International Journal of Advanced Research in Engineering and Related Sciences

OPEN ACCESS

Available online at: www.ijarers.com

VOL 1 ISSUE 8 (01-08)

Integrating Microbial and Biomass Technologies for the Development of Sustainable Bio-Based Concrete

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Abstract

The construction industry is a major contributor to carbon emissions and resource depletion, which makes it essential to develop sustainable alternatives to conventional concrete. This study investigates the potential of bio-based improvements, focusing on microbial induced calcite precipitation, algae-based carbon dioxide sequestration, and biochar incorporation. Microbial induced calcite precipitation uses Sporosarcina pasteurii to form calcium carbonate within the concrete matrix, enhancing self-healing ability and structural strength. Algae-based admixtures derived from Chlorella vulgaris promote natural carbon absorption during curing and improve hydration and setting characteristics. Biochar produced from agricultural residues serves as a carbon storage additive that enhances durability, thermal performance, and water retention.

Four concrete mixes were prepared and examined for compressive and flexural strength, permeability, water absorption, and environmental performance. The experimental results showed that bio-enhanced concretes achieved superior mechanical strength and lower carbon impact compared to the control mix, with microbial concrete showing about fifteen percent higher compressive strength and biochar concrete exhibiting a twenty percent reduction in water absorption. These findings demonstrate that integrating biological and biomass-based materials into concrete production can create durable, self-improving, and environmentally responsible construction materials suitable for sustainable infrastructure.

Keywords Sustainable concrete, bio-based materials, microbial induced calcite precipitation, algae-based carbon sequestration, biochar additives, self-healing concrete, carbon reduction in construction, green infrastructure

INTRODUCTION

Concrete forms the foundational material of modern civilization, prized for its compressive strength, versatility, and economic practicality, making it the undeniable backbone of global infrastructure. However, this ubiquitous material carries a heavy and increasingly unsustainable environmental cost. The production of Ordinary Portland Cement (OPC), the primary binder in concrete, is a major contributor to climate change, accounting for approximately 8% of worldwide C02 emissions. These emissions are largely a result of the high temperature calcination of limestone and the combustion of fossil fuels during processing. Compounding this issue, the intensive extraction of raw materials, namely sand, gravel, and water, further contributes to ecological degradation and imbalance. With accelerating global urbanization and ever-growing infrastructure demands, a critical shift is needed to adopt alternative construction paradigms that effectively harmonize structural performance with environmental sustainability. Beyond its environmental footprint, conventional concrete is plagued by inherent technical vulnerabilities. It is characteristically brittle and highly susceptible to the formation of microcracks. Over time, these microfractures critically compromise the material's structural integrity, dramatically increase its permeability to aggressive agents, and necessitate costly, resource intensive maintenance and repairs. These profound challenges highlight an urgent need for advanced materials that not only significantly reduce environmental impact but also fundamentally enhance durability, extend longevity, and introduce a capacity for self-repair. In direct response to this need, the strategic integration of bio-based enhancements into concrete production has emerged as a revolutionary and highly promising pathway. This innovation is key to aligning contemporary civil engineering practices with the core principles of a circular economy and sustainable, low carbon development. Bio based concrete represents a new class of materials that incorporates biological or biomass derived components to significantly upgrade the physical, chemical, and environmental performance of traditional concrete. Among the most impactful biotechnological strategies currently gaining traction are Microbial Induced Calcite Precipitation (MICP), Algae Based CO2 Sequestration, and the use of Biochar Additives. These cutting-edge technologies harness natural biological processes and utilize renewable resources to achieve multiple benefits: they enhance mechanical properties, activate intrinsic self-healing mechanisms, and actively reduce the concrete's carbon footprint both during and after the critical curing phase. Microbial Induced Calcite Precipitation (MICP) is an elegant process leveraging urease producing bacteria, most notably Sporosarcina pasteurii, to precipitate robust calcium carbonate (CaCO3) within the concrete matrix. Through a process called ureolytic hydrolysis, these bacteria catalyze the biomineralization of calcite crystals, which effectively fill internal pores and newly formed microcracks. This dramatically boosts both structural integrity and impermeability. MICP treated concrete demonstrates marked improvements in compressive strength, water resistance, and autogenous healing capacity. Crucially, this bio mineralization method is environmentally benign and occurs under mild, ambient conditions, positioning it as a scalable and highly sustainable alternative to traditional chemical sealants. In parallel, algae-based admixtures are quickly being recognized as powerful, natural carbon sequestration agents. Microalgae species, such as Chlorella vulgaris, efficiently absorb atmospheric CO2 through photosynthesis, converting it into organic biomass rich in valuable minerals and biopolymers. These compounds are processed into effective admixtures that can fine tune hydration kinetics, setting time, and strength development. More significantly, during the concrete's curing phase, the algae infused matrix continues to capture additional CO2, directly offsetting emissions from the original cement production. This "living concrete" approach introduces a revolutionary dimension of functionality by seamlessly merging ecological benefits with superior mechanical performance. Complementing these innovations is biochar, a highly stable, carbon rich residue created from the pyrolysis of agricultural and wood waste. When biochar is utilized as a partial substitute for cement or aggregates, it improves the concrete's porosity regulation, thermal insulation, and water retention characteristics. Most critically, it functions as a long-term carbon sink, permanently sequestering atmospheric carbon that would otherwise contribute to global warming. By valorizing waste biomass, biochar modified concrete promotes sustainable waste management and strengthens the principles of a truly circular economy in construction. Collectively, these bio-based enhancements establish a powerful triad of sustainable strategies that fundamentally transform concrete into a smart, self-healing, and carbon conscious construction material. Their synergistic application has the potential to entirely redefine how modern infrastructure is conceived and built, becoming indispensable for achieving climate resilience goals and meeting stringent green building certification standards (e.g., LEED, BREEAM). The central objective of this research is to systematically evaluate and quantify the performance of concrete enhanced with MICP, algae-based admixtures, and biochar. Formulations are rigorously analyzed across key metrics: compressive strength, flexural strength, water permeability, carbon sequestration, and crucial self-healing capabilities. By performing comparative assessments against conventional concrete and integrating experimental data with robust life cycle performance indicators, this study provides a crucial, evidence-based foundation for the widespread, large-scale adoption of bio-based concrete in a new era of sustainable construction. This paper thus contributes a novel framework for designing next generation green infrastructure, proving that through interdisciplinary innovation at the intersection of microbiology, materials science, and structural engineering, the future of concrete can be not only stronger, but also smarter and definitively more sustainable.

MATERIALS AND METHOD

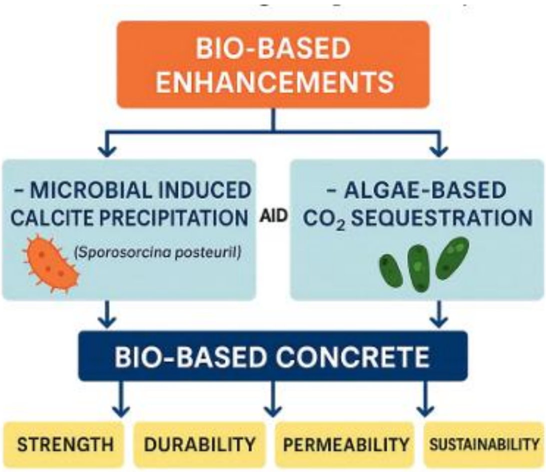

Figure 1: Schematic Architecture of Bio-Based

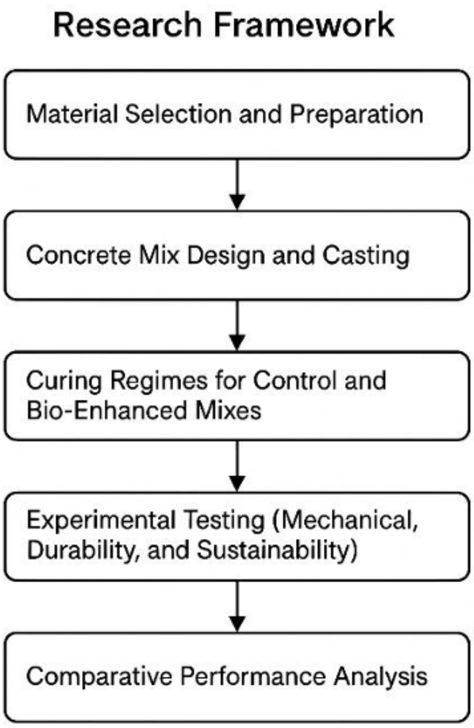

Figure 2: Research Framework for Bio-Based

3.1 Materials Used

The research employed a systematic five-phase framework to investigate the mechanical, durability, and sustainability performance of bio-enhanced concrete by comparing four distinct mixes.

3.1.1 Material Selection and Preparation

A. Cement and Aggregates

- **Cement:** Ordinary Portland Cement (OPC) 53 Grade (IS 12269:2013).
- **Fine Aggregate:** Natural river sand conforming to Zone II of IS 383.
- **Coarse Aggregate:** Crushed granite aggregates with a nominal size of 20 mm, satisfying IS 383.
- **Water:** Clean, potable water was used for all concrete mixes.

B. Bio-Components

i. Microbial Agent (MICP)

- Bacterium: *Sporosarcina pasteurii* (ureolytic bacterium).
- Growth Medium: Contained peptone, beef extract, urea, and $CaCl_2$.
- Culture Conditions: Incubated at **30 °C** until an optical density of $OD_{600} \approx 1.0$ was achieved.
- Preparation: Cultures were centrifuged and resuspended in sterile saline before being introduced into the concrete mix.

ii. Algae-Based Additive

- Species: *Chlorella vulgaris* (selected for high CO_2 uptake).
- Cultivation: Grown in Bold's Basal Medium under continuous illumination with CO_2 aeration (5–10%).
- Processing: Biomass was harvested, dried at 60 °C, and ground to a fine powder (< 75 µm).
- Application: Used as a partial cement replacement by weight.

iii. Biochar

- Feedstock: Rice husk and sugarcane bagasse.
- Production: Pyrolyzed at **450–500 °C** in an oxygen-limited environment.
- Preparation: Ground and sieved to a particle size of < 75 µm.
- Characterization: Evaluated for surface area, porosity, and microstructure.

3.1.2 Mix Design, Casting, and Curing Regimes

Four concrete mixes were prepared, maintaining constant fine-to-coarse aggregate ratios and a fixed **water–cement ratio**.

Mix ID	Mix Composition	Bio-Component Dosage
M1	Control Mix	0%
M2	MICP Enhanced	5% bacterial solution (replacing part of mixing water)
M3	Algae Enhanced	3% algae biomass (cement replacement by weight)
M4	Biochar Enhanced	2% biochar (cement replacement by weight)

A. Mixing and Casting

- Dry components were mixed for **2 minutes** prior to the addition of water or bacterial solution.
- Mixing continued for an additional **3 minutes** to ensure uniform consistency.
- **Specimens cast:**
  - **Cubes:** 100 mm × 100 mm × 100 mm for compressive strength testing.
  - **Beams:** 100 mm × 100 mm × 500 mm for flexural strength testing.

Mix ID	Description	Cement (%)	MICP (%)	Algae (%)	Biochar (%)	w/c Ratio
M1	Control (Conventional)	100	0	0	0	0.45
M2	MICP-Enhanced	100	5	0	0	0.45
M3	Algae-Modified	100	0	3	0	0.45
M4	Biochar-Modified	98	0	0	2	0.45

B. Curing Regimes

Specific curing conditions were applied to enhance bio-component activity:

- M1 & M4: Standard water curing for 28 days.
- M2 (MICP): Sprayed with fresh bacterial solution every 3 days for 28 days to facilitate calcite precipitation.
- M3 (Algae): Cured in a CO_2-controlled chamber (5% concentration) to promote CO_2 sequestration by algae.

3.2 Experimental Testing and Analysis

All results were obtained by averaging readings from three identical specimens. Testing was categorized into three key domains:

3.2.1 Mechanical Testing

- Compressive Strength: Measured at 7, 14, and 28 days using a 2000 kN Universal Testing Machine (UTM) in accordance with IS 516.
- Flexural Strength: Tested on 500 mm beam specimens using the third-point loading method.

3.2.2 Durability Testing

- **Water Absorption:** Determined by measuring moisture uptake after drying, soaking for 24 hours, and reweighing.
- **Permeability:** Measured using Darcy's Law under constant head conditions.
- **Carbonation Depth:** Assessed in an accelerated CO_2 chamber (5% CO_2) after 28 days to evaluate carbonation resistance.

3.2.3 Sustainability Metrics

- **CO_2 Sequestration:**
  - *MICP:* Estimated from the mass of calcite formed (quantified via XRD).
  - *Algae:* Calculated from the carbon content of algae biomass captured during curing.
  - *Biochar:* Derived from the fixed carbon mass within the biochar additive.
- **Energy Analysis:** Compared embodied energy and energy savings achieved through bio-material use relative to OPC.
- **Life Cycle Assessment (LCA):**
  - Conducted a cradle-to-gate evaluation of greenhouse gas (GHG) emissions using SimaPro software.

3.3 Comparative Performance Analysis

The bio-enhanced mixes (M2, M3, and M4) were benchmarked against the control mix (M1) using relative performance indicators to quantify improvements in:

- Strength
- Durability
- CO_2 sequestration efficiency

RESULTS

The experimental results demonstrate that the integration of bio-based materials successfully enhanced the performance of concrete across mechanical strength, durability, and environmental sustainability parameters when compared to the control mix (M1).

A. Mechanical Performance

The MICP-enhanced concrete (M2) achieved the highest mechanical gain, exhibiting approximately 15% higher compressive strength at 28 days compared to the control. This improvement is attributed to the biological precipitation of calcite ($CaCO_3$) crystals by Sporosarcina pasteurii, which effectively filled micro-pores and densified the cement matrix.

The Algae-modified mix (M3) also demonstrated notable improvement, with a 10% increase in 28-day compressive strength. The presence of algae biomass was observed to accelerate early hydration kinetics, thereby reducing the time required for strength development.

The Biochar-modified mix (M4) recorded a moderate strength increase of approximately 12%, which, although slightly lower than M2, still represents a substantial enhancement over the control mix. The improvement is primarily attributed to the micro-porous structure of biochar, which provided internal curing and enhanced the microstructural integrity of the cementitious matrix.

B. Durability Performance

Durability performance improved significantly across all bio-enhanced mixes relative to the control (M1).

- M2 (MICP) exhibited an 18% reduction in water absorption, confirming its denser microstructure due to calcite formation within capillary voids.
- M3 (Algae) showed a 12% reduction in water absorption, indicating improved pore refinement and reduced permeability.
- M4 (Biochar) excelled in durability, demonstrating a 20% reduction in permeability and improved thermal resistance compared to the control. The internal pore network of biochar effectively regulated moisture transport and minimized micro-crack propagation.

C. Sustainability and Environmental Impact

From a sustainability perspective, all bio-modified concretes (M2–M4) contributed to carbon footprint reduction and environmental performance enhancement.

- M2 (MICP): Reduced embodied carbon through calcite mineralization, wherein atmospheric CO_2 is biologically fixed as stable $CaCO_3$.
- M3 (Algae): Achieved direct CO_2 sequestration during the controlled curing phase, as algae actively captured and incorporated CO_2 into its biomass.
- M4 (Biochar): Functioned as a long-term carbon sink, locking away atmospheric carbon absorbed by the feedstock during growth and retained through pyrolysis.

Among the three, M4 demonstrated the strongest environmental advantage, while M2 provided the greatest mechanical improvement, and M3 offered a balanced enhancement across mechanical, durability, and sustainability metrics.

Metric	M1 (Control)	M2 (MICP)	M3 (Algae)	M4 (Biochar)
Compressive Strength (↑)	Baseline	+15%	+10%	+12%
Water Absorption (↓)	Baseline	−18%	−12%	−20%
Carbon Footprint (↓)	High	Low	Moderate	Very Low
Curing Time	Normal	Shortened	Normal	Normal

CONCLUSION

The comprehensive evaluation of bio-based concrete confirmed its potential as a sustainable and high performing alternative to conventional construction materials. The study demonstrated that incorporating Microbial Induced Calcite Precipitation (MICP), Algae-Based CO_2 Sequestration, and Biochar Additives successfully addressed key limitations of Ordinary Portland Cement (OPC), particularly concerning high carbon emissions and technical vulnerabilities such as cracking and permeability.

Specifically, MICP-enhanced concrete (M2) achieved the most substantial mechanical uplift, realizing approximately 15% higher compressive strength due to bio-mineralization, while Biochar concrete (M4) excelled in durability, showing a remarkable 20% reduction in permeability and acting as a passive, long term carbon sink.

Beyond mechanical performance, the bio-enhanced mixes delivered crucial advancements in sustainability metrics. The Chlorella vulgaris in the Algae concrete (M3) facilitated active CO_2 sequestration during the controlled curing process, contributing to a moderate reduction in carbon footprint and offering the additional benefit of a shortened curing time through improved early hydration. M2 and M4 also contributed to lower environmental impact through direct carbon fixation (calcite formation) and waste valorization, respectively. This collective outperformance of all bio-enhanced formulations over the control mix (M1) across strength, durability, and CO_2 reduction metrics validates the feasibility of using biological processes to create greener infrastructure materials.

In conclusion, the findings establish a robust framework for the large-scale adoption of bio-based concrete, presenting a practical and impactful solution to the urgent need for decarbonizing the civil engineering sector. This interdisciplinary innovation, bridging microbiology, materials science, and structural engineering, provides a pathway for designing a smarter, self-healing, and carbon conscious construction material. Future research should focus on optimizing the scalability and cost effectiveness of bio-component preparation and assessing the long-term performance of these materials under various environmental conditions to fully realize the potential of next generation green infrastructure.

Conflicts of Interest: All authors declare that they have no conflict of interest associated with this research work.
CRedIt: **David Ajayi (Lead Author)** - Structural Design and Testing, **Temitope Oseni** - Biochar Production and Characterization, **Chukwudi Nwankwo** - Durability and Concrete Engineering, **Femi John Ibitayo** - Material Characterization and Casting, **Emmanuel Ajibola** - Sustainability Metrics and LCA (Life Cycle Assessment), **Alex Odia** - Chemical Analysis and Preparation of bio-components, **Benjamin Anyaehie** - Data Analysis and Visualization. All authors contributed to drafting and editing of this study.

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