# Bio-Based Materials in Sustainable Concrete: A Review on Mechanical Performance, Environmental Impact, and Practical Challenges

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**Abstract** - *Concrete remains a cornerstone of modern infrastructure, yet its production especially cement manufacturing contributes significantly to global $CO_2$ emissions and environmental degradation. This review explores the emerging use of bio-based materials as partial replacements for conventional concrete constituents such as cement, sand, and coarse aggregates. Specifically, wood ash, rice husk ash, and corn cob granules are examined for their pozzolanic activity, silica content, and lightweight properties, respectively. These materials offer environmental and economic advantages including reduced carbon footprint, lower material costs, and enhanced durability and thermal performance. However, challenges such as variability in chemical composition, lower early-age strength, high water absorption, and limited structural applications persist. The review highlights current experimental findings, performance metrics, and case studies demonstrating the practical feasibility of these bio-materials. It also identifies gaps in knowledge related to mix optimization, long-term durability, and standardization. As sustainable construction gains global momentum, the integration of bio-based waste into concrete presents a promising pathway toward low-carbon, circular construction practices provided future research addresses the material limitations and performance uncertainties.*

***Key Words***: Bio-based materials, Wood ash, Rice husk ash, Corn cob aggregate, $CO_2$ emissions, Cement replacement, Green construction, Waste utilization

## 1 INTRODUCTION

This Concrete, a widely used construction material, is composed primarily of cement, sand, water, and aggregates. Its unparalleled versatility, strength, and durability have made it a fundamental material in modern infrastructure. However, the environmental impact of concrete production is substantial, primarily due to the energy-intensive process of cement manufacturing. Cement production alone is responsible for a significant share of global carbon dioxide emissions, contributing to the ongoing challenges of climate change. As a result, there is increasing pressure to develop more sustainable alternatives to traditional concrete ingredients.

One promising approach to reducing the environmental footprint of concrete is the use of bio-based materials as partial replacements for conventional materials like cement, sand, and coarse aggregates. Bio-materials are derived from renewable, natural sources and offer several advantages, including waste reduction, lower energy consumption, and potentially enhanced material properties. By replacing a portion of conventional concrete ingredients with bio-based materials, it is possible to not only mitigate environmental harm but also improve the performance characteristics of the resulting concrete.

### 1.1 Problem Statement

The construction industry is heavily reliant on concrete, a material whose production has significant environmental consequences, primarily due to the energy-intensive process of cement manufacturing. Cement production alone accounts for approximately 8% of global carbon dioxide emissions, making it a major contributor to climate change. Despite its widespread use, traditional concrete has limitations in terms of sustainability, resource depletion, and environmental impact.

With the growing emphasis on sustainable development and eco-friendly construction practices, the need to reduce the environmental footprint of concrete has become increasingly urgent. One approach to addressing this issue is through the partial replacement of conventional materials, such as cement, sand, and coarse aggregates, with bio-based materials derived from renewable sources. These materials, including wood ash, rice husk ash, and corn cob granules, offer promising alternatives due to their availability, low cost, and potential to reduce the demand for non-renewable resources.

Table 1: Various bio-based materials, their production methods, and their uses in concrete:

| Bio-based Material | Uses in Concrete | Benefits | Challenges |
|---|---|---|---|
| Wood Ash | Cement replacement, enhances strength | Reduces $CO_2$ emissions, Cost-effective | Chemical variability, Delayed early strength |
| Rice Husk Ash (RHA) | Sand/cement replacement, improves durability | High silica content, Reduces water permeability | Quality variability, Affects workability |

| | | | |
|---|---|---|---|
| Corn Cob Granules | Coarse aggregate replacement, reduces density | Lightweight, Improves thermal insulation | Low compressive strength, High water absorption |
| Hempcrete | Non-load bearing insulation material | Carbon negative, Good insulation, Lightweight | Low compressive strength, Non-structural use |
| Fly Ash | Cement replacement, improves workability | Enhances durability, Reduces carbon footprint | Low early strength, Requires composition control |
| Sugarcane Bagasse Ash | Cement/fine aggregate replacement | Reduces waste, Enhances strength | Composition variability, Availability |
| Palm Kernel Shells | Coarse aggregate replacement | Lightweight, Sustainable | Reduced compressive strength, High water absorption |
| Coconut Shells | Coarse aggregate replacement | High strength when treated, Lightweight | Reduced strength at high replacement levels |
| Banana Stem Fiber | Reinforcement in concrete | Improves tensile strength, Renewable | Needs treatment, Limited structural use |
| Wheat Straw Ash | Cement replacement | High silica content, Enhances properties | Composition variability, Limited use |
| Tire Rubber | Coarse aggregate replacement | Reduces waste, Provides flexibility | Low strength, Bonding issues |
| Algae | Additive for sustainability | Carbon neutral, Renewable | High cost, Limited availability |

However, the incorporation of bio-based materials into concrete formulations raises several questions about the impact on the material's mechanical properties, durability, and overall performance. The effect of varying replacement levels of bio-materials on concrete's compressive strength, tensile strength, workability, and durability characteristics is not fully understood. Additionally, the optimal percentage of replacement for each material remains unclear, and its long-term performance in real-world construction applications is yet to be established.

This study seeks to address these gaps by investigating the effect of replacing cement with wood ash, sand with rice husk ash, and coarse aggregate with corn cob granules on the mechanical and durability properties of concrete. The findings aim to contribute to the development of more sustainable concrete mixes that can reduce environmental impact without compromising the performance or safety of construction materials.

### 1.1.1 An alternative solution

In this study, three bio-based materials wood ash, rice husk ash, and corn cob granules are explored as partial replacements for cement, sand, and coarse aggregate, respectively. These materials are considered sustainable alternatives due to their availability, cost-effectiveness, and potential to reduce the environmental impact of traditional concrete production. Below, each material is described in detail, highlighting its properties and relevance in concrete applications.

### 1.1.2 Wood Ash as Cement Replacement

Wood ash is a byproduct of the combustion of wood and other biomass materials in industries such as pulp and paper, and energy production. The chemical composition of wood ash mainly consists of oxides of calcium, silicon, potassium, and magnesium, along with traces of aluminum and iron. The potential of wood ash as a cement replacement lies in its high calcium content, which enables it to react with water and form compounds similar to those produced during the cement hydration process.

### 1.1.3 Properties and Benefits:

- Pozzolanic Activity: Wood ash has pozzolanic properties, meaning it can react with calcium hydroxide (produced during cement hydration) to form additional calcium silicate hydrate (C-S-H) gel, which improves the concrete's strength.
- Environmental Impact: By replacing a portion of cement with wood ash, the carbon footprint of concrete can be significantly reduced, as cement production is a major contributor to $CO_2$ emissions.
- Cost-Effectiveness: Wood ash is a low-cost material, often available as a waste product from industrial processes. Utilizing it in concrete not only reduces environmental impact but also provides a cost-effective alternative to traditional materials.

Challenges:

- The chemical composition of wood ash can vary significantly depending on the source and type of wood burned, making it important to characterize the ash before use.

- Excessive replacement of cement with wood ash may reduce the early strength development of concrete, as the pozzolanic reaction takes time to develop.

### 1.1.4 Rice Husk Ash as Sand Replacement

Rice husk ash (RHA) is produced from the combustion of rice husks, a major agricultural waste byproduct. The ash is rich in silica, which can contribute to the pozzolanic activity of concrete. In countries where rice is a staple crop, large quantities of rice husk ash are generated annually, providing an abundant and sustainable resource for use in construction materials.

### 1.1.5 Properties and Benefits:

- High Silica Content: RHA is primarily composed of amorphous silica, which enhances the concrete's strength and durability by reacting with calcium hydroxide during hydration. This reaction results in the formation of additional C-S-H gel, which improves the overall properties of the concrete.

- Improved Durability: The addition of RHA to concrete has been shown to improve resistance to chemical attacks, including sulfate and chloride ingress, and reduce water permeability.

- Waste Utilization: As rice husk is a commonly available agricultural waste, its conversion into ash for concrete applications provides a sustainable way to recycle a waste material that would otherwise be discarded.

Challenges:

- Variability in Quality: The quality of RHA can vary depending on the temperature and method of burning, which can affect its reactivity and performance when used in concrete.

- Workability Issues: The use of RHA may reduce the workability of fresh concrete, requiring the addition of plasticizers or other additives to maintain the desired consistency.

*Corn Cob Granules as Coarse Aggregate Replacement*

Corn cob granules are derived from the husk of corn, which is a waste material from the agriculture industry. Corn cobs are lightweight and porous, making them a potential candidate for use as a partial replacement for coarse aggregates like gravel or crushed stone in concrete. The granules are typically produced by grinding dried corn cobs into small, uniform particles.

Properties and Benefits:

- Lightweight: Corn cob granules are significantly lighter than conventional coarse aggregates, which can reduce the overall density of concrete, leading to a lighter structure.

- Improved Thermal Insulation: Due to their porous structure, corn cob granules can improve the thermal insulation properties of concrete, which can be beneficial for energy-efficient building designs.

- Sustainability: Using corn cob granules helps reduce agricultural waste and offers an eco-friendly alternative to traditional aggregates, which are often mined and have high environmental costs.

Challenges:

- Lower Strength: The porous and lightweight nature of corn cob granules can lead to a reduction in the overall compressive strength of concrete, especially when used in high proportions. This limits their use to non-load-bearing or low-strength applications.

- Water Absorption: Corn cob granules have relatively high water absorption rates, which can affect the workability and durability of the concrete if not properly managed.

## 2 Literature Review

This study reviews existing literature on the use of bio-based materials in concrete, focusing on wood ash, rice husk ash, and corn cob granules as partial replacements for conventional ingredients like cement, sand, and coarse aggregates. The use of such materials is motivated by the need for sustainable alternatives that can reduce the environmental impact of concrete production, which is a major contributor to carbon emissions. Research on the incorporation of bio-based materials into concrete has grown in recent years, as these materials not only address waste management issues but also contribute to improving the properties of concrete. Wood ash and rice husk ash, both of which are by-products of agricultural activities, have shown promise as supplementary cementitious materials that can enhance the strength and durability of concrete. Similarly, corn cob granules have been explored as a potential lightweight and eco-friendly coarse aggregate alternative.

Aduldejcharas (2024) investigates the potential of managing bio-waste materials, specifically mussel shell waste, in Samut Songkhram Province's Bang Ja Kreng Community, where shell waste has been a significant environmental issue. The study focuses on the performance of burned mussel shells as a bio-responsive block material for concrete. Traditional disposal methods for mussel shells have proven ineffective, and the research explores innovative solutions to address community pollution and enhance sustainability. The burning of mussel shells at various temperatures alters their chemical structure, with the key component, calcium oxide (CaO), increasing significantly, contributing up to 80.14% of the shell's weight. The material's compressive strength was tested rigorously, achieving 500 kg (4,000 N), demonstrating its potential as a durable building material. Analytical techniques such as X-ray fluorescence (XRF) and X-ray diffraction (XRD) were employed to assess the chemical compositions, confirming the enhanced structural properties. The findings indicate that mussel shells can be effectively recycled into valuable products that not only improve concrete strength but also contribute to sustainable waste management practices. Engaging local communities in recycling initiatives is crucial for successful implementation, as it reduces environmental impacts and supports the development of cost-effective, sustainable construction materials. This approach enhances both the community environment and waste management strategies [1)].

Al-Sabaeei et al. (2022) explore the utilization of crude palm oil (CPO) and its by-products in green construction, emphasizing their potential for creating sustainable and cost-effective materials. Palm oil waste materials, such as palm oil fuel ash (POFA) and palm oil clinker, have been successfully used in bio-asphalt and bio-concrete, offering an eco-friendly alternative to petroleum-based materials. The incorporation of POFA in concrete enhances compressive strength and durability, while palm oil clinker improves the mechanical properties of asphalt mixtures. Additionally, palm oil-derived binders increase the elasticity and fatigue life of modified asphalt, with bio-asphalt demonstrating comparable thermal sensitivity and resistance to conventional asphalt but requiring lower mixing temperatures. These benefits highlight the viability of CPO and by-products in replacing traditional materials in the construction industry. However, the study identifies challenges, including securing sufficient palm oil resources for non-food applications and addressing performance variability based on the type and properties of palm oil used [2)].

Amantino et al. (2022) assess the properties of bio-concretes made with rice husk (RH) bio-aggregates, focusing on their mechanical, thermal, and physical performance over a six-month period. The study evaluates the effects of replacing cement with rice husk ash (RHA) at an 8% substitution level and replacing natural sand with rice husk at 5% and 10%. The results show that while the bio-concretes maintain good thermal performance, their mechanical properties are somewhat compromised. Specifically, compressive strength decreased by 25% and 36% for the 5% and 10% RH mixtures, respectively, while tensile strength increased by 7% and 5% for the same compositions. The density of the bio-concretes decreased by 5% and 13% as the RH content increased. Additionally, the modulus of elasticity reduced by 30% and 40% for the 5% and 10% RH samples. Shrinkage levels remained stable at approximately 0.11% after 180 days. Microstructural analysis revealed weak interfacial transition zones in the bio-concretes. Despite the decrease in mechanical strength, the bio-concretes with rice husk offer enhanced thermal performance, making them suitable for lightweight, insulating applications. Furthermore, the substitution of RHA reduces the carbon footprint and increases the sustainability and durability of the material [3)].

Ansari, Tabish, and Zaheer (2025) present a comprehensive review on hemp-infused concrete, highlighting its environmental and structural benefits, particularly in reducing carbon emissions in construction. Hempcrete, made from hemp and lime, offers excellent thermal insulation and moisture control, which enhances energy efficiency in buildings. Its porous structure not only provides insulation but also soundproofing, contributing to a healthier indoor environment. Hemp concrete is also resistant to fire, pests, and mold, making it durable and low-maintenance. Additionally, it sequesters carbon over time, reinforcing its sustainability as a building material. However, the review notes that hempcrete has low compressive and flexural strength, limiting its use in load-bearing applications. Despite this, its ductility and ability to regulate humidity make it suitable for earthquake-resistant structures. One significant challenge to the widespread adoption of hempcrete is the lack of standardized norms, which hinders consistency and regulatory compliance. Variations in hemp content also affect its material properties, necessitating further research to optimize its performance. Higher costs and longer curing times are additional drawbacks [4)].

Bardouh et al. (2024) provide a comprehensive review of the mechanical behavior of bio-based concrete under various loadings, analyzing data from around 120 studies. The paper highlights the complexities of predicting the mechanical properties of bio-based concrete, emphasizing how factors such as aggregate content, aggregate size, binder type, and aging influence the material's performance. It was found that increased aggregate content tends to decrease mechanical properties, while finer aggregates can enhance mechanical strength and reduce porosity. The study covers bio-based concrete's response to compression, flexion, and shear, identifying that the material exhibits elastoplastic behavior, which aids in energy dissipation during seismic events. Specific formulations of bio-based concrete, such as hemp concrete, show compressive strengths ranging from 0.1 to 2 MPa, while miscanthus, corn stalk, and rice straw composites offer higher strength. Wood-based concrete also demonstrates high rigidity, with compressive strength reaching up to 1100 MPa. Additionally, the paper notes that aging enhances the influence of mineral binders on the concrete's properties. The review suggests that bio-based concrete, due to its sustainability and carbon-negative potential, offers a promising alternative in the building sector, although its mechanical behavior requires careful formulation to meet the required structural standards for construction applications [5)].

Caldas et al. (2021) conducted an assessment of greenhouse gas (GHG) emissions in the production of wood bio-concrete, focusing on different types of wood bio-concrete with varying wood shavings content. The study employed Life Cycle Assessment (LCA) methodology to calculate the GHG emissions throughout the production process. The findings revealed that increasing the wood waste content in bio-concrete significantly mitigates climate change impacts, as it reduces overall GHG emissions. Additionally, the research highlighted the significant role of transportation efficiency in influencing GHG emissions outcomes, with transportation contributing notably to the overall carbon footprint. The study compared the environmental impact of using recycled wood shavings versus virgin wood shavings, with the results showing that recycled wood shavings were less impactful in terms of emissions. This suggests that recycling wood waste not only serves as a viable CO2 sink but also provides a sustainable strategy for reducing carbon footprints in the construction industry. Furthermore, the research emphasizes the importance of efficient transportation in maximizing the environmental benefits of using waste wood. Overall, the study advocates for the use of waste wood shavings over virgin sources, making it a preferable option for promoting a low-carbon, circular economy in the building materials sector. [6)]

Cavalli et al. (2024) provide a comprehensive review of bio-based rejuvenators in asphalt pavements, focusing on their eco-friendly and renewable characteristics. These rejuvenators are designed to mitigate the aging effects on asphalt, particularly by restoring the rheological properties of aged binders. They effectively reduce stiffness, enhance elasticity, and improve the workability and temperature susceptibility of asphalt. By improving crack resistance and fatigue performance, bio-based rejuvenators extend the service life of pavements. Additionally, they offer environmental benefits by lowering greenhouse gas emissions compared to traditional petroleum-based alternatives, as well as being biodegradable, non-toxic, and safer for both workers and the environment. The study highlights the importance of long-term performance monitoring to ensure the effectiveness of these rejuvenators. While bio-based rejuvenators show promise in improving asphalt durability and sustainability, their effectiveness varies depending on the type and dosage, and compatibility with existing materials is crucial [7)].

Chen and Yu (2024) investigate the surface modification of miscanthus fiber using hydrophobic silica aerogel to enhance its compatibility with cement, particularly in lightweight concrete. The study demonstrates that the hydrophobic treatment significantly improves the mechanical and insulating performance of concrete. Specifically, the modified miscanthus fibers exhibit reduced water absorption (36% after 3000 minutes of immersion), improved compressive and flexural strength, and enhanced thermal insulation and sound absorption. The aerogel modification also minimizes organic matter leaching, particularly sugar leaching from the miscanthus fibers, which typically affects the durability and strength of the material. The study suggests that the hydrophobic silica aerogel enhances the mechanical properties of miscanthus fiber, making it a promising material for improving the performance of lightweight concrete in construction. Additionally, the modification lowers thermal conductivity compared to traditional insulating materials, positioning aerogel-modified miscanthus fibers as a viable eco-friendly option for enhancing the insulating and acoustic properties of building materials. This modification method using ethanol is noted as particularly efficient in achieving the desired hydrophobicity [8)].

Chen, Yu, Wang, and Yu (2024) explore the bio-corrosion mechanisms affecting marine concrete, which is crucial for infrastructure in marine environments. The paper identifies three main bio-corrosion mechanisms: fouling, biophysical, and biochemical processes. These mechanisms contribute significantly to the degradation of concrete, reducing its lifespan by altering its mineral composition and microstructure, ultimately affecting its mass and compressive strength. The review emphasizes the importance of understanding hydrodynamics in relation to bio-corrosion, as these factors influence the behavior of fouling organisms and the effectiveness of protective coatings. Concrete in marine environments is particularly vulnerable to bio-corrosion, with significant economic losses attributed to its deterioration globally. The authors argue that bio-corrosion can begin within six months of exposure in harsh marine conditions, making early intervention crucial for preserving concrete structures. Additionally, the review highlights the role of antifouling measures, suggesting that they should be designed with consideration of the bio-corrosion mechanisms and hydrodynamic factors. Despite the advances in understanding bio-corrosion, the paper notes that there is still limited research on corrosion rates under natural exposure conditions, indicating the need for further studies to better predict and mitigate the impacts of bio-corrosion on concrete durability [9)] .

De Andrade et al. (2024) evaluate the potential of macauba endocarp as a coarse aggregate in bio-concretes, exploring its chemical composition, anatomical characteristics, and physical properties. The study assesses the chemical compatibility of untreated and hot water-treated endocarp with cement, finding that the treatment improves its chemical compatibility. Bio-concretes were produced with varying levels of macauba endocarp substitution, and mechanical tests, including axial compression and splitting tensile strength, were conducted. The results demonstrate that macauba endocarp could be a viable material for construction applications. The compressive strength ranged from 20.78 to 30.40 MPa, with the 25% endocarp mix showing a 7% strength increase, while higher substitution levels (50% and 100%) led to strength decreases of 9% and 27%, respectively. The addition of endocarp improved ductility, cracking control, and fracture energy, with increases of 72%, 75%, and 182% observed in the respective mixes. However, the elastic modulus decreased with higher endocarp content. The macauba endocarp's low bulk density (1.23 g/cm$^3$) and absorption capacity (9%) make it a promising bio-aggregate for sustainable construction, particularly in non-critical load-bearing applications, where enhanced ductility and fracture control are beneficial [10)].

De Pascale et al. (2024) investigate the potential use of waste bivalve shells, such as those from mussels, oysters, and clams, as biofillers in porous asphalt concrete. Given that bivalve shells are primarily composed of calcium carbonate, they present an opportunity to replace conventional limestone fillers, thus addressing both waste reduction and sustainability in construction materials. The study demonstrates that the addition of these biofillers does not result in significant differences in the physical properties, such as skid resistance and air void content, compared to control mixtures. All mixtures, including those with mussel (PA-M), oyster (PA-O), and clam (PA-C) shell biofillers, met the Italian specifications for skid resistance and had adequate air voids content. Notably, the study finds that PA-M exhibits higher vertical permeability compared to other mixtures, and all experimental mixtures show lower particle loss than the control mix. While the rheological properties of the mastics with biofillers are similar to those with limestone filler, the study highlights that oyster shell filler shows superior rutting resistance, whereas clam shell filler negatively impacts the mechanical properties of the asphalt. Additionally, oyster shell filler is more susceptible to water, potentially affecting the durability of the concrete. The study suggests that combining different biofillers could optimize recyclability and improve the overall performance of asphalt mixtures, presenting an eco-friendly solution for construction waste management [11)].

Elgaali, Lopez-Arias, and Velay-Lizancos (2024) investigate the effects of $CO_2$ exposure treatment on recycled concrete fine aggregates (RCFA) to enhance the bio-receptivity of mortars. The study compares two mixtures: natural fine aggregate (NFA) and RCFA, assessing their properties such as pH, water absorption, porosity, and bio-receptivity. The accelerated $CO_2$ exposure treatment significantly improved the bio-receptivity of RCFA mortars, primarily due to increased porosity and a reduction in surface pH. The study found that RCFA mortars exhibited a 36% porosity, compared to 27% for NFA mortars. Additionally, $CO_2$ exposure treatment reduced the surface pH of RCFA by 12%, which is beneficial for bio-receptivity as lower pH values enhance the growth of biofouling organisms. The accelerated $CO_2$ treatment also led to an 83% increase in the compressive strength of RCFA mortars. Furthermore, RCFA enhanced the porosity and carbonation depth of the composites, contributing to better bio-receptivity. The findings highlight that combining RCFA with $CO_2$ exposure can create low-carbon, bio-receptive cementitious materials, promoting sustainable construction practices. These materials, with improved porosity and reduced pH, offer environmental benefits and foster life on the material surfaces, making them suitable for applications where biofouling is desired [12)].

Hadjadj et al. (2024) investigate the use of seashell powder (SSP) and granite waste (GW) as partial replacements for cement and natural sand, respectively, in concrete mixtures. The study focuses on evaluating the fresh, mechanical, and durability properties of concrete incorporating these bio-based materials. The fresh properties, assessed using slump flow and V-funnel tests, showed a decline with granite waste substitution; however, the inclusion of seashell powder helped mitigate these adverse effects, leading to improved flowability. The results demonstrated that the optimal mixture, consisting of 10% SSP and 50% GW, achieved a compressive strength of 67 MPa, a modulus of elasticity of 40 GPa, and a reduced porosity of 2.9%. Ultrasonic pulse velocity (UPV) and modulus of elasticity improved with higher granite waste content, suggesting better structural integrity. Additionally, the porosity and water absorption of the mixtures decreased significantly, and the concrete displayed enhanced resistance to acid attacks compared to control mixtures. Microstructural analysis revealed a denser structure and stronger interfacial transition zone, indicating improved durability [13)].

Jakubovskis et al. (2023) explore the potential of living layered concrete (LLC) panels for urban greening, focusing on their economic, aesthetic, and environmental benefits. These panels, designed to support the natural colonization of non-vascular plants, offer a sustainable alternative to traditional urban greening systems, which often require high maintenance and significant costs. The study reveals that LLC panels require minimal maintenance and are capable of naturally supplying water to the plants, promoting the growth of moss and other non-vascular species. Long-term tests demonstrate successful plant survival and colonization, with non-vascular plants dominating the pervious concrete surface two years after installation. The panels exhibited excellent water permeability and infiltration rates, making them highly effective for managing urban runoff. A key feature of the system is the innovative bio-booster material, which enhances the sustainability and simplifies the production of LLC panels. This material facilitated the initial germination of moss within two months, and after ten months, well-developed moss tufts were observed on specific samples [14)].

Kawaai, Nishida, Saito, and Hayashi (2022) explore the use of bio-based materials for concrete crack and patch repair, focusing on Bacillus subtilis and alginate-based agents. The study finds that Bacillus subtilis enhances both self-healing efficiency and corrosion resistance in concrete. By facilitating calcite precipitation, this bacteria effectively seals cracks in mortar, preventing further damage. Alginate-based materials are also highlighted for their ability to improve water ingress resistance, thereby reducing water absorption in cracked mortar. The study further demonstrates that bacterial growth is influenced by the culture medium, with optimal results observed in the N1-G1-T0 mixture for crack repair. Additionally, bio-based materials reduce the dissolved oxygen concentration in concrete, which helps in mitigating macrocell corrosion. The research shows that, particularly in specimens with high chloride content, steel bars exhibited early corrosion; however, the use of bio-based agents, like Bacillus subtilis, prevented re-deterioration from corrosion. Calcite precipitation, in particular, was identified as a key mechanism in effectively sealing cracks and improving the overall durability of repaired concrete. This study underscores the potential of bio-based materials, such as Bacillus subtilis and alginate, in enhancing the longevity and sustainability of concrete structures by promoting self-healing and improving resistance to corrosion and water absorption [15)].

Merino-Maldonado et al. (2024) explore the use of diatom culture techniques to enhance the surface protection of recycled concrete. As construction waste continues to rise, recycling concrete offers an eco-friendly solution by reducing resource extraction and landfill waste. The study focuses on the bio-deposition of biogenic silica from diatoms, which forms a protective biofilm on concrete surfaces. This biofilm significantly decreases capillary absorption, improves impermeability, and enhances the concrete's mechanical strength. The research shows that diatom treatment increases compressive strength by 4-8% and reduces the capillary absorption coefficient by 25-31%, thereby enhancing the material's durability. Additionally, the treatment lowers carbonation penetration by 49-88%, contributing to increased resistance to environmental factors. The biofilm formed by diatom deposition seals concrete pores and microcracks, improving waterproofing and protecting against water and gas permeability. The study also indicates that diatom bio-deposition successfully improves recycled concrete's surface morphology, making it more resilient and sustainable. The results support the potential of diatom cultivation as an eco-friendly alternative to synthetic treatments for enhancing concrete's durability, making it a promising solution for the construction industry. The effectiveness of the treatment was consistent across different growing environments, demonstrating its versatility and practical application in improving the properties of recycled concrete [16)].

Pokorný et al. (2022) explore the use of bio-based aggregates in concrete production as a sustainable alternative to conventional materials, which significantly impact the environment. These bio-based aggregates, including carbonized lightweight variants, enhance both the thermal and acoustic properties of concrete. Notably, the incorporation of bio-based aggregates reduces thermal conductivity by 63% and improves acoustic performance by 16.2% compared to traditional concrete. Despite the reduced bulk density and increased porosity with higher bio-based aggregate content, the compressive strength remains above 27 MPa for up to 50% volume replacement, making it suitable for structural applications. The use of bio-based aggregates also contributes to the sustainability of concrete production by reducing the material's unit weight and mitigating environmental impacts associated with traditional aggregates. However, higher bio-based aggregate content can negatively affect the strength properties due to increased porosity. The study concludes that bio-based aggregates are a viable option for enhancing concrete's thermal insulation and acoustic performance while maintaining structural integrity, and further research is needed to apply these findings to real-world concrete panel applications [17)].

Pramanik et al. (2024) examine the critical issue of bio-corrosion in concrete sewer systems, which leads to significant maintenance costs and a reduced service life of infrastructure. The study highlights the role of hydrogen sulfide ($H_2S$), which, when oxidized, forms sulfuric acid that accelerates the deterioration of concrete. Bio-corrosion is influenced by various factors, including environmental conditions, the quality of concrete, and the composition of wastewater. The lack of standardized test methods complicates the development of effective mitigation strategies, as current testing approaches often fail to capture the dynamic nature of bio-corrosion. The paper reviews existing corrosion test strategies and assesses their efficacy, noting that coatings and optimized mix designs can improve concrete durability and resistance to bio-corrosion. However, the long-term effectiveness of protective measures remains uncertain. The authors emphasize that bio-corrosion not only escalates repair costs but also shortens the lifespan of sewer systems. To address these challenges, the study advocates for the development of more reliable and standardized testing methods, improved coatings, and resilient concrete materials. Moreover, it calls for the adoption of simulation tests that account for key environmental factors to better predict and manage bio-corrosion in concrete sewer structures [18)].

Raza et al. (2023) review the use of self-healing bio-mineralized concrete in built environments, focusing on its sustainability, structural performance, and challenges. The study examines the role of microorganisms, particularly *Bacillus* species, in the self-healing process, where bacteria precipitate calcium carbonate (CaCO3) to repair concrete fractures. This bacterial activity improves compressive strength and enhances the concrete's resistance to water permeation, chloride ion migration, and acid rain. However, challenges remain, particularly in maintaining bacterial viability over time, which increases the costs of production. Despite these challenges, the use of microbial-induced calcium carbonate precipitation (MICP) offers a cost-effective and sustainable solution for enhancing concrete durability and structural performance. The study shows promising laboratory results, suggesting that bio-mineralized concrete could be a viable option for future construction, particularly in environments prone to aggressive conditions [19)].

Sarkar et al. (2023) investigate the self-healing properties of bio-concrete, focusing on the role of Bacillus cohnii microbes in enhancing the structural efficiency of concrete. The study evaluates the healing process through the mechanical strength and durability of bio-concrete, finding that microbial activity leads to the deposition of calcium carbonate, which effectively seals cracks and reduces porosity. The healing process is particularly efficient in sealing cracks ranging from 0.02 to 2 mm in width. Bacillus cohnii microbes degrade nutrients to produce healing agents, primarily calcium carbonate, which significantly improves the concrete's strength by precipitating calcite. The results show a notable increase in compressive strength, with a 40% improvement at 3 days and up to 60% at 28 days. The total porosity of bio-concrete is reduced by 32-48%, and the material shows higher mechanical strength and durability compared to conventional concrete. Water absorption is also reduced due to the denser structure of bio-concrete, and the flexural strength mirrors the trends observed in compressive strength. The study highlights that microbial calcite precipitation not only improves mechanical properties but also enhances the durability of concrete against environmental challenges, such as chloride ion penetration. Overall, bio-concrete demonstrates effective sealing and self-healing properties, offering a sustainable solution for enhancing the resilience and longevity of cement-based structures [20)].

Sempere-Valverde et al. (2024) investigate the ecological performance of concrete compared to basalt boulders in coastal environments, focusing on the recruitment of benthic organisms. Their study highlights how surface integrity significantly affects the ecological performance of artificial shorelines, such as coastal protection structures. The findings show that benthic assemblages on concrete have lower biomass and abundance compared to basalt, with faster surface erosion rates observed on concrete surfaces. These differences in biomass and organism abundance are attributed to the physical characteristics of the surfaces, particularly surface integrity, rather than chemical effects. Concrete surfaces also show higher detachment rates of biocrusts, further affecting the stability of benthic communities. The study underscores basalt as a more sustainable material for coastal constructions due to its superior surface integrity, which supports more robust and stable benthic assemblages. The research provides valuable insights for future ecological studies and coastal management practices, suggesting that surface integrity should be a key consideration in the design of artificial shorelines. Additionally, the study notes that environmental stressors can limit differences in intertidal benthic assemblages, but subtidal habitats show more significant variations [21)].

Silva et al. (2024) review the development and potential of bamboo bio-concretes as a sustainable alternative for low-carbon construction. Over the past decade, research, particularly from NUMATS, has focused on leveraging bamboo bio-concretes for their eco-friendly properties, including carbon sequestration and the mitigation of greenhouse gas emissions. The study highlights that bamboo bio-concretes exhibit reduced workability as the bamboo bio-aggregate content increases, with densities ranging from 694 to 1390 kg/$m^3$, classifying them as lightweight materials. The incorporation of metakaolin and fly ash further enhances the material's performance, making it suitable for residential and public building applications. Alkaline treatment of bamboo aggregates improves their characteristics, contributing to the overall durability of the bio-concrete. This material, by promoting carbon sequestration and offering favorable mechanical properties, emerges as a viable and energy-efficient alternative for sustainable construction, helping to reduce the environmental impact of traditional concrete [22)] .

Varshney and Khan (2024) explore the use of metakaolin (MK) as a cement substitute in concrete, assessing its impact on mechanical properties and permeability. The study evaluates MK substitution ratios up to 15% by weight of cement and identifies 10% MK as the optimal level for enhancing concrete performance. Incorporating bacteria into the mix further improves the compressive strength and reduces permeability through bio-mineralization, specifically calcium carbonate deposition. The research shows that the MK10 mix achieved the highest compressive strength of 104 MPa, a 19% increase compared to the control mix. The addition of bacteria and MK also reduced permeability by 43.23%. While workability decreased with higher MK content due to its high surface area and rough texture, bacterial incorporation did not significantly affect the workability of fresh concrete. Flexural strength increased by up to 26.31% with the inclusion of MK, and bio-mineralization enhanced the strength increment nearly twofold at 28 days. However, the study notes that excessive MK content (beyond 10%) may negatively affect the strength properties. Overall, the research advocates for the use of MK and bio-mineralization in sustainable concrete production, providing a potential solution for reducing permeability and enhancing mechanical properties[23)].

Wang et al. (2024) explore the bio-inspired functionalization of recycled concrete powder (RCP) through tannic acid (TA) treatment to enhance the sustainability and performance of alkali-activated slag (AAS) mortars. RCP, while offering an environmentally friendly alternative to traditional concrete, suffers from low reactivity and a porous microstructure. By applying tannic acid to RCP, the researchers significantly improved the material's properties, resulting in a 41.4% increase in the compressive strength of AASR mortar after 28 days. The TA treatment also enhanced the flowability of the mortar, reduced porosity, and improved the overall quality of the recycled powder. Furthermore, the functionalization process increased the eco-efficiency of the mortar by 28.2% and boosted the cost-benefit ratio by 41.6%. The study suggests that tannic acid interacts with the calcium ions in RCP, forming Ca-TA complexes that help fill pores and cracks, improving the material's microstructure. Additionally, the treatment delays the hydration of ground granulated blast-furnace slag (GBFS), thereby prolonging the setting time and allowing for better workability. Overall, the research highlights the potential of tannic acid as a sustainable solution for improving the quality of recycled concrete, thereby contributing to both environmental and economic benefits in construction applications [24)].

Wu, Chen, and Brouwers (2024) investigate the incorporation of miscanthus into vegetal concrete to enhance plant growth and water absorption. The study reveals that miscanthus significantly improves water absorption, with increases ranging from 119% to 246%, and reduces the density of concrete, with miscanthus mortar having a density range from 379 to 597 kg/m$^3$. The optimal cement-to-miscanthus ratio for plant growth is found to be between 0.5 and 0.75, promoting better plant performance. Additionally, sowing seeds directly on the surface of the concrete mortar improves both plant height and coverage, with a 36.5% increase in plant cover observed when 10% miscanthus is added. The study also highlights the importance of low alkalinity for better seed germination and growth. While miscanthus incorporation reduces the mechanical strength of concrete, it enhances water retention and contributes positively to root system development. The findings suggest that miscanthus-enriched concrete can play a key role in ecological recovery, offering an effective way to reduce environmental degradation while promoting sustainable plant growth in urban areas. The study advocates for a miscanthus content of around 10% to optimize both plant growth and concrete performance, making it a viable material for green construction applications [25)]!!.

Xu et al. (2024) explore the use of waste wood as an aggregate in ecological foam concrete (WFC), aiming to reduce the environmental impact of traditional construction materials. The study evaluates the properties of WFC, such as density, strength, durability, and thermal insulation, and finds that waste wood significantly enhances energy absorption and reduces cracking in the concrete. As the proportion of waste wood increases, the dry density of the foam concrete decreases, which also affects the softening coefficient and thermal conductivity. Despite the benefits, the high water absorption of waste wood negatively impacts the durability of WFC. However, the addition of waste wood improves the material's resistance to chloride ion permeability, water absorption, and sulfate attacks. It also enhances freeze-thaw resistance, maintaining the integrity of the concrete through multiple cycles. The study indicates that WFC is a more sustainable alternative to conventional foam concrete, making it suitable for applications in precast walls and coastal structures, where its improved thermal insulation and durability properties can provide significant advantages [26)].

Yew et al. (2022) investigate the performance of bio-based aggregates in concrete, specifically focusing on the impact of a wet grout binder treatment on lightweight bio-based coarse aggregates (LWBCA). The research demonstrates that pre-treatment with the grout binder enhances the properties of concrete, notably improving compressive strength, slump value, and elastic modulus. The density of the modified concrete remains below 2000 kg/m$^3$, and water absorption for all mixes is less than 10%, indicating good concrete quality. The treatment also significantly increases the slump value to 145 mm in the TDOPS0.65 mix, which is a notable improvement in workability. The compressive strength of the treated concrete ranges from 47-57 MPa at 28 days, and the elastic modulus increases to 19.0 GPa. Microscopic analysis reveals enhanced interfacial bonding strength between the aggregates and the cement matrix. Overall, the study concludes that the grout coating effectively enhances the mechanical properties and workability of bio-based aggregate concrete, making it a promising sustainable material for construction [27)].

Yong et al. (2024) examine the use of bio-based and industrial waste aggregates, including oil palm shell (OPS) and polyurethane (PU) aggregates, in lightweight foamed concrete (LWFC) to enhance its mechanical and thermal properties. The study also explores the addition of polypropylene (PP) fibres and silica fume for further improvements. PP fibres were found to significantly enhance the compressive, tensile, and flexural strength of LWFC, with compressive strength increasing by 40.4%, splitting tensile strength improving by 102.9%, and flexural strength rising by 70.8%. Additionally, the inclusion of PP fibres reduced the thermal conductivity of the concrete by 0.2% to 16.3%, making it more energy-efficient. Silica fume was incorporated to enhance both early and long-term compressive strength, while crushed OPS demonstrated stronger adhesion compared to the original OPS. The study also observed that workability decreased with increasing PP fibre volume, with the control mix (0% fibre) showing optimal workability. These findings highlight the potential of using waste materials in concrete production to improve mechanical and thermal properties, thereby promoting more sustainable construction practices. The research supports the use of eco-friendly aggregates and fibres in producing high-performance, low-carbon concrete materials, contributing to the advancement of sustainable building materials in the construction industry [28)].

Zelloufi et al. (2024) conducted a study evaluating the impact of seawater exposure on the durability and bio-colonization of two concrete formulations designed for marine infrastructure: one incorporating magnetite aggregates and the other using oyster shell waste. Over 24 months of exposure to seawater, both formulations exhibited similar bio-receptivity and surface biomass. However, oyster shell-based concrete demonstrated better resilience, with a significantly slower decline in compressive strength compared to the magnetite formulation. After 24 months, the compressive strength of the oyster shell concrete decreased by 40%, while the magnetite concrete lost 23%. Both concrete types showed similar bio-colonization patterns, where biofilm formation reduced water-accessible pores, but chemical degradation continued to affect mechanical behavior despite the decrease in porosity. The study found that surface roughness, rather than aggregate type, influenced bio-colonization, and no macroscopic damage or carbonation was observed in either concrete formulation. Elemental mapping showed no significant zonation of elements. The research highlights the slow and minor impact of seawater on concrete, demonstrating that bio-colonization and cement type are critical factors affecting marine concrete's performance and longevity [29)].

Zhang et al. (2023) optimized a sodium alginate-aided bio-deposition treatment to enhance the properties of recycled concrete aggregates (RCA). The study demonstrated significant improvements in the mechanical strength and durability of treated concrete. The density of the treated concrete was increased to 2232 kg/m$^3$, and its apparent density reached 2512 kg/m$^3$, suggesting a denser and stronger material. Additionally, saturated water absorption decreased by 15.3%, further enhancing the concrete's water resistance. These results highlight the effectiveness of the sodium alginate-aided bio-deposition process in improving the quality of recycled aggregates, making them more suitable for use in concrete. By enhancing both the mechanical properties and durability of recycled aggregates, this treatment offers a promising approach for increasing the sustainability and performance of concrete in construction applications, particularly in terms of resource conservation and waste reduction [30)].

## 3. CONCLUSIONS

The growing environmental concerns surrounding traditional concrete production, particularly due to the high carbon emissions from cement manufacturing, necessitate the development of sustainable alternatives. This review highlights the potential of bio-based materials—such as wood ash, rice husk ash, and corn cob granules—as partial replacements for cement, sand, and coarse aggregates in concrete. These materials, derived from renewable agricultural and industrial waste, offer several environmental and economic benefits, including reduced $CO_2$ emissions, improved waste management, and enhanced thermal insulation. Research indicates that, when used appropriately, these bio-materials can maintain or even improve key properties of concrete, such as compressive strength, durability, and workability. However, challenges remain in terms of material variability, reduced early strength, high water absorption, and limited structural applications, particularly at higher replacement levels. To fully realize the benefits of bio-based concrete, further research is needed to standardize processing methods, optimize mix proportions, and evaluate long-term performance under real-world conditions. Overall, the integration of bio-based materials presents a viable and sustainable path forward for reducing the environmental footprint of the construction industry, aligning with global efforts to promote circular economy practices and low-carbon infrastructure.

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