

WASTE-DERIVED BIOCHAR AND GGBS FOR LOW-CARBON CONCRETE: A RESOURCE MANAGEMENT APPROACH

Prof. Reena Pantawane ^{*1}, Jagruti Joshi ², Sayali Purbhe ³

^{*1} Head of Department (HOD), Department of Civil Engineering, Jawaharlal Darda Institute of Engineering and Technology, Yavatmal, Maharashtra, India .

hod_civil@jdiet.ac.in

² Student , Department of Civil Engineering, Jawaharlal Darda Institute of Engineering and Technology, Yavatmal, Maharashtra, India

jagrutijoshi251@gmail.com

³ Student , Department of Civil Engineering, Jawaharlal Darda Institute of Engineering and Technology, Yavatmal, Maharashtra, India

sayalipurbhe428@gmail.com

ABSTRACT

Growing quantities of biomass residues and industrial by-products create challenges for waste management, while ordinary Portland cement concrete has a considerable environmental impact. This review examines the potential of combining waste-derived biochar with ground granulated blast furnace slag (GGBS) to support lower-carbon cementitious materials and more effective resource use. Biochar is produced by heating biomass under limited oxygen and may act as a fine filler, support internal curing, modify pore structure and retain biogenic carbon. GGBS is an industrial by-product that can replace a portion of the cementitious binder and reduce clinker demand. The reviewed literature indicates that the performance of biochar-modified concrete depends on feedstock, pyrolysis conditions, particle characteristics and dosage. Low biochar contents have been associated with improvements in selected strength and water-absorption results, whereas higher contents may increase water demand and porosity and reduce performance. One study reported that 2% biochar by weight increased compressive strength by 18.95%, splitting tensile strength by 19.64% and flexural strength by 12% relative to its control mix; these values are findings reported in the literature, not results of the present work. Research also identifies durability, chloride immobilisation, microstructure, life-cycle assessment and cost as important areas for further investigation. The review highlights gaps in the comparability of biochar materials, understanding of biochar–GGBS interactions, long-term performance and standardised testing. A proposed research framework is presented to compare a control mixture with selected biochar and GGBS combinations. It considers fresh and hardened properties, durability, waste utilisation, estimated greenhouse-gas impacts and cost rather than strength alone. The paper is a literature synthesis and proposed framework; no original laboratory results are claimed. The approach is intended to guide future experimental work on resource-efficient, lower-carbon construction materials.

Keywords: waste management; biochar; GGBS; sustainable concrete; waste valorisation; carbon sequestration; circular economy; resource optimisation.

1. INTRODUCTION

The quantity of waste generated is increasing as cities expand, industry grows and consumption patterns change. Agricultural residues, other biomass leftovers and industrial by-products are often discarded even though they may be converted into useful resources. Resource management therefore needs to move from a take-use-dispose approach towards recovery, reuse and value addition.

The construction industry offers opportunities to use waste-derived materials. Concrete requires cement and natural resources, while cement production contributes greenhouse-gas emissions. Replacing a portion of conventional binder with suitable secondary materials can reduce demand for new resources and provide a useful application for waste.

Biochar is a carbon-rich solid produced by heating biomass with limited oxygen. Its porous structure, water-retention capacity and relatively stable carbon content have led to research into its use in cement-based materials. The effect is dosage-dependent: an appropriate amount may fill small voids and support internal curing, while excessive addition may increase water demand and porosity.

Ground granulated blast furnace slag (GGBS), a by-product of iron production, is commonly used as a supplementary cementitious material. Combining biochar with GGBS may use two waste streams for different purposes: GGBS can reduce clinker demand, while biochar may modify pore structure and retain carbon. This review summarises the available evidence, identifies research gaps and proposes a framework for evaluating engineering and environmental performance.

1.1 Aim and scope

The aim is to review the reported use of waste-derived biochar and GGBS in cement-based materials and to outline a practical research framework. The discussion focuses on mechanical performance, durability, microstructure, environmental assessment, resource utilisation and cost.

1.2 Review approach

The paper synthesises the studies and references listed in the source manuscript. Their reported findings are described as literature evidence. The experimental mix matrix and testing programme presented later are proposed work and should not be interpreted as completed laboratory research.

2. LITERATURE REVIEW

2.1 Biochar and solid waste valorisation

Studies describe biochar as a way to convert biomass residues into a potentially useful product. Its properties depend on the feedstock and production conditions, including pyrolysis temperature and residence time. Therefore, biochar should not be treated as a single uniform material; feedstock and processing details are important when comparing results. Reviews published in 2024–2025 identify strength, durability, microstructure, carbon storage, life-cycle assessment and cost as important research areas. The environmental benefit also depends on the complete pathway from collection and drying through pyrolysis, processing and transport.

2.2 Mechanical performance

The effect of biochar on concrete depends strongly on dosage. At low contents, biochar may fill small spaces and support internal curing because of its porous structure. The reported changes are associated with pore filling, water availability and changes in cement hydration. In a 2025 study discussed in the source manuscript, 2 wt% biochar increased compressive strength by 18.95%, splitting tensile strength by 19.64% and flexural strength by 12% compared with the control mixture. These are literature values and apply to that study's materials and test conditions. At higher contents, biochar may raise water demand, reduce workability and introduce additional pores, potentially weakening the material.

2.3 Durability and microstructure

Durability is essential for practical structural use. Some studies report lower water absorption and drying shrinkage at selected biochar contents, but long-term evidence remains limited compared with short-term strength data. Research on wood-waste biochar in GGBS-blended cement composites has also investigated chloride immobilisation. Scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), X-ray diffraction (XRD) and pore analysis can help examine hydration products and pore structure. These investigations are important because the water-retention characteristics of biochar may be beneficial at an appropriate dosage but harmful if they lead to excessive porosity.

2.4 Environmental performance and resource management

The environmental case for biochar–GGBS concrete includes diverting biomass and industrial by-products from disposal, reducing Portland cement use and retaining biogenic carbon in a durable material. However, carbon claims should include emissions associated with collection, drying, pyrolysis, grinding, transport, concrete production and end-of-life assumptions. A life-cycle assessment (LCA) is needed before describing a mixture as carbon-neutral or carbon-negative. The best mixture should be judged on engineering performance and resource and environmental efficiency together.

2.5 Summary of selected studies

The studies listed below cover biochar performance, sustainable cement composites, waste management, durability and data-driven mix optimisation. The descriptions are based on the summaries and references provided in the source manuscript.

Author(s), year	Focus reported in the source paper	Relevance to this review
Patel, Stobbs and Acharya (2025)	Biochar in green concrete composites; workability, strength and microstructure.	Supports the use of low biochar contents as filler/curing aid.
Kiran et al. (2025)	Strength, durability and carbon sequestration in cement-based materials.	Connects engineering performance with carbon storage.

Murali and Wong (2024)	Review of biochar concrete and microstructural behaviour.	Highlights feedstock, pyrolysis and dosage effects.
Room and Bahadori-Jahromi (2024)	Scientometric review of biochar-enhanced cement composites.	Identifies research growth and gaps in durability and standardisation.
Ahmed et al. (2025)	Functionalised biochar for cementitious composites.	Considers treatment to improve dispersion and performance.
Nanda and Berruti (2021); Chen et al. (2024)	Waste management, biomaterials and building-sector policy.	Provides resource-management and adoption context.
Tayebani, Said and Memari (2023)	Environmental and performance perspectives on lower-carbon concrete.	Supports assessment of both emissions and practical performance.
Naik et al. (2025); Huang et al. (2025); Parhi et al. (2025)	Waste-glass concrete and machine-learning approaches to low-carbon mix design.	Provides methods relevant to data-driven optimisation of variable waste materials.
Qu et al. (2024)	Wood-waste biochar for chloride immobilisation in GGBS-blended cement composites.	Relevant to durability and chloride-related performance.

Table 1. Summary of selected studies discussed in the source manuscript.

3. RESEARCH GAP AND PROPOSED FRAMEWORK

3.1 Research gap

The reviewed literature indicates several gaps. First, biochar properties vary with feedstock and pyrolysis conditions, making direct comparison between studies difficult. Second, the interactions between biochar and GGBS hydration products require further investigation. Third, long-term durability data are limited compared with early-age strength results. Fourth, environmental assessments do not always use consistent system boundaries. Finally, standardised testing and optimisation methods that balance strength, durability, carbon impact, waste utilisation and cost are still needed.

3.2 Proposed research methodology

The proposed laboratory framework begins with biomass waste drying and size reduction, followed by controlled pyrolysis. The biochar would be cooled, ground, sieved and characterised. GGBS would be used as a supplementary cementitious material. Exact proportions should be finalised using the applicable mix-design standard and the materials available in the laboratory.

Mix ID	Biochar replacement	GGBS replacement	Purpose
C0	0%	0%	Control mixture
G1	0%	20%	GGBS reference
B1	1%	20%	Low biochar content
B2	2%	20%	Optimum candidate for evaluation
B3	3%	20%	Higher biochar content
B4	2%	30%	Higher GGBS content

Table 2. Proposed experimental mix matrix. Replacement percentages and the final mix design must be confirmed before testing.

Fresh concrete tests should include workability and density. Hardened-state tests should measure strength at suitable curing ages and, where facilities permit, splitting tensile and flexural strength. Durability tests should include water absorption and sorptivity; chloride penetration and carbonation may be added for a more extensive study. SEM, EDS and XRD may be used for microstructural examination where facilities are available.

The environmental assessment should estimate cement saved, waste utilised and greenhouse-gas impacts. An LCA should include feedstock collection, drying, pyrolysis, grinding, transport, concrete production and end-of-life assumptions. The selected mixture should be based on multiple criteria rather than compressive strength alone.

3.3 Resource-management framework

The proposed pathway is: biomass waste → preprocessing → pyrolysis → biochar; industrial by-product → GGBS; and biochar + GGBS + cementitious binder → sustainable concrete. This pathway aims to turn two waste streams into construction resources and reduce reliance on virgin inputs. Five dimensions should be considered together: mechanical performance, durability, waste utilisation, carbon impact and cost.

3.4 Discussion

The evidence reviewed suggests that optimised low biochar contents may be more promising than simply maximising the amount of waste added. GGBS provides a route to reduce cement demand, while biochar may influence pore structure and carbon storage. The main scientific opportunity is to connect biochar characteristics and GGBS content with hydration, pore structure, durability and environmental performance. Once genuine experimental data are available, statistical or machine-learning models could be explored to predict performance and identify a balanced mixture.

The present paper separates published findings from proposed work. It does not report laboratory measurements. If a submission category requires original experimental research, the methodology must be completed and supported with genuine results before submission.

3.5 Expected outcomes and limitations

The proposed work is expected to establish a practical route for using biomass residues in construction, reduce dependence on conventional cement through GGBS, identify a suitable low-biochar range, improve understanding of the relationship between dosage, pore structure and durability, estimate waste utilisation and potential carbon benefits, and provide a basis for multi-objective optimisation.

This paper is a literature synthesis and proposed research framework, not an experimental study. Reported values are literature findings. Differences in feedstock, pyrolysis conditions, cement chemistry, water-to-binder ratio, curing regime and test standards can influence performance; therefore, numerical comparisons between studies should be made cautiously.

4. CONCLUSIONS

Waste-derived biochar and GGBS offer a potential route for linking solid-waste management with sustainable construction. Biochar converts biomass residues into a carbon-rich material that may provide filler and internal-curing functions, while GGBS can utilise an industrial by-product and reduce clinker demand. The literature indicates that low biochar contents may improve selected strength or water-absorption characteristics, whereas excessive contents may increase porosity and reduce performance.

Further work should optimise strength, durability, waste utilisation, carbon impact and cost together. Long-term durability testing, investigation of biochar–GGBS interactions, consistent biochar characterisation and life-cycle assessment are important next steps. The proposed framework provides a basis for future experiments; original laboratory data are required before making claims about the performance of the authors' own mixtures.

5. FUTURE SCOPE

- Compare agricultural and other suitable biomass feedstocks.
- Study the influence of pyrolysis temperature and residence time on concrete performance.
- Investigate hydration and microstructural interactions in biochar–GGBS systems.
- Conduct long-term studies on chloride ingress, carbonation, sulphate exposure and shrinkage.
- Perform life-cycle and techno-economic assessments.
- Develop standardised procedures for construction-grade biochar.
- Use experimental datasets for machine-learning-based multi-objective optimisation.
- Validate optimised mixtures at pilot scale.

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