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Perspective

Biochar-Based Low-Carbon Construction Materials

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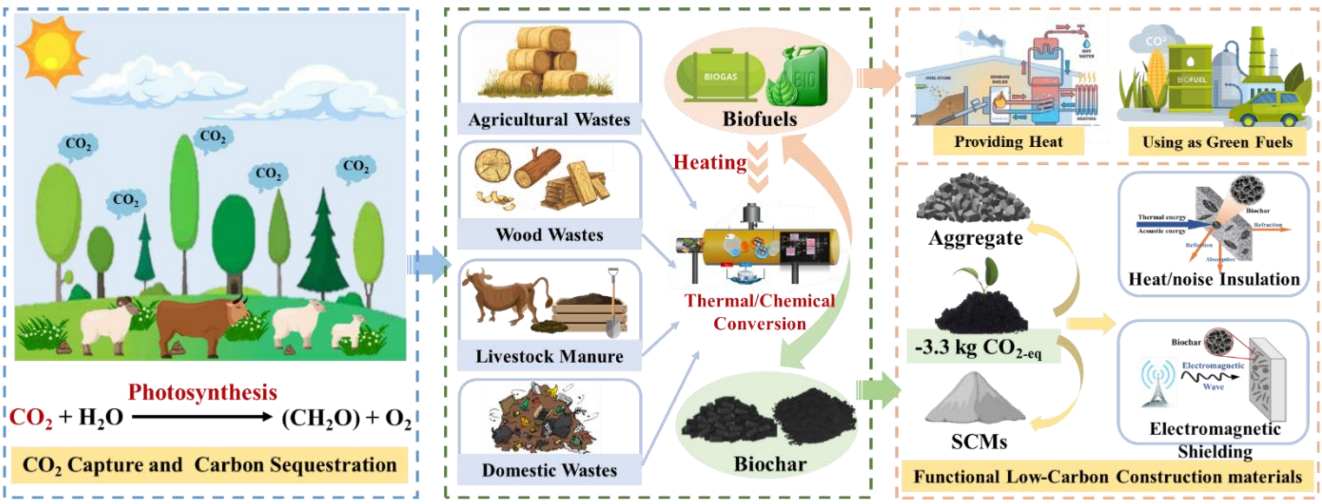
Standfirst: Construction sector is one of the largest contributors of global carbon emissions. To achieve carbon neutrality, it is urgent to promote the low-carbon transformation of the construction sector. Biochar is a typical carbon-negative material that can be used as a supplementary cementitious material or aggregate to reduce the carbon footprint of construction materials and promote cement hydration through the internal curing effect and filler effect. Biochar with a porous structure can promote the diffusion of carbon dioxide (CO_2) in concrete and improve carbonation efficiency. Moreover, the porous structure and high conductivity of biochar can make construction materials have special functions including thermal insulation, noise reduction and electromagnetic shielding. Therefore, recycling biochar into concrete is a promising approach to reduce the carbon footprint and enhance the performance of construction materials.

Keywords: waste recycling; biochar; climate-positive composites; functional construction materials; carbon neutrality

Graphical Abstract



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1. Urgency of Reducing Carbon Emission in the Construction Sector

With the growth of the global population and the acceleration of industrialization, global CO_2 emissions have reached alarming levels (approaching 40 billion tons annually) [1], triggering climate crisis. The construction sector, responsible for approximately 21% of global carbon emissions, is a significant contributor [2]. To address this challenge, many countries have taken measures aligned with the Paris Agreement to promote low-carbon transformation in the construction sector. For example, the European Union's Directive on the Energy Performance of Buildings mandated substantial energy efficiency improvements and zero-carbon standards for new constructions by 2030 [3]. Similarly, China's 14th Five-Year Plan emphasized green building standards and construction practices [4]. Therefore, it is urgent to promote low-carbon transformation of the construction sector and take effective carbon emission reduction measures.

The Global Building Climate Tracker (GBCT) is a UN Environment Programme tool to assess progress in decarbonizing the construction sector. The 2022 GBCT results showed that the current status was equivalent to 40 decarbonization points away from the required decarbonization path, among which there was a lack of significant progress in the decarbonization of construction materials [5]. Carbon emissions from construction materials accounted for approximately 40% of total emissions from the construction sector [2]. The development and application of lower-carbon and greener construction materials could significantly reduce carbon emissions in the construction sector. In recent years, utilizing bulk industrial solid wastes to develop low-carbon cementitious materials and reduce the use of cement clinker have become important measures to reduce carbon emissions from construction materials [6]. Furthermore, researchers used carbon-negative materials such as biochar as a supplementary cementitious material or aggregate to develop lower-carbon or even carbon-negative construction materials.

2. Using biochar to reduce carbon emissions from construction materials

Biochar is produced through the thermochemical conversion of various biomass sources, including agricultural residues, forestry waste, livestock manure, and municipal sludge, under anaerobic or oxygen-limited conditions [6]. And it features a highly porous structure, extensive surface area, and diverse surface functional groups, making it suitable for applications such as soil remediation and catalytic reactions [7]. In addition, it was found that biochar was a typical carbon-negative material through life cycle analysis, with a carbon footprint of $-2.0 \sim -3.3$ tone CO_2-equivalent per ton [8]. Biomass immobilizes atmospheric CO_2 through photosynthesis, which is subsequently sequestered in biochar during thermochemical conversion. The process also generates bio-oil and bio-gas, which can be utilized as fuels to achieve self-sustaining energy cycles, further minimizing energy consumption and emissions. Moreover, carbon in biochar remains stable for significantly longer periods than its biomass precursor, amplifying its carbon sequestration capacity [9].

Fine-grained biochar could serve as a supplementary cementitious material, while coarse-grained biochar could replace traditional aggregates in concrete. These applications significantly reduced construction materials' carbon footprint while improving mechanical properties through internal curing and filler effects [10]. The porous structure of biochar can temporarily retain water. When biochar is added to cement-based materials, moisture is gradually released due to osmotic pressure, restoring part of the moisture lost due to internal or external drying to improve the hydration reaction of cement. Additionally, the biochar with a large specific surface area can provide nucleation sites for heterogeneous nucleation of cement hydration products, further enhancing mechanical performance. A recent study showcased that climate-positive biochar was a carbon-negative additive for decreasing the carbon footprint of 3D printable concrete, while enhancing its performance [11].

In the natural environment, cement-based materials can absorb CO_2 from the surroundings through a process known as carbonation. CO_2 diffused into the pore solution of concrete and then reacted with calcium hydroxide and hydration products, resulting in the formation of stable calcium carbonate precipitation [12]. However, the carbonation reaction between CO_2 and cement-based materials was a diffusion-controlled process. Continuous carbonation led to the formation of a dense carbonate film within the cement clinker, impeding further diffusion of CO_2 and carbonation reactions. Biochar's porous structure mitigated this issue by promoting CO_2 diffusion and improving carbonation efficiency [13]. Moreover, the resulting carbonates fill biochar pores, strengthening the interfacial bonding between biochar and the cement matrix. Additionally, the high specific surface area of biochar and its affinity for non-polar compounds enabled it to adsorb and store CO_2 within the concrete [7].

3. Prospects of biochar-based construction materials

Although the addition of biochar could significantly reduce carbon emissions, the high-dose incorporation of biochar caused a significant decrease in the mechanical properties of construction materials [14,15]. Qing et al. [16] found that with the increase in corn stalk biochar content from 1 wt.% to 15 wt.%, the compressive strength of biochar-modified concrete showed a trend of first increasing and then decreasing. Small-dose incorporation of biochar could fill the pores and make the specimen denser due to the filler effect. However, when the biochar content was too high (>5 wt.%), the density of the construction material was significantly reduced due to biochar's high porosity and brittleness [10]. In addition, high-dose incorporation of biochar would weaken the boning with the cement matrix and cause a large number of pores and defects in the interface transition zone (ITZ), affecting the development of the mechanical properties [17]. Therefore, how to increase the proportion of biochar in construction materials to further reduce carbon emissions while ensuring that the mechanical properties meet application requirements is an urgent challenge. Recently, studies showed that the mechanical properties of construction materials could be improved by loading calcium on the biochar surface to react with the cement matrix. Xu et al. [18] used shell waste to modify wood biochar via ball milling to enhance the compatibility of biochar with cement and found that the compressive strength of cement-based composites with 30 wt.% of the modified biochar incorporation increased by 58.2%. Additionally, Chen et al. [19] found that the accelerated carbonation curing could form a hard calcium carbonate "shell" on the surface of biochar and make ITZ denser, thereby enhancing the mechanical strength. Future research should focus on enhancing the durability and service life of cement-based composites with large-dose incorporation of biochar [10,20].

On the other hand, the porous structure, large specific surface area and high conductivity of biochar could be used to develop construction materials with special functions including thermal insulation, noise reduction, and electromagnetic shielding [6,21]. The introduction of 6wt% sugarcane biochar resulted in a 45% reduction in the thermal conductivity of the specimens [22]. When porous biochar was evenly distributed in concrete, the pores in the biochar would destroy the thermal bridge and induce the dispersed propagation of heat, enhancing the thermal insulation capacity [23]. At the same time, biochar could create an interconnected pore network in construction materials. When sound waves entered these pores, they would continue to refract and eventually dissipate into heat energy, thereby enhancing sound absorption and noise reduction capabilities [24]. In addition, researchers found that incorporating biochar into cement-based materials could also provide electromagnetic shielding effects, especially in the micro-range [25]. The electromagnetic shielding performance may be related to the crystallization produced during the pyrolysis process of biochar, the dissipation of surface currents, and polarization in an electric field [6,26]. However, the above explanations for the special functionalities of biochar-based construction materials are mostly based on empirical speculation and need further in-depth research. Furthermore, the special functionalities of biochar-based composites also need to be developed to enhance the market competitiveness of biochar-based construction materials.

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References

[1] International Energy Agency (IEA). 2023. World Energy Outlook 2024. https://www.iea.org/reports/world-energy-outlook-2024

[2] United Nations Environment Programme. 2024. Global

Status Report for Buildings and Construction: Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector. Nairobi. https://wedocs.unep.org/20.500.11822/45095

[3] European Union (EU). 2018. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance). http://data.europa.eu/eli/dir/2018/844/oj

[4] National Development and Reform Commission of China. 2021. 14th Five-Year Plan for Ecological and Environmental Protection. https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202103/P020210323538797779059.pdf

[5] Intergovernmental Panel on Climate Change (IPCC) (ed.). 2023. Buildings. In Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 953 – 1048. https://doi.org/10.1017/9781009157926.011

[6] Zhang, Y.Y., He, M.J., Wang, L., Yan, J.H., Ma, B., Zhu, X.H., Ok, Y.S., Mechtcherine, V., Tsang, D.C.W. 2022. Biochar as construction materials for achieving carbon neutrality. *Biochar*. 4, 59. https://doi.org/10.1007/s42773-022-00182-x

[7] Zaid, O., Alsharari, F., Ahmed, M. 2024. Utilization of engineered biochar as a binder in carbon negative cement-based composites: A review. *Constr. Build, Master.* 417, 135246. https://doi.org/10.1016/j.conbuildmat.2024.135246

[8] Wang, L., Nerella, V.N., Li, D.M., Zhang, Y.Y., Ma, B., Ivaniuk, E., Zhang, J.Y., Zhu, X.H., Yan, J.H., Mechtcherine, V., Tsang, D.C.W. 2024. Biochar-augmented climate-positive 3D printable concrete. *Commun. Mater*. 5, 257. https://doi.org/10.1038/s43246-024-00700-3

[9] Chen, L., Zhu, X.H., Zheng, Y., Wang, L., Poon, C.S., Tsang, D.C.W. 2024. Development of high-strength lightweight concrete by utilization food waste digestate based biochar aggregate. *Constr. Build. Mater.* 411, 134142.
https://doi.org/10.1016/j.conbuildmat.2023.134142

[10] Chen, L., Zhang, Y.Y., Wang, L., Ruan, S.Q., Chen, J.F., Li, H.Y., Yang, J., Mechtcherine, V., Tsang, D.C.W. 2022. Biochar-augmented carbon-negative concrete. *Chem. Eng. J.* 431, 133946. https://doi.org/10.1016/j.cej.2021.133946

[11] Wang, L., Nerella, V.N., Li, D., Zhang, Y.Y., Ma, B., Ivaniuk, E., Zhang, J.Y., Zhu, X.H., Yan, J.H., Mechtcherine, V., Tsang, D.C.W. 2024. Biochar-augmented climate-positive 3D printable concrete. *Commun. Mater.* 257. https://doi.org/10.1038/s43246-024-00700-3

[12] Wang, L., Chen, L., Provis, J.L., Tsang, D.C.W., Poon, C.S. 2020. Accelerated carbonation of reactive MgO and Portland cement blends under flowing CO_2 gas. *Cement Concrete Comp.* 106, 103489. https://doi.org/10.1016/j.cemconcomp.2019.103489

[13] Wang, L., Chen, L., Poon, C.S., Wang, C.H., Ok, Y.S., Mechtcherine, V., Tsang, D.C.W. 2021. Roles of biochar and CO_2 curing in sustainable magnesia cement-based composites. *ACS Sustain. Chem. Eng.* 9, 8603 – 8610. https://doi.org/10.1021/acssuschemeng.1c02008

[14] Gupta, S., Tulliani, J.M., Kua, H.W. 2022. Carbonaceous admixtures in cementitious building materials: Effect of particle size blending on rheology, packing, early age properties and processing energy demand. *Sci. Total Environ.* 807, 150884. https://doi.org/10.1016/j.scitotenv.2021.150884

[15] Wang, L., Chen, L. Tsang, D.C.W., Guo, B.L., Yang, J., Shen, Z.T., Hou, D.Y., Ok, Y.S. Poon, C.S. 2020. Biochar as green additives in cement-based composites with carbon dioxide curing. *J. Clean. Prod.* 258, 120678. https://doi.org/10.1016/j.jclepro.2020.120678

[16] Qing, L.B., Zhang, H., Zhang, Z.K. 2023. Effect of biochar on compressive strength and fracture performance of concrete. *J. Build. Eng.* 78, 107587. https://doi.org/10.1016/j.jobe.2023.107587

[17] Zhu, X.H., Zhang, Y.Y., Chen, L., Wang, L., Ma, B., Li, J.Q., Poon, C.S., Tsang, D.C.W. 2023. Bonding mechanisms and micro-mechanical properties of the interfacial transition zone (ITZ) between biochar and paste in carbon-sink cement-based composites. *Cement Concrete Comp.* 139, 105004. https://doi.org/10.1016/j.cemconcomp.2023.105004

[18] Xu, W.J., Zhang, Y.Y., Su, Y.L., Zhu, X.H., Wang, L., Tsang, D.C.W. 2024. Using waste to improve the weak: Recycled seashell as an ideal way to regulate the interfacial transition zone in biochar-cement composites. *Constr. Build. Mater.* 444, 137765. https://doi.org/10.1016/j.conbuildmat.2024.137765

[19] Chen, L., Zhu, X.H., Zhang, Y.Y., Wang, L., Ma, B., Zheng, Y., Poon, C.S., Yan, J.H., Tsang, D.C.W. 2024. Carbonation-enhanced interfacial transition zone in

biochar-cement mortar. *Constr. Build. Mater.* 451, 138606. https://doi.org/10.1016/j.conbuildmat.2024.138606

[20] Qu, F.L., Zhang, Y.Y., Zhu, X.H., Xu, W.J., Poon, C.S., Li, W.G., Tsang, D.C.W., 2024. Roles of wood waste biochar for chloride immobilization in GGBS-blended cement composites. *Constr. Build. Mater.* 411, 134389. https://doi.org/10.1016/j.conbuildmat.2023.134389

[21] Park, J.H., Kim, Y.U., Jeon, J., Yun, B.Y., Kang, Y.J., Kim, S. 2021. Analysis of biochar-mortar composite as a humidity control material to improve the building energy and hygrothermal performance. *Sci. Total Environ.* 775, 145552. https://doi.org/10.1016/j.scitotenv.2021.145552

[22] Rodier, L., Bilba, K., Onesippe, C., Arsene, M.A. 2019. Utilization of bio-chars from sugarcane bagasse pyrolysis in cement-based composites. *Ind. Crops Prod.* 141, 111731. https://doi.org/10.1016/j.indcrop.2019.111731

[23] Cuthbertson, D., Berardi, U., Briens, C., Berruti, F. 2019. Biochar from residual biomass as a concrete filler for improved thermal and acoustic properties. *Biomass Bioenergy.* 120, 77–83. https://doi.org/10.1016/j.biombioe.2018.11.007

[24] Xiong, T., Ok, Y.S., Dissanayake, P.D., Tsang, D.C.W., Kim, S., Kua, H.W., Shah, K.W. 2022. Preparation and thermal conductivity enhancement of a paraffin wax-based composite phase change material doped with garlic stem biochar microparticles. *Sci. Total Environ.* 827, 154341. https://doi.org/10.1016/j.scitotenv.2022.154341

[25] Natalio, F., Corrales, T.P., Feldman, Y., Lew, B., Graber., E.R. 2020. Sustainable lightweight biochar-based composites with electromagnetic shielding properties. *ACS Omega.* 5, 32490–32497. https://doi.org/10.1021/acsomega.0c04639

[26] Khushnood, R.A., Ahmad, S., Savi, P., Tulliani, J.M., Giorcelli, M., Ferro., G.A. 2015. Improvement in electromagnetic interference shielding effectiveness of cement composites using carbonaceous nano/micro inerts. *Constr. Build. Master.* 85, 208–216. https://doi.org/10.1016/j.conbuildmat.2015.03.069