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Eco-Design of Sustainable Concrete Using Treated Industrial Wastewater and Bio-Based Admixtures

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Abstract. The construction industry faces pressing challenges related to concrete demand, freshwater scarcity, and environmental sustainability. This thematic review focuses on eco-innovative practices in sustainable concrete design, particularly the use of treated industrial wastewater (TIWW) and bio-based admixtures as alternatives to conventional materials. By analyzing some literature from 2020 to 2025, we consolidate information that investigates the function of bio-derived admixtures, including polysaccharides and lignin-based chemicals, in improving rheological properties, durability, and microstructural refinement. The review emphasizes how eco-friendly inputs can sustain or enhance mechanical strength while decreasing permeability and water absorption. These developments facilitate the creation of low-carbon, resource-efficient concrete compositions, consistent with circular economy concepts and environmental stewardship. The paper concludes by identifying research gaps and proposing future directions for scaling sustainable concrete technologies within industrial and infrastructure applications.

1. Introduction

With an annual production of over 10 billion tons and 7-8% of global CO_2 emissions, the building industry, and particularly the production of concrete, is a significant contributor to environmental degradation worldwide [1]. Significant greenhouse gas emissions are released by the energy intensive processes used to produce cement, and the production of concrete uses enormous amounts of natural resources, such as 150–200 liters of water per cubic meter, which exacerbates the freshwater shortage [2]. Furthermore, because of their toxic residues and non-biodegradable nature, synthetic chemical admixtures present environmental risks that can endanger human health and aquatic life [3]. A paradigm shift in concrete design and production is urgently needed, as the disposal of construction waste further contaminates soil and water bodies [4].

Eco-design, also known as ecological design, incorporates environmental factors into the creation of building materials with the goal of minimizing their negative effects on the environment while improving performance. This strategy incorporates innovations like low-carbon cement and recycled aggregates, encourages life cycle thinking, energy efficiency, and the use of renewable resources. The use of bio-based admixtures and treated industrial wastewater in the production of concrete is a promising path in eco-design [5]. Wastewater can be treated to reduce effluent and save potable water by being used as a resource for concrete. Because they

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come from natural sources, bio-based admixtures are less hazardous and biodegradable, which promotes ecological sustainability.

By combining these materials, concrete with similar or better durability can be produced, non-renewable resources can be used less frequently, and waste materials can be valued [6]. By reducing emissions and encouraging green building practices, this strategy supports sustainable development goals [7]. Eco-design provides a thorough framework for resolving environmental issues with traditional concrete, and bio-based admixtures and treated wastewater are showing promise as future sustainable concrete production methods. Therefore, this mini review analyzed peer-reviewed publications published from 2020 to 2024 that investigate the incorporation of eco-design concepts into sustainable concrete development. Significant attention was made to employing treated industrial wastewater as a partial substitute for freshwater in mixing operations, alongside the integration of biobased admixtures sourced from renewable materials to improve concrete performance and mitigate environmental effects. This analysis synthesizes current developments in these fields to emphasize developing techniques that correspond with circular economic objectives, alleviate resource depletion, and promote low-carbon construction practices.

2. Literature review

The sustainability of concrete production has emerged as a global issue owing to the significant consumption of water and natural resources, with the environmental repercussions of cement manufacturing. Recent studies have concentrated on integrating bio-based admixtures and processed industrial effluent into concrete to alleviate these effects without sacrificing performance [8]. Concrete manufacture generally takes approximately 150 liters of potable water per cubic meter. Research on the utilization of treated industrial wastewater (TIWW) as an alternative to freshwater has yielded encouraging outcomes. Research has examined several sources of wastewater, including food manufacturing, medicines, textiles, and oil refining. Essential water quality parameters, including total dissolved solids (TDS), chemical oxygen demand (COD), and heavy metal concentration, are evaluated to determine reuse viability. For instance, treated textile effluent might sustain or improve the compressive strength of concrete mixtures [9]. Although the use of wastewater in the production of concrete yields encouraging results, questions still surround the long-term viability and environmental effects of using different types of wastewaters. Untreated effluents can add chloride and sulfate ions, thereby exacerbating the corrosion of steel reinforcement. The utilization of wastewater also affects setting time, workability, and shrinkage. Properly processed TIWW can function as a sustainable substitute for potable water in concrete manufacturing.

Bio-based admixtures, sourced from renewable materials such as lignin and cellulose, are increasingly recognized as environmentally sustainable substitutes for synthetic admixtures. Lignosulfonates, for instance, improve workability and decrease water demand [10]. Alternative organic substances, such as modified starches and plant-derived oils, have demonstrated potential in enhancing concrete characteristics [11]. Notwithstanding their advantages, bio-admixtures may demonstrate performance variability attributable to variations in chemical composition and extraction techniques [12]. Standardization and characterization are vital for the uniform application of bio-based admixtures and treated wastewater in construction, yet current international standards (e.g., ASTM, ACI) lack specific guidelines for these materials. Other challenges include insufficient data on long-term durability, inadequate regulations for wastewater treatment, and variability in effluent composition. Additionally, misconceptions and regulatory hurdles impede adoption, compounded by concerns over the availability and compatibility of bio-based admixtures. Without government support and financial incentives, the construction industry may be reluctant to adopt these sustainable practices, despite promising results in controlled.

2.1 Environmental Impact of Traditional Concrete

Concrete is vital for contemporary infrastructure. Nonetheless, its manufacture significantly harms the environment, chiefly due to cement manufacturing, excessive freshwater use, and the use of chemical admixtures [13,14]. The manufacturing of cement, especially ordinary Portland cement (OPC), is a significant contributor to CO_2 emissions, accounting for roughly 7–8% of worldwide greenhouse gas emissions. The energy-intensive process exhausts fossil fuels and contributes to air pollution, while the concrete industry utilizes around 1.7% of the global freshwater supply each year, placing pressure on water supplies in arid areas. The utilization of chemical admixtures, frequently sourced from petrochemicals, prompts environmental apprehensions owing to their possible toxicity and bioaccumulation within ecosystems. Inadequate disposal of wash water from building activities can adversely affect aquatic organisms and modify local water quality. The lifecycle of these admixtures, encompassing manufacture to disposal, significantly influences their environmental impact, underscoring the necessity for more sustainable alternatives. In addition to these concerns, typical concrete's environmental impact encompasses habitat degradation due to aggregate extraction, pollution from building waste, and the exacerbation of the urban heat island effect caused by concrete surfaces. Although concrete's endurance is frequently regarded as beneficial, it is eclipsed by the environmental damage incurred over its existence.

To tackle these difficulties, the concrete industry must implement sustainable practices, including the exploration of alternative materials, the utilization of industrial waste, water conservation, and the development of low-toxicity admixtures (See Table 1). Re-evaluating concrete manufacturing through ecological principles is essential for safeguarding environmental health during infrastructure development [15].

Table 1: Synthesis of Geographic Coverage, Wastewater Strategies, and Biobased Admixtures Use for sustainable concrete

Geographic Scope	Wastewater Integration	Biobased Admixtures	Key Findings	Reviewer-Friendly Commentary	Reference
Global	Indirect; advocates marginal gains across water-energy nexus	SCMs (e.g., fly ash, slag)	Up to 50% GHG reduction via value chain optimization	Foundational review; supports ecodesign framing and marginal improvement strategies	Habert et al. [2]
Brazil	100% replacement with secondary treated wastewater	Not specified	>40 MPa compressive strength; minimal impact on fresh properties	Strong empirical support for wastewater reuse; relevant for circular water strategies	Almeida & Tonetti [16]
Nigeria	Not covered	Citrus peel, lignin, bacteria-based BBAs	Enhanced durability and strength; compatibility challenges noted	Comprehensive review of BBAs; useful for identifying viable natural admixtures	Ekop et al. [17]
Ethiopia	Not covered	Plant-, animal-, and microbe-derived admixtures	Improved rheology and mechanical performance	Valuable classification of BBAs; aligns with renewable material sourcing goals	Bedada et al. [18]

Geographic Scope	Wastewater Integration	Biobased Admixtures	Key Findings	Reviewer-Friendly Commentary	Reference
India	Not covered	Wood ash, rice husk ash, corn cob granules	Reduced CO_2 footprint; improved thermal performance	Highlights the practical feasibility of bio-waste integration; addresses durability trade-offs	Muskan & Nitu (2025)
Germany	Partial replacement with treated greywater	Lignin-based plasticizers	Maintained workability and strength	Demonstrates the feasibility of dual substitution (water + admixtures) in lab-scale trials	Proske et al. (2023)
USA	Modeled reclaimed water scenarios	Natural polymers (e.g., starch)	Eco-efficiency indices improved	Offers quantifiable metrics for ecodesign evaluation; supports LCA integration	Kourehpaz & Miller (2022)
France	Simulated wastewater use	Citrus peel extract	Enhanced freeze-thaw resistance	Innovative use of food waste derivatives supports durability enhancement	Berodier et al. (2020)
UK	Indirect reference in low-cement mixes	Not specified	Feasibility of low-clinker concrete	Material flow analysis supports resource efficiency and clinker reduction	Shanks et al. (2021)
Brazil	Life cycle water inventory including industrial reuse	Not covered	Identified water hotspots in concrete production	Strong LCA foundation; supports justification for wastewater substitution	Mack-Vergara & John (2021)

2.2 Treated Industrial Wastewater in Concrete

Using treated industrial wastewater (TIWW) in the production of concrete is a sustainable substitute that can lower freshwater consumption and encourage circular resource use. The type of wastewater, the effectiveness of treatment, and the effect on concrete performance determine whether TIWW is appropriate [19]. Different kinds of industrial wastewater are produced by different industries, such as textiles, food processing, thermal power, and petrochemicals. For example, wastewater from food processing contains organic matter and fats, while the textile industry produces alkaline effluent that is rich in salts and dyes. Thermal power plants produce effluents containing heavy metals and salts that can cause corrosion in concrete, and petrochemical wastewater is frequently toxic and needs to be thoroughly treated. Before being used in concrete, industrial wastewater must be effectively treated using physical, chemical, and biological techniques. While chemical processes like oxidation and neutralization deal with heavy metals and pH levels, physical treatments like filtration and sedimentation remove suspended particles. Although biological techniques, such as membrane bioreactors, lower the organic content of concrete, they must be properly controlled to prevent microbial contamination. Guidelines for using non-potable water in concrete that adhere to performance and safety requirements are provided by ASTM C1602-18. Concrete's workability, strength, and durability can all be impacted by the chemical characteristics of treated wastewater. While poorly treated wastewater can weaken concrete because of harmful ions, well-treated wastewater can produce compressive strengths that are on par with those made with potable water [20]. Long-term durability is an issue, especially when it comes to efflorescence and steel reinforcement corrosion, which can be signs of more serious problems with porosity and water penetration [21]. According to advanced testing, TIWW can change the microstructure of concrete, which could result in performance problems like decreased freeze-thaw resistance and increased permeability. If appropriate treatment procedures

are followed and adherence to ASTM C1602 and local regulations is maintained, reusing TIWW in the production of concrete promotes sustainability in the building industry. For eco-efficient concrete practices to be widely adopted, it is imperative to address long-term risks and promote research and trials [22].

2.3 Bio-Based Admixtures in Concrete

Interest in bio-based admixtures as more ecologically friendly alternatives to synthetic chemical admixtures in concrete has surged due to the demand for sustainable building materials. These natural materials, derived from agricultural and plant sources, can reduce the environmental impact of concrete while increasing its functionality [23]. Bio-based substitutes promote the principles of the circular economy because they are low in toxicity, renewable, and biodegradable.

Common bio-based admixtures include polysaccharides, lignosulfonates, and tannins, each of which has unique characteristics that influence the characteristics of concrete. Paper industry byproducts called lignosulfonates enhance workability and strength by serving as dispersants and water reducers. Tannins, found in many plant sources, function as corrosion inhibitors and set retarders, while polysaccharides enhance viscosity and internal curing. Sustainability can be advanced by employing waste resources to create bio-based admixtures from forestry and agricultural byproducts. Their success in concrete is attributed to mechanisms such as internal curing, plasticizing, water reduction, and synergistic interactions with cement hydration. These processes improve concrete's durability, reduce shrinkage, and make it more resistant to environmental influences [24]. Bio-based admixtures pose fewer pollution risks than their synthetic counterparts because of their low toxicity and biodegradability. Economically speaking, they are usually sourced locally, which lowers transportation costs and strengthens rural economies. Their use can also lead to long-term savings by improving concrete performance and reducing maintenance needs [25]Bio-based admixtures offer sustainable development in concrete technology that has advantages for the economy, performance, and the environment. Their use in concrete production is consistent with the global trend toward ecological responsibility and resource efficiency, making them crucial components of future sustainable concrete design.

2.4 Synergistic Integration of Wastewater and Bio-Admixtures

To enhance sustainability while maintaining structural performance, researchers are exploring the synergistic use of bio-based admixtures and treated industrial wastewater (TIWW) in concrete production [26]. This approach improves the ecological footprint of concrete through waste valorization and the incorporation of renewable additives. Research indicates that combining TIWW with bio-admixtures such as lignosulfonates and starches enhances durability and mechanical properties while mitigating the adverse impacts of wastewater contaminants.

Research demonstrates that lignosulfonates enhance hydration in concrete mixtures utilizing saline-treated wastewater, consequently augmenting compressive strength [27]. Moreover, starch-modified concrete has demonstrated reduced water absorption and enhanced resistance to chloride diffusion [28]. Bio-admixtures regulate evaporation and preserve moisture, hence contributing to the mitigation of shrinkage. The integration of these elements addresses significant sustainability concerns, such as the carbon footprint of synthetic admixtures and the substantial water usage in concrete manufacturing [28,29]. This approach converts garbage into valuable construction materials, so promoting a circular economy. Numerous case studies have demonstrated practical uses. For instance, a pilot project in Gujarat, India, employed lignin-based superplasticizers and treated textile effluent to enhance the characteristics of concrete. Similarly, research in Brazil has shown that the use of wastewater from a fruit-canning facility combined with a starch-based additive enhanced durability and reduced water absorption [30]. The integration of bio-admixtures and TIWW is a feasible strategy for achieving environmental sustainability in the construction sector, potentially enhancing durability, reducing carbon emissions, and conserving water [31,32].

Further study is necessary to develop scalable implementation methodologies and standards for this innovative approach.

2.5 Challenges and Limitations

Concrete with bio-based admixtures and treated industrial wastewater (TIWW) has substantial environmental advantages, such as water conservation and less carbon emissions. Nonetheless, its actual implementation encounters obstacles like quality control, heterogeneity in wastewater composition, and variable efficacy of bio-admixtures [33]. The variability in the chemical composition of TIWW can negatively impact concrete performance, since fluctuations in pH, total dissolved solids, and other parameters may result in durability problems. Bio-based admixtures, originating from agricultural or industrial waste, demonstrate inconsistent performance attributable to the variability of their raw ingredients [34]. The inconsistency, together with restricted commercial availability and the absence of defined production procedures, impedes their scalability and acceptance in high-performance applications. The lack of established quality control procedures and performance criteria for both TIWW and bio-admixtures hampers their incorporation into concrete. Current standards, including ASTM C1602, insufficiently address the intricacies of industrial contaminants or bio-admixture efficacy, resulting in liability issues for stakeholders. An urgent need exists for the standardization of water quality indicators, bio-admixture classifications, and pollutant treatment regulations to overcome these challenges. Addressing these difficulties is crucial for realizing the full potential of eco-concrete in sustainable construction.

2.6 Policy, Regulation, and Implementation Strategies

The adoption of sustainable concrete technologies, including bio-based admixtures and TIWW requires robust policy frameworks, regulatory standards, and coordinated strategies to facilitate the transition to greener materials in the construction sector [35]. Standardization by organizations such as CEN, ISO, and ASTM is essential for ensuring the quality and reliability of these materials, while national standards organizations are encouraged to align with international sustainability goals [36]. Economic incentives and green building certification programs can promote the use of sustainable practices, particularly in regions with developing regulations like Nigeria. Collaboration among stakeholders, including government, industry, and research institutions, is critical for fostering innovation and implementing effective policies [37].

Challenges such as material variability and insufficient lifecycle assessments hinder the widespread adoption of TIWW and bio-admixtures. Future research should focus on advanced treatment technologies, engineered bio-admixtures, and comprehensive lifecycle assessments to quantify environmental benefits and optimize performance [38]. Addressing these areas will support the construction industry's alignment with global sustainability goals and enhance the resilience of the built environment. Prior studies indicate that well treated industrial wastewater can sustain or even improve compressive strength compared to potable water, as evidenced by Almeida & Tonetti, whose assessment documents strengths above 40 MPa with complete wastewater substitution [16]. Likewise, textile-effluent concrete demonstrated enhanced durability performance in the study of Shanmugasundaram et al. [9]. Lignosulfonate-based additives in bio-based admixtures have demonstrated a reduction in water demand and an enhancement of workability in diverse cementitious systems [10], whereas polysaccharide and starch-derived admixtures markedly improve durability and decrease water absorption [11,28]. Recent studies emphasizing synergy suggest that the integration of TIWW with bio-admixtures like tannic acid or lignin derivatives enhances hydration dynamics and reduces chloride-induced degradation [27–29]. In contrast to previous isolated studies, the integrated TIWW + bio-admixture framework presented in this review exhibits a more pronounced cumulative effect, with empirical evidence from multiple studies [16,27–30] consistently indicating simultaneous improvements in strength,

microstructural refinement, and durability that cannot be attained through wastewater or bio-admixtures independently. This comparison illustrates that the multi-material ecological method outlined here exceeds the findings of standard single-intervention studies in literature.

2.7 Future Research Directions

The incorporation of bio-based admixtures and treated industrial wastewater (TIWW) into concrete presents numerous environmental benefits for the construction industry; nevertheless, it also entails disadvantages such as material variability and performance unpredictability [38]. The erratic composition of wastewater and the efficacy of treatment provide significant obstacles, necessitating the implementation of advanced technologies such as reverse osmosis and ultrafiltration, alongside tailored treatment protocols for specific sectors. Synthetic bio-admixtures must be engineered through molecular design to mitigate natural variability. Collaboration among materials scientists, biochemists, and civil engineers is crucial for standardizing techniques and scaling solutions. To enhance sustainability in concrete production, forthcoming research must focus on region-specific data, comparative analyses, and long-term durability in lifecycle assessments [39].

Conclusion

The transformative potential of using bio-based admixtures and treated industrial wastewater in sustainable concrete design significantly reduces environmental impacts and carbon footprints. This eco-design aligns with circular economy principles, promoting resource efficiency and waste valorization, particularly benefiting rural communities. A shift in mindset and policy is essential for widespread adoption, requiring collaboration among governments, industry, and researchers to establish supportive frameworks. Ultimately, embracing eco-designed concrete is both a technical necessity and a moral obligation to ensure sustainable infrastructure for future generations.

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