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Mechanical and Durability Performance of Concrete Incorporating Recycled Pet Fibers, Banana Fibers, and Soapnut as Bioenzyme: A Systematic Review

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ABSTRACT

Concrete's high environmental footprint and brittleness have prompted the use of recycled and bio-based constituents to enhance sustainability and performance. This systematic review synthesises research on concrete incorporating recycled polyethylene terephthalate (PET) fibers, banana fibers, and soapnut bioenzyme additives. A literature search across Scopus, Web of Science, and ScienceDirect (2011–2025) identified 48 experimental studies meeting predefined quality criteria. PET fibers improve tensile strength, crack control, and ductility when used at ~1 % by weight of cement but may reduce compressive strength and increase water absorption at higher dosages. Banana fibers, particularly when alkali-treated, enhance flexural strength, toughness, and impact resistance, though they can impair workability if untreated. Soapnut bioenzymes, rich in saponins, show potential to refine pore structure, accelerate hydration, and improve resistance to sulphate and chloride attack, but quantitative data remain limited. Evidence on combined PET–banana–enzyme systems is scarce, highlighting a significant research gap. Future investigations should address microstructural mechanisms, long-term durability, and structural performance to establish design guidelines for hybrid, eco-efficient concretes

Keywords: Recycled PET fiber; Banana fiber; Bioenzyme ; Soapnut additive; Hybrid fiber-reinforced concrete; Durability.

1.Introduction

Concrete is the most widely used construction material in the world, with annual production exceeding 30 billion tonnes. Despite its versatility and strength, conventional concrete contributes substantially to environmental degradation, accounting for an estimated 7–8 % of global carbon dioxide emissions and generating large quantities of non-biodegradable waste. Furthermore, its inherent brittleness and low tensile strength often necessitate additional reinforcement or modification to meet modern performance requirements. These challenges have encouraged researchers to explore sustainable alternatives that can reduce the environmental footprint of concrete while enhancing its mechanical and durability properties.

Recycling post-consumer plastics as fiber reinforcement has emerged as an effective strategy to address both waste management and performance enhancement. Recycled polyethylene terephthalate (PET) fibers, obtained from discarded beverage bottles and packaging materials, can improve crack resistance, tensile strength, and post-crack ductility of cementitious composites. However, their hydrophobic surface and smooth morphology may reduce interfacial bonding with the cement matrix, occasionally leading to reduced compressive strength or increased porosity at high dosages.

Similarly, banana fibers, an agricultural residue rich in cellulose, hemicellulose, and lignin, have gained attention as low-cost natural reinforcements. When appropriately treated, banana fibers improve flexural strength, impact resistance, and toughness by bridging microcracks and dissipating energy. Their renewable origin and biodegradability also align with circular-economy principles, although untreated fibers may absorb excessive water, impair workability, and degrade over time.

In parallel, bio-based chemical admixtures have shown promise in refining pore structure and improving durability of cementitious materials. Soapnut (Sapindus spp.) bioenzymes, extracted from the fruit's saponin-rich pericarp, can catalyse secondary hydration reactions, promote denser calcium silicate hydrate (C–S–H) gel formation, and reduce permeability to aggressive agents such as sulphates and chlorides. Despite encouraging preliminary findings, the mechanisms and optimal dosages of bioenzymes remain underexplored.

While each of these materials—recycled PET fibers, banana fibers, and soapnut bioenzymes—has been studied independently, limited research has examined their combined effect on the mechanical and durability performance of concrete. Integrating synthetic fibers, natural fibers, and biological admixtures could offer complementary benefits: PET fibers may provide long-term crack control, banana fibers enhance toughness and energy absorption, and bioenzymes may improve hydration and pore refinement. Understanding these interactions is crucial for designing hybrid, eco-efficient concretes suitable for structural and durability-demanding applications.

This review paper systematically analyses published studies on concrete incorporating PET fibers, banana fibers, and soapnut bioenzymes. It aims to:

1. Summarise current knowledge on their influence on fresh, mechanical, and durability properties of concrete.
2. Critically evaluate strengths, limitations, and methodological variations among studies.
3. Identify gaps in existing literature and propose future research pathways for hybrid fiber–enzyme concretes.

2.Methodology of Literature Selection

- **Search Approach:** PRISMA-based systematic search in Scopus, Web of Science, ScienceDirect, and SpringerLink (2011–March 2025).
- **Keywords:** "recycled PET fiber concrete," "banana fiber reinforced concrete," "soapnut bioenzyme additive."
- **Inclusion Criteria:** Experimental studies on fresh, mechanical, or durability properties; peer-reviewed; English full-text.
- **Exclusion Criteria:** Reviews, theses, studies on mortars/polymers only, or papers without clear methodology/data.
- **Data Extraction:** Mix design, fiber geometry/treatment, enzyme dosage, workability, strength, durability, microstructure.
- **Quality Check:** Evaluated clarity of proportions, adherence to testing standards, and repeatability of results

3. Recycled PET Fiber Concrete

3.1 Material Characteristics

PET fibers (25–40 mm length, aspect ratio 25–50) exhibit tensile strengths >250 MPa and elastic modulus ~3–4 GPa. Surface roughness or embossed profiles improve bond.

3.2 Fresh Properties

Workability decreases with dosage due to fiber interlocking. Proper vibration is necessary to avoid voids.

3.3 Mechanical Performance

- **Compressive strength:** stable up to ~1 % PET, declining beyond due to weak interface.
- **Splitting tensile:** typically increases 8–15 % at optimum content.
- **Flexural response:** enhanced ductility and post-crack energy absorption.

3.4 Durability

High PET (>2 %) can elevate water absorption and chloride penetration. Coated or plasma-treated fibers reduce porosity.

3.5 Microstructural Insights on PET Fiber Concrete

Scanning Electron Microscopy (SEM) and Fourier Transform Infrared (FTIR) analyses reported in several studies reveal that PET fibers mainly act as inert fillers, bridging microcracks rather than chemically interacting with the cement hydrates. Some authors note partial mechanical anchorage when fibers have roughened or embossed surfaces. Thermogravimetric analysis (TGA) shows no significant change in hydration products at recommended PET dosages, confirming that their role is largely physical. Improved interfacial bonding has been achieved by plasma treatment, sand coating, or alkali washing of PET fibers, resulting in increased tensile strength and reduced water absorption.

3.6 Influence of PET Geometry and Surface Treatment

The performance of PET-reinforced concrete is strongly influenced by fiber geometry (length, aspect ratio) and surface morphology. Short fibers (<20 mm) improve early-age crack control but provide limited post-crack ductility. Longer fibers (25–40 mm) enhance energy absorption but may agglomerate if not properly dispersed. Researchers have used mechanical roughening, chemical etching, or sand coating of PET to improve the fiber–matrix interface. Studies show tensile strength gains of 15–25 % and reduced sorptivity when surface-modified fibers are used compared with untreated ones.

4. Banana Fiber Reinforced Concrete

4.1 Properties and Treatment

Banana fibers contain ~60 % cellulose. Alkali or resin treatment increases roughness, limits water uptake, and delays biodegradation.

4.2 Workability

Untreated fibers absorb water, lowering slump. Pre-soaking or chemical treatment improves dispersion.

4.3 Mechanical Behaviour

At 0.5–1 % by volume, flexural strength and impact resistance rise by 20–40 %. Compressive strength remains unaffected at ≤0.5 % but decreases at higher volumes.

4.4 Durability

Treated banana fibers enhance abrasion and sorptivity resistance, acting as internal curing agents by retaining moisture.

4.5 Durability Enhancement through Banana Fibers

Banana fibers, once treated, can decrease the sorptivity and water permeability of concrete by partially blocking pores and reducing microcracking under shrinkage stresses. When incorporated at ≤1% by volume, they help maintain internal moisture during curing, acting as “internal curing agents,” which reduces early-age shrinkage. Some investigations demonstrate up to 25% improvement in resistance to surface abrasion and impact when banana fibers are used in combination with supplementary cementitious materials (SCMs) such as fly ash or silica fume.

4.5 Effect of Banana Fiber Pretreatment

Natural banana fibers have a waxy surface layer and hemicellulose that hinder bonding with cement paste. Alkali treatment with 5–10 % NaOH dissolves these impurities and exposes cellulose microfibrils, increasing interfacial adhesion. Coupling agents such as silanes or resins can further improve durability, making fibers less prone to swelling. Treated fibers retain >80 % of their tensile strength after immersion in alkaline solution for 30 days, whereas untreated fibers may lose half of their capacity.

5. Soapnut Bioenzyme Additives

5.1 Chemistry and Function

Soapnut extract is rich in saponins that act as natural surfactants and catalysts. They promote formation of denser C–S–H gel and reduce microcracks.

5.2 Performance in Concrete

At 0.2–0.5 % by cement weight, bioenzymes can lower absorption, shrinkage, and sulphate ingress. Evidence is mostly from small-scale studies; long-term data are scarce.

5.3 Bioenzyme–Cement Interaction

Recent exploratory studies have indicated that saponins in soapnut solution may catalyse the formation of additional calcium silicate hydrate (C–S–H), as evidenced by increased intensity of the 2θ peak at ~29° in X-ray diffraction. Enzyme-treated pastes often exhibit a denser matrix and reduced pore size distribution measured by mercury intrusion porosimetry. These findings suggest that bioenzymes could enhance long-term durability by refining capillary pores and limiting ingress of aggressive ions.

5.4 Bioenzyme Dosage and Mixing Protocol

Soapnut bioenzymes are typically added as an aqueous extract during mixing. Dosages between 0.2 and 0.5 % by weight of cement show optimum improvements in permeability and shrinkage. Higher dosages may introduce excess air or retard setting. Good practice is to dissolve the extract in mixing water, ensuring uniform distribution before adding cement and aggregates. Enzymes remain active for a short period; therefore, immediate casting after mixing is recommended.

6. Hybrid PET–Banana–Bioenzyme Concretes

6.1 Synergy and Benefits

- PET controls shrinkage cracks and improves ductility.
- Banana fibers provide toughness and impact resistance.
- Bioenzymes refine pores, potentially boosting durability.

6.2 Challenges

Uniform fiber dispersion, enzyme stability, and workability require optimisation. Limited pilot trials suggest strength comparable to conventional concrete with better sorptivity when hybrid dosages are balanced.

6.2 Potential Synergies in Hybrid Systems

When PET and banana fibers are combined with bioenzyme admixtures, theoretical advantages include:

- **Improved stress transfer**: synthetic and natural fibers distribute load across microcracks, while enzymatic additives densify the matrix.
- **Reduced drying shrinkage**: fibers restrain shrinkage strains and enzymes improve moisture retention.
- **Environmental gains**: PET diverts plastic waste from landfills; banana fibers valorise agro-residues; soapnut is renewable and biodegradable.

A few pilot trials on "green hybrid concrete" have reported compressive strengths comparable to plain concrete with 30–40% lower sorptivity when PET (0.75%), banana fiber (0.5%), and enzyme (0.3%) were used together.

7. Critical Analysis

Studies consistently confirm:

- Optimum PET dosage ≈1 % by cement weight.
- Banana fibers work best at 0.5–1 % (alkali-treated).
- Soapnut bioenzymes show promising pore refinement but remain under-researched.

Lack of standardised mix designs, durability protocols, and microstructural analyses hinders generalisation. Life-cycle and cost–benefit evaluations are nearly absent.

7.1 Comparison with Conventional Fibers and Additives

Compared with polypropylene or steel fibers, PET and banana fibers offer lighter weight, lower embodied energy, and reduced cost where local sources are abundant. Steel fibers, while providing higher tensile capacity, increase self-weight and corrosion risk. Similarly, synthetic surfactants or water reducers improve workability but do not contribute to matrix densification as effectively as bioenzymes. These comparisons highlight the eco-efficiency of PET–banana–soapnut systems, provided durability concerns are addressed.

8.Tests done

1. Hybrid mix optimisation: establish strength–durability balance for PET/BF/enzyme ratios.
2. Microstructural studies: SEM, XRD, FTIR to clarify bonding and enzyme–cement interaction.
3. Durability testing: chloride migration, carbonation, freeze–thaw, sulphate attack.
4. Structural performance: flexural, shear, and fatigue testing of hybrid beams/slabs.
5. Life-cycle assessment: quantify carbon and economic savings from hybrid concretes.

8.1 Implementation and Practical Considerations

For real-world application:

- **Mixing sequence**: dry-blend fibers with aggregates before adding water and enzyme solution to prevent clumping.
- **Curing**: maintain moist curing for at least 7 days to allow enzymatic reactions to stabilise.

- **Quality control**: monitor fiber dispersion and air entrainment, as both affect mechanical strength and permeability.
- **Health & safety**: PET fibers may generate fine particles during cutting; soapnut extract should be handled with gloves due to natural saponins.

Material	Optimum Dosage	Mechanical Effects	Durability Effects	Key Limitations
PET Fibers	~1% by weight of cement	↑ Tensile strength (8–15%), ↑ Flexural ductility; compressive stable up to 1%, ↓ beyond	At >2%, ↑ water absorption & chloride penetration; surface-treated PET improves bond	Workability loss; weak fiber–matrix bond if untreated
Banana Fibers	0.5–1% by volume (alkali-treated)	↑ Flexural strength (20–40%), ↑ Toughness & impact resistance; compressive unaffected ≤0.5%	↓ Sorptivity & permeability when treated; untreated absorbs excess water	High water absorption; biodegradability if untreated
Soapnut Bioenzyme	0.2–0.5% by weight of cement	Indirect improvement (denser C–S–H gel formation)	↓ Permeability, shrinkage, sulphate & chloride ingress	Limited data; dosage standardisation required
Hybrid (PET + Banana + Enzyme)	PET ~0.75%, Banana ~0.5%, Enzyme ~0.3%	Comparable compressive strength to control; ↑ Crack resistance & toughness	Sorptivity ↓ by 30–40%; improved pore refinement	Few pilot trials; need long-term durability studies

9. Research Gaps and Future Directions

- Limited studies on combined use of PET fibers, banana fibers, and bioenzymes in conventional concrete.
- Need for evaluation of mechanical and durability properties of such hybrid mixes, especially under aggressive exposure conditions.
- Further investigation into fiber treatment methods, optimum proportions, and long-term performance is necessary.

9.1 Policy and Sustainability Implications

Adoption of hybrid green concrete aligns with Sustainable Development Goals (SDG 9: Industry, Innovation, and Infrastructure; SDG 12: Responsible Consumption and Production). Recycling PET waste and valorising banana stems support circular-economy initiatives in developing regions. Widespread use could significantly reduce landfill waste and carbon intensity of construction materials, particularly in tropical countries where banana cultivation and soapnut trees are abundant.

10. Recommendations for Future Research

- Develop **design-oriented constitutive models** for hybrid concretes accounting for fiber pull-out, bioenzyme hydration kinetics, and crack bridging.

- Explore **compatibility with supplementary cementitious materials** (fly ash, slag, metakaolin) to further enhance durability and sustainability.
- Undertake **field-scale trials** in pavements, panels, or low-rise buildings to validate laboratory findings.
- Investigate **long-term biodegradation of banana fibers** in alkaline matrices and its effect on structural integrity.
- Quantify **economic feasibility** and carbon reduction via life-cycle costing and embodied energy analysis.

11. Conclusion

Recycled PET fibers, banana fibers, and soapnut bioenzymes provide complementary benefits for developing eco-efficient concretes. PET improves tensile behaviour, banana fibers enhance toughness, and bioenzymes refine microstructure. Hybridisation has clear potential but requires systematic research, durability evaluation, and field validation to enable adoption in structural applications. The integration of recycled PET fibers, banana fibers, and soapnut bioenzymes presents an innovative pathway for sustainable construction materials. Collectively, these components promote resource conservation, crack mitigation, toughness, and potential durability gains. Nevertheless, the absence of unified standards, scarcity of hybrid investigations, and limited microstructural understanding restrict immediate adoption. With systematic research, clear design recommendations, and real-scale demonstrations, hybrid PET–banana–soapnut concrete could become a practical alternative for eco-conscious structural and non-structural applications. Hybrid concretes containing recycled PET fibers, banana fibers, and soapnut bioenzymes represent a promising strategy for greener infrastructure. By merging plastic recycling, agro-waste valorisation, and biological admixture technology, they address both environmental and performance concerns. PET contributes tensile strength and ductility, banana fibers enhance toughness and impact resistance, while bioenzymes densify the matrix and limit ingress of aggressive agents. Evidence to date is positive but fragmented. A coherent research agenda—covering microstructure, long-term durability, design modelling, and economic feasibility—is essential for hybrid mixes to transition from laboratory to large-scale construction.

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