and is contributing to the achievement of carbon neutrality targets. The incorporation of biochar in construction materials can mitigate CO_2 emissions and natural resource depletion whilst improving the mechanical performance and providing value-added merits for biochar construction materials. Biochar, having a porous nature and highly functionalised surface, can provide nucleation sites for chemical reactions and exhibit compatibility with cement, asphalt, and polymer materials. This study highlighted the roles of biochar in cement hydration, surface functional groups of engineered biochar for promoting chemical reactions, and value-added merits of biochar construction materials (such as humidity regulation, thermal insulation, noise reduction, air/water purification, electromagnetic shielding, and self-sensing). The versatility of biochar gives biochar construction materials the potential to revolutionise the industrial manufacture of conventional construction materials and become an advocate of sustainable and green development. We also highlighted that tailoring the favourable physicochemical properties of engineered biochar based on adequate and scientific designs and advancing the scientific understanding of interfacial reactions in biochar construction materials would facilitate the large-scale development and widespread applications of biochar construction materials.

1. Introduction
Integrating biochar into innovative biochar construction materials could facilitate waste valorisation and reduce CO_2 emissions of construction materials. This strategy could also bring additional economic benefits through carbon trade, incentivising the construction and building industry to curtail overall CO_2 emissions (Wang et al. 2021). Although it has often been overlooked in the construction-related literature, the feedstock of biomass and manufacturing technologies of biochar would significantly affect the properties of biochar construction materials, which should be critically investigated. To the best of our knowledge, no literature review has articulated the state-of-the-art knowledge about designing different types of engineered biochar as construction materials, especially for maximising their technical benefits, value-added functionality, and decarbonisation capacities. Hence, we firstly introduced different processes for biochar production and emphasised the efficacy of biochar construction materials in achieving carbon neutrality. As illustrated in Figure 1, we highlighted sustainable waste management towards a circular economy and proposed a novel strategy for achieving carbon neutrality by adopting biochar construction materials.

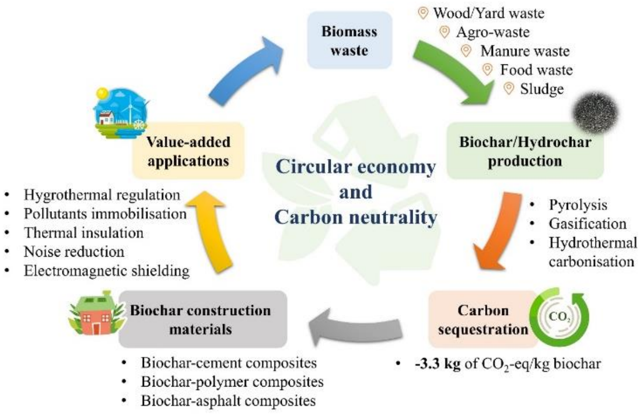

Figure 1. Sustainable waste management towards the circular economy and carbon neutrality by adopting biochar construction materials.

2. Carbon neutrality and biochar-enhanced construction materials
The adoption of fillers as a partial clinker substitution is a promising method for reducing CO_2 emissions and energy consumption (John et al., 2018). Grinding is crucial for ensuring the high mechanical performance of fillers with high fineness, which together with raw material collection and transportation, contributes to CO_2

emissions in fillers production (Batuecas et al., 2021). The calcination of fillers (e.g., limestone) requires lower temperature and less energy, thereby less CO_2 emissions (John et al., 2018). The cement system incorporating 10% limestone and 5% silica fume as fillers can reduce CO_2 emissions by more than 13% while having comparable mechanical strength with plain cement. In recent years, biochar has been adopted as a filler in cement systems, demonstrating good performance owing to its internal curing effect and provision of nucleation sites. The lightweight and brittle nature of biochar can alleviate the burden on transportation and energy consumption compared to conventional fillers. Meanwhile, a high dosage of fillers (up to 60%) can make carbon-negative concrete feasible (Habert et al., 2020). Overall, biochar as a carbon-negative filler can revolutionise the construction industry by improving the properties of cement-based composites and environmental sustainability.

It is estimated that approximately 17.5 Gt of aggregates are utilised to manufacture concrete each year, whose crushing and transportation induce considerable CO_2 emissions (Miller et al., 2018). The over-extraction of natural aggregates (e.g., sand and gravel) has already caused massive environmental damage with cascading effects that affect human well-being. Crushing the demolition waste into smaller particles for reuse as recycled aggregates is a sustainable approach to reducing the CO_2 emissions associated with natural aggregates. The recycled aggregates with porous nature and increased surface area are suitable for CO_2 curing that can densify the matrix, enhance mechanical performance, and increase the lifetime CO_2 uptake (Habert et al., 2020). Accelerated carbonation is a promising approach for CO_2 mineralisation and performance enhancement of cementitious materials. The CO_2 utilisation potential of cementitious construction materials is expected to remove 100−1400 tonnes CO_2 by 2050 while generating the highest breakeven cost of US$70 per ton of CO_2 utilised (Hepburn et al., 2019). However, the carbonised areas are concentrated on the surface of cementitious materials due to the dense structure and closed pores, which under-utilise the decarbonisation potentials. Future research should intend to tailor the adsorption and desorption kinetics of different engineered biochar to control the CO_2 diffusion and regulate the crystalline forms of $CaCO_3$ (i.e., calcite, aragonite, and vaterite) for desirable interfacial chemistry and optimal performance.

3. Conclusions

Biochar is demonstrating its tremendous promise for applications in carbon-neutral/-negative construction materials and is contributing to the achievement of carbon neutrality targets. The incorporation of biochar derived from waste biomass in construction materials can mitigate CO_2 emissions and natural resource depletion whilst improving the mechanical performance and providing value-added merits for biochar construction materials. Biochar construction materials also offer environmental and technical advantages, such as hygrothermal regulation, electromagnetic shielding, contaminants immobilisation, indoor air quality improvement, self-healing capacity, and acoustic insulation. The versatility of biochar gives biochar construction materials the potential to revolutionise the industrial manufacture of conventional construction materials and become an advocate of sustainable and green development. We also highlight that tailoring the favourable physicochemical properties of engineered biochar based on adequate and scientific designs and advancing the scientific understanding of interfacial reactions in biochar construction materials would facilitate the large-scale development and widespread applications of biochar construction materials.

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