Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 9, 1454-1461
2025
Publisher: Learning Gate
DOI: 10.55214/2576-8484.v9i9.10152

Harnessing the impact of biodegradable materials for sustainable concrete innovations, enhanced mechanical and corrosion mitigation A Mini review

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Abstract: This mini review explores the use of agricultural waste as supplementary cementitious materials (SCMs) to address environmental and performance challenges in the construction industry. The study employs a secondary data approach through a literature review for a comprehensive overview. Agricultural residues such as rice husk ash, sugarcane bagasse ash, and coconut shell ash possess pozzolanic properties that enhance the mechanical and durability characteristics of concrete while reducing the consumption of conventional cement. These materials contribute to sustainability by decreasing carbon dioxide emissions during concrete production and addressing agro-waste management issues. Additionally, natural fibers like sugarcane bagasse fibers improve tensile strength, offer superior flexural properties, and exhibit excellent resistance to corrosion, making them suitable for structural applications. The review emphasizes the potential of agricultural wastes to reduce greenhouse gas emissions and conserve natural resources, while also discussing challenges and future research directions to optimize their utilization.

Keywords: *Agricultural waste, Concrete sustainability, Corrosion resistance, Pozzolanic materials, Supplementary cementitious materials.*

1. Introduction

Concrete is the backbone of modern infrastructure and due to its versatility, durability, and affordability, it is the most consumed construction material in the world [1-3]. However, its high-volume production has raised serious environmental concerns, such as high greenhouse gas emissions, resource depletion, and ecological degradation. The cement industry, one of the largest contributors to CO_2 emissions, is under increasing pressure to adopt sustainable practices to align with global climate goals. Agricultural waste is a promising direction for solving these problems. The materials like rice husk ash, sugarcane bagasse ash, and coconut shell ash have pozzolanic properties that make them feasible as supplementary cementitious materials. These materials improve the mechanical and durability properties of concrete, including compressive strength, tensile strength, and corrosion resistance, while reducing the amount of conventional cement used [4-12]. Other agro-waste fibers, such as sugarcane bagasse and banana fiber, were further found to enhance the flexural-shear behavior and retard the crack propagation that enhances the integral structural performance of concrete [13, 14].

The addition of agricultural waste in concrete not only addresses the environmental footprint of traditional concrete production but also provides a sustainable solution for managing agro-waste [15-17]. This mini review investigates the dual benefits resulting from the addition of agricultural residues and fibers to concretes, underlining improvements in performance and environmental benefits. Based on recent research, this review intends to enlighten readers about the revolutionary role these materials could play in the development of sustainable construction.

History: Received: 7 July 2025; Revised: 14 August 2025; Accepted: 18 August 2025; Published: 23 September 2025
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2. Agricultural Waste as Supplementary Cementitious Materials (SCMs)

Agricultural residues like Sugarcane bagasse ash, peanut shell ash, rice husk ash, coconut coir, bamboo fibers and maize stalk fibers, have been recognized for their pozzolanic characteristics, suggesting they can partially substitute cement in construction applications. They are seen as cementitious materials. These materials not only serve as eco-friendly alternatives but also contribute to improved mechanical properties when incorporated into concrete mixes. Research has demonstrated that these agricultural wastes can effectively replace a portion of cement, leading to enhanced durability and strength in concrete structures [18-20]. Studies carried out on Rice husk ash (RHA), show that RHA enhances fresh and mechanical properties of concrete a reason being that it has very smooth particle size and high amorphous silica content. It improves workability, consistency, and setting time, while also increasing compressive, tensile, and flexural strength up to an optimal RHA content. It also showed that RHA boosts durability by enhancing the rate at which water is absorbed, preventing chloride corrosion, and providing resistance to sulphates. It can replace cement by 10–20 percent without affecting concrete durability negatively, hence enabling resource conservation and agricultural wastes management, thus promoting a promising economy [21].

In their investigation on the suitability of Coconut Shell Ash (CSA) as a cement replacement in concrete, Bheel, et al. [22] established through various studies that the addition of 10% CSA improves the mechanical properties needed for concrete durability. Vasanthi, et al. [23] studied the influence of cement replacement with coconut shell ash and coarse aggregate replacement with coconut shell on the mechanical properties of concrete. Density reduction was found to be more than 4% at optimum replacement levels and more than 13% at higher replacement levels. Compressive strength of concrete improved with the replacement of up to 15% CSCA and 10% CSA, beyond which compressive strength gradually decreased. Similarly, the flexural strength increased with the compressive strength, reaching its maximum at 15% CSCA and 12% CSA replacement, while the flexural strength was about 11% of the corresponding compressive strength.

Bheel, et al. [24] investigated the possibility of using SCBA as a replacement for sand and CBA as a replacement for Portland cement. They found that the substitution of cement and fine aggregate with CBA and SCBA, respectively, produced a concrete mix that reduced the environmental impact of concrete production. Their results also showed an improvement in compressive and tensile strengths for all grades of CBA replacement, provided the percentage of SCBA did not exceed 20% for fine aggregate. On the other hand, workability, dry density, as well as water absorption in hardened state, were generally considerably below that of the referenced mixture, whatever the value of substitution rate. It also investigated the carbon footprint of the concrete mixed with SCBA and CBA and reported on the eco-efficiency strength of concrete. Their study revealed that SCBA utilization as a fine aggregate replacement, together with CBA usage as a cement replacement in concrete mixtures, could result in significantly lowering the carbon footprint arising from cement production. Other common methods involve adding fibers to concrete to achieve improved mechanical and corrosion properties; most of these fibers have been derived from agricultural wastes. Examples are carbon fiber, sugarcane bagasse fiber, and banana fiber. It is worthy to note that fibrous wastes, as revealed in studies such as those by [25-27] make concrete more resistant, specifically by improving its cracking resistance and enhancing flexural and tensile strength. These works give reasons why agricultural wastes are proven partial substitutes for both cement and fine aggregate, providing an assurance of acceptable performance.

3. Environmental Impacts of Traditional Concrete

Concrete is the most widely used construction material in the world due to its unparalleled advantages over other materials [28]. It finds such widespread application because of its excellent mechanical properties and reasonable pricing [29]. However, concrete use is under increasing scrutiny because it will be very difficult and expensive to transition it to the low-carbon future by investing heavily in carbon capture and storage technology. Additionally, ongoing urbanization is anticipated to drive continued growth in the concrete industry, leading to increased resource consumption and emissions [30]. The extraction of natural resources for concrete production harms green landscapes, disrupts habitats for plants and animals, and poses risks of ecological imbalance. Ongoing exploitation of these vital resources also increases the risk of future depletion. Additionally, processing raw materials in factories produces particulate matter, sound pollution, and atmospheric pollutants, especially CO_2, which contaminates the environment and exacerbates global warming, adversely impacting human lifestyles [31]. Although the environmental impacts of cement and concrete per unit of material are relatively low, their extensive global use highlights the importance of efforts to reduce associated emissions [30].

4. Mechanical Properties Enhancement

Concrete is one of the most widely used and valued building materials due to its excellent mechanical properties [29]. However, plain concrete has poor tensile strength and little resistance to cracking before reaching its peak load-carrying capacity [32]. The incorporation of agricultural waste into building materials has shown potential in improving structural properties. Various agricultural wastes, such as rice husk ash, sugarcane bagasse ash, and palm oil fuel ash, had been studied for potential use to enhance the mechanical properties of concrete and other binding materials. Several works reported an improvement of concrete properties by the use of agriculture wastes [17].

4.1. Strength and Durability

Various studies have evaluated the load-carrying capacity, tensile strength, and bending strength that agricultural wastes impart to concrete. The presence of agricultural waste has proven to have improved these due to inducing pozzolanic action and filler actions, creating a stronger and much more durable concrete matrix. Studies have highlighted the significance of using agro-waste ash and fibers by partially substituting up to 10–30% of cement with these agro-wastes to produce high-strength concrete [33]. Most of the studies related to RHA as agricultural waste indicate that the replacement of 20-30% of cement with RHA improves the physical and mechanical properties and operational performance of concrete. These studies were conducted by Amran, et al. [34].

The application of Sugarcane Bagasse-fiber as an organic admixture into the concrete had significantly increased the compressive strength. The study shows that after 28 days of curing, the lesser percentage of fiber added on the contrary, showed more compressive strength than the sample without fiber. Higher percentage of fiber, however, results to decrease in compressive strength [35]. Not always the same are such agricultural wastes that are incorporated into mixes like that. After burning to ash, these could be added at very high percentages (even up to 30). There has been an increase in compressive strength and hardened density due to burning of the sugarcane fiber and turning it into ash. At 28 days of curing, a compressive strength of 21 Mpa was reached, which is quite suitable for structural applications. Similar results can also be obtained with RHA, which can be added to the same percentages and still give impressive compressive strength [29, 36].

4.2. Flexural and Shear Behavior

Flexural ability has always been one of the major considerations in construction. This is one reason why reinforcements are used in concrete: to prevent beams and slabs from breaking when they are too long. So, using agricultural wastes will influence the flexural and shear characteristics of concrete if at all it is to be used in those applications. Several studies have been conducted on the effect of these wastes in applications relating to flexure and shear. These investigations reveal that the incorporation of agricultural residues could strengthen pliability and endurance of concrete, critical for the structural integrity of buildings and infrastructure [37, 38]. Agricultural waste fibers are useful in improving bending and lateral strengths of concrete structures; they also perform the task of controlling thermal cracking and shrinkage beyond its ductile state, which is additionally accompanied by micro-cracking in the concrete under load [25].

As a waste fiber, sugarcane bagasse has been found to enhance tensile strength in normal concrete. Khalid, et al. [35] conducted a study after 28 days of curing and found that there was an increase in tensile strength with more fiber inclusion. Another example of such agricultural waste fibers that studies have been carried out on is the banana and palm leaf sheaf fiber. These fibers have been seen to improve both the mechanical strength and more importantly now the flexural strength. In the research carried out by Saad, et al. [39] the fibers were able to achieve high flexural strength of up to 11.7Mpa at 1% inclusion of fiber. At higher percentage of fiber inclusion, the flexural strength decreases. Apart from waste fibers, burnt agricultural wastes have also been seen to improve flexural properties, in fact doubling that of conventional concrete as seen in a study carried out by Gaddafi, et al. [40].

5. Corrosion Resistance

5.1. Corrosion Mechanisms in structural concrete

One of the things that impacts concrete structures is the aspect of deterioration of steel rebar. This is a major concern especially in environments where the corrosion of the rebar progresses faster. Conventional concrete is prone to cracking and has low tensile strength, allowing harmful substances such as chlorides and carbonation to penetrate, leading to corrosion, freeze-thaw damage, and discoloration. The penetrability of concrete is influenced by the aggregate type and quality, cement type and proportion, and the ratio of water to cement (binder), as well as production variables like mixing consistency, placement, compaction degree, and curing effectiveness [41-43]. The roughness of the steel and how clean the steel is are always considered because they are the onset of corrosion in reinforcements. In reinforced concrete, there are always local variations which is usually observed at the interface between steel and concrete. For structures exposed to atmospheric conditions, the moisture levels and pore structure at the interface play a crucial role in dictating the corrosion process. Whether caused by carbonation or chloride penetration, the corrosion typically exhibits non-uniform patterns, driven by environmental disparities and the presence of interconnected rebars with differing characteristics [44].

Concrete carbonation happens because of exposure to atmospheric CO_2, along with SO_x and NO_x gases. The carbon dioxide (CO_2) in the atmosphere reacts with the alkaline pore water in concrete, resulting in pH lowering to approximately 9. The decrease in pH disrupts the stability and integrity of the layer that normally protects the steel surface from corrosion by blocking corrosive agents. However, when the pH levels begin to reduce due to carbonation, the passive film can destabilize, exposing the steel to these corrosive agents. The extraction of alkalis from concrete lowers the pH, which makes the whole process of steel deterioration faster in concrete. This degradation would actually reduce the future structural durability of concrete. How these corrosion mechanisms develop in the context of reinforced concrete structures is quite complicated because most types of RC structures differ significantly and because the location of their actual environment affects them considerably [43].

5.2. Corrosion Inhibition with Agricultural Waste

Corrosion inhibitors are chemical substances used to protect rebar steel in reinforced concrete by reducing the rate of its rusting without significantly altering the overall properties of concrete [45]. On the other hand, attempts to replace natural materials with wastes have indicated that adding agro-waste ash or fiber into cement resulted in outstanding performances in mortar and concrete under hostile conditions like exposure to hydrochloric acid [42]. Several agricultural wastes have been studied on their corrosion-inhibiting properties. The surface of the reinforcement has afterwards been observed. These wastes have been able to create a layer on the reinforcement surface which reduces penetration of aggressive agents and mitigates the corrosion process [46, 47]. The ability of these wastes to develop a protective layer on the reinforcement surface makes them good inhibitors. They are also more ready to form protection layers on the reinforcement surface in contact, as Sugarcane bagasse ash [46]. In addition, the efficacy in still inhibiting remarkably the corrosion process under harsh conditions, as experimented with by Cui and Wang [48] using RHA, predisposes these wastes to suitable applicability in cases where easy degrading of concrete through the corrosion process may easily set in. Various factors like chloride infiltration, acid durability, and moisture uptake have been tested while using these materials that can replace cement. These materials reflect very promising results when tested against these factors [49].

Fibers are known to enhance the durability of reinforced concrete by delaying the formation and spread of cracks, thus increasing its resistance to corrosion. The addition of fibers to concrete brings a tremendous advantage in structural integrity by preventing the initiation and propagation of micro-cracks, thus reducing the likelihood of sudden fractures. This inclusion results in shorter crack propagation within the concrete matrix once it has hardened, thereby significantly improving the composite's resistance to environmental conditions and its overall durability [50]. How effectively fibers used can improve conventional concrete is governed by multiple factors such as the aspect ratio of the fibers, their stiffness, the concentration of fibers in the composite, size of coarse aggregate, fiber alignment, and the workability of the concrete which affects how well the fibers are dispersed and aligned. To take full advantage of this reinforcement, the elements must be carefully considered during both material selection and structural design. The presence of cracks in concrete also plays an important role in the corrosion process; it not only affects the initiation time but also accelerates the progression. Since the cracking behavior in FRCs is very different from that in unreinforced concrete, it is well expected that the mechanisms of degradation will be different as well [51].

Thus, examine experimental methods of evaluating enhancement capability of fibers toward corrosion resistance subjecting them to corrosives like chloride in such an environment for several hours while exposing test samples to determine its performance in reducing or preventing corrosion [52]. Several natural compounds present in agricultural wastes such as lignins tannins polyphenols, and organic acids, do play a role in corrosion inhibition by more than one [45, 53]. Protective film formation, metal ion chelation, free radical scavenging, and surface passivation are examples of these processes. This is one of the properties that make agricultural waste good for the sustainability [39, 45, 54-56].

6. Conclusion

The use of agricultural waste in concrete is an innovative solution that has tried to address these two important issues related to environmental sustainability and performance improvement in the construction industry. Materials such as RHA, SCBA, and CSA reduce the carbon footprint in concrete production while improving its mechanical properties and durability. Concrete is also improved in its structural integrity and corrosion resistance with the addition of agro-waste fibers and has found a place in many applications. Besides these advantages, the challenges with respect to material properties, cost of processing, and scalability need further deliberation. Future studies are recommended in order to achieve performance uniformity in the application of agricultural waste in concrete, with wider industrial applications. In harmony with the innovative practices in response to global sustainable development imperatives, agricultural waste presents an opportunity for the building and construction industry to construct a more resilient and sustainable future.

Transparency:

The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Acknowledgement:

The Bells University of Technology is duly acknowledged for their support during this research.

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Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 9: 1454-1461, 2025
DOI: 10.55214/2576-8484.v9i9.10152