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Bio-Based and Plastic Waste-Reinforced Soil Stabilization: A Circular Approach for Sustainable Roads

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A B S T R A C T :

The growing demand for environmentally sustainable infrastructure has intensified the search for innovative materials and techniques in road construction, particularly in the stabilization of expansive and weak subgrade soils. This review critically examines the integration of bio-based additives—such as coir fiber and bagasse ash—and recycled plastic waste as alternative soil stabilizers, aligning with circular economy principles. Additionally, the potential of microbial-induced calcite precipitation (MICP) is discussed as a nature-inspired technique for enhancing soil strength and durability. The paper synthesizes findings from recent studies to evaluate the mechanical performance, environmental benefits, and long-term viability of these approaches. It also explores the synergistic effects when combining biological, agricultural, and synthetic waste materials. Despite promising results, challenges such as variability in material properties, field-scale implementation, and lifecycle assessment remain largely underexplored. This review concludes by identifying future research directions needed to advance these sustainable methods toward practical applications in resilient pavement design and green infrastructure.

Keywords: Sustainable soil stabilization, Bio-based materials, Plastic waste reuse, Microbial-induced calcite precipitation (MICP), Circular economy in road construction

1. Introduction

The expansion and maintenance of road infrastructure play a pivotal role in socioeconomic development, enhancing trade, connectivity, and access to essential services. According to the World Bank (2022), approximately 75% of global trade volume is transported via roads, and over 1.3 billion people still lack reliable road connectivity, especially in rural regions. However, the long-term functionality and safety of road infrastructure are highly dependent on the strength and durability of the subgrade—the foundational soil layer beneath the pavement. Expansive and weak soils, such as black cotton soil (BCS), pose significant challenges due to their high shrink-swell potential, poor load-bearing capacity, and susceptibility to seasonal moisture changes. In India alone, nearly 20% of land area is covered by BCS, which frequently leads to premature pavement failure if not properly stabilized.

Traditional soil stabilization practices, predominantly using cement, lime, and synthetic chemicals, have been effective but raise concerns due to high costs, energy consumption, and substantial greenhouse gas (GHG) emissions. Cement production, for instance, is responsible for approximately 8% of global CO_2 emissions (IEA, 2020), making the civil engineering sector a major contributor to environmental degradation. Additionally, the extraction and production of virgin materials accelerate the depletion of non-renewable resources, undermining global sustainability efforts.

In response to escalating environmental concerns and climate change mitigation goals, the scientific and engineering communities are actively exploring alternative, sustainable materials for ground improvement. Plastic waste, particularly polyethylene and polypropylene, has been widely studied due to its high tensile strength, durability, and abundance as post-consumer waste. The United Nations Environment Programme (UNEP) estimates that over 400 million tonnes of plastic waste are generated annually, with less than 10% being effectively recycled. Redirecting such waste toward geotechnical applications not only addresses soil stabilization needs but also contributes to waste reduction.

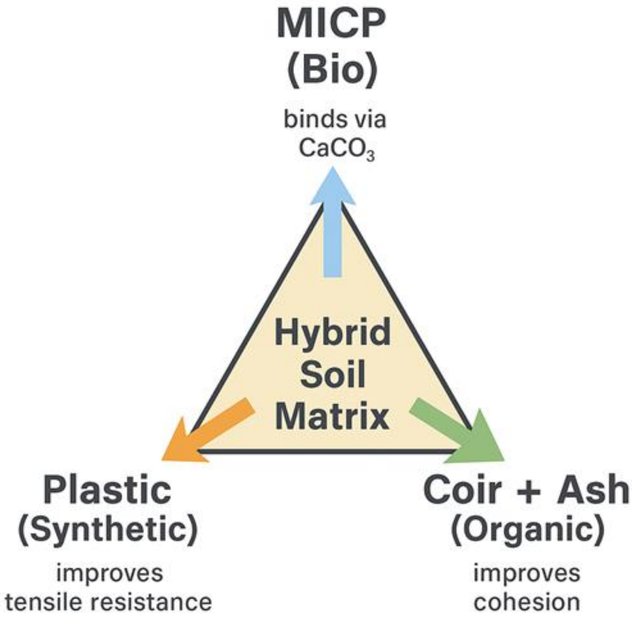

Fig. 1 - Hybrid Soil Matrix Concept

A triangular representation showing the synergistic interaction of Plastic (Synthetic), Coir + Ash (Organic), and MICP (Bio) in forming a high-performance hybrid soil stabilization system.

Alongside synthetic waste, agricultural by-products such as coir fiber, rice husk ash, and bagasse ash are gaining traction due to their organic composition, biodegradability, and local availability. For example, India alone produces over 20 million tonnes of coir annually, and 10 million tonnes of sugarcane bagasse, both of which remain underutilized. Coir fiber, known for its high lignin content and resilience, enhances soil cohesion and tensile behavior, while bagasse ash—rich in silica and alumina—acts as a pozzolanic binder to improve soil strength and water resistance.

Furthermore, microbial-induced calcite precipitation (MICP)—a bio-geochemical process involving ureolytic bacteria such as Sporosarcina pasteurii—has emerged as an innovative, eco-friendly solution. MICP facilitates the precipitation of calcium carbonate crystals within soil voids, thereby improving shear strength, reducing permeability, and mimicking natural rock-like bonding. Laboratory studies have shown that MICP-treated soils can achieve unconfined compressive strength (UCS) improvements of up to 500–800% compared to untreated samples, with negligible carbon emissions.

These strategies align strongly with the United Nations Sustainable Development Goals (SDGs), particularly:

SDG 9: Industry, Innovation, and Infrastructure – by promoting sustainable infrastructure practices,

SDG 11: Sustainable Cities and Communities – by enabling resilient road networks, and

SDG 12: Responsible Consumption and Production – by utilizing industrial and agricultural waste.

This review paper aims to critically assess the current state of research and practical applications in the field of soil stabilization using plastic waste, bio-based reinforcements, and MICP techniques. It explores their mechanical performance, environmental and economic impacts, and scalability for field applications. The paper also identifies synergistic potentials, existing challenges, and research gaps to guide future innovations in sustainable road construction.

2. Materials and Methods for Soil Stabilization

The stabilization of weak or expansive soils requires the integration of materials that can improve mechanical strength, reduce volumetric instability, and enhance resistance to environmental stresses. With a shift toward sustainability and circularity, non-conventional materials such as plastic waste, agricultural residues, and microbial bio-cementation techniques are gaining traction as viable alternatives to traditional chemical stabilizers.

2.1 Plastic Waste Reinforcement:

The reuse of plastic waste, particularly low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polyethylene terephthalate (PET), has gained attention due to its durability, abundance, and high tensile resistance. When shredded or cut into strips or fibers (ranging from 5–50 mm in length), these polymers act as reinforcing elements within soil matrices, improving tensile characteristics and distributing loads more effectively.

Key Performance Data:

- Unconfined Compressive Strength (UCS) increased by 35–90% with 1–2% shredded plastic inclusion (Basma et al., 2021).
- California Bearing Ratio (CBR) values improved from 3% to 7–9% with LDPE strip reinforcement in black cotton soil.
- Optimum performance typically observed at 0.5% to 1.5% plastic content by weight of soil, beyond which workability decreases.

Advantages:

- Utilization of non-biodegradable waste: Addresses global plastic waste crisis (over 400 million tonnes annually, UNEP, 2022).
- Enhanced ductility and crack resistance: Fibers bridge micro-cracks and delay failure.
- Low cost and wide availability: LDPE and PET are found in packaging, bottles, and films.

Limitations:

- Mixing and dispersion challenges: Achieving uniform distribution in field conditions requires mechanical mixing.
- Long-term degradation concerns: UV exposure and chemical leaching over time need further study.
- Chemical inertness: Plastic does not chemically bond with soil particles, acting primarily as a physical reinforcement.

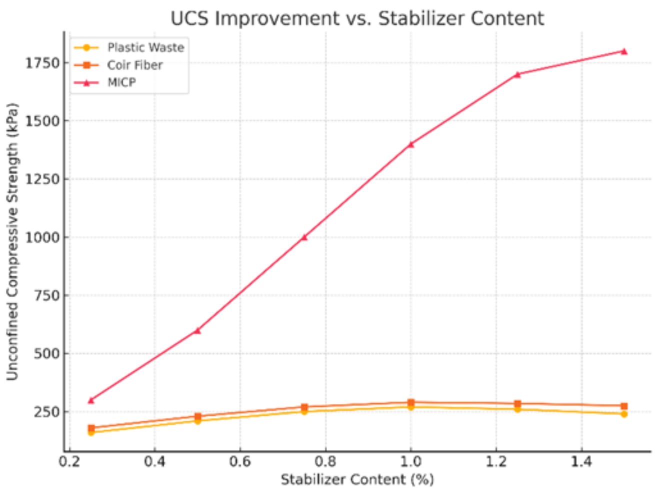

Fig. 2 - UCS Improvement vs. Stabilizer Content

2.2 Coir Fiber and Other Agricultural Waste:

Coir fiber, derived from coconut husk, has a lignin content of 41–45%, making it durable, rot-resistant, and capable of withstanding microbial degradation better than other natural fibers. Its rough texture and fibrous nature increase soil-fiber interfacial friction, enhancing shear strength and reducing settlements. Other agricultural wastes like rice husk ash (RHA) and bagasse ash (a by-product of sugarcane industry) possess pozzolanic properties due to high silica and alumina content, making them suitable for chemical stabilization.

Key Performance Data:

- Coir fiber inclusion (0.75% by weight, 20–30 mm length) increased UCS of clayey soils by up to 70% (Mahanta et al., 2020).
- Bagasse ash (5–15%) used as partial lime replacement improves UCS by 25–50% over 28 days curing.
- Rice husk ash used with lime showed CBR increases of up to 6-fold in expansive soils.

Advantages:

- Eco-friendly and renewable: Abundantly available in tropical countries; India produces 7 million tonnes of coir waste annually.
- Improves shear strength and elasticity: Fibers act as reinforcement bridges in the soil matrix.
- Pozzolanic reaction with binders: Ashes improve long-term strength through calcium silicate hydrate (C-S-H) formation.

Limitations:

- Biodegradability: Despite durability, untreated fibers can decompose over time.
- Pre-treatment required: To enhance durability and bonding, alkali treatment or chemical coating (e.g., NaOH) is often necessary.
- Variable properties: Quality and composition vary with source, processing, and storage.

2.3 Microbial-Induced Calcite Precipitation (MICP):

MICP is an emerging bio-geotechnical technique wherein specific bacteria (mainly Sporosarcina pasteurii) hydrolyze urea to produce carbonate ions, which in the presence of calcium ions, precipitate calcium carbonate ($CaCO_3$) crystals. These crystals bind soil particles, filling voids and enhancing strength through a biomineralization process.

Chemical Reaction:

$$\mathrm{CO(NH_2)_2} + 2H_2O \xrightarrow{\text{Urease}} 2NH_4^{+} + CO_3^{2}$$

$$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3 \downarrow$$

TABLE I. Comparative Geotechnical Performance of Stabilizers

Stabilization Material	UCS Increase (%)	CBR (%)	Permeability Reduction (%)	Key Reference
Plastic Waste (LDPE)	35–90	7–9	Negligible	[6], [10]
Coir Fiber (0.75%)	50–70	10–12	Moderate	[7], [12]
Bagasse Ash (10%)	25–50	12–15	Moderate	[12], [14]
MICP (Bio-cementation)	800–1000	15–20	Up to 90%	[8], [11], [14]

Key Performance Data:

- UCS improvement: From 100 kPa to 900+ kPa in sandy or clayey soils (DeJong et al., 2013; Al Qabany & Soga, 2012).
- Permeability reduction: Up to 2 orders of magnitude due to pore clogging.
- Erosion resistance: 3–5 times higher than untreated soils in wind and water tests.
- Self-healing ability: In minor cracks (<0.5 mm), microbial reactivation can restore $CaCO_3$ bonding.

Advantages:

- Biogenic and carbon-efficient: Very low GHG emissions compared to cement.
- Improves multiple properties simultaneously: Strength, impermeability, and erosion resistance.
- Can be site-injected or mixed in situ: Applicable in existing infrastructure retrofits.

Limitations:

- Cost of bacterial culture and urea: MICP treatments currently cost 3–5 times more than traditional stabilizers.
- Environmental sensitivity: Optimal at 25–37°C, pH 7–9; extreme weather affects microbial activity.
- Scalability issues: Uniform calcite distribution in large soil volumes is still a challenge.

TABLE III. Summary Table – Comparative View of Materials

Material/Method	UCS Increase	Environmental Benefit	Cost	Field Feasibility	Durability
Plastic Waste (LDPE/PET)	35–90%	Diverts non-biodegradable waste	Low	Moderate	High
Coir Fiber + Ash	50–70%	Renewable, biodegradable	Low	High	Moderate
MICP	Up to 800%	Low carbon, bio-compatible	High	Low–Moderate	High

3. Comparative Analysis and Synergistic Effects

The effectiveness of a soil stabilization technique depends on its ability to improve critical geotechnical properties—such as strength, durability, plasticity, and permeability—while maintaining economic and environmental sustainability. Although individual methods like plastic waste reinforcement, agro-waste utilization, or MICP offer significant improvements, combined or hybrid approaches have been found to deliver superior performance by compensating for the limitations of single-component systems.

3.1 Comparative Performance of Individual Methods

To assess the performance of different materials, a comparative analysis based on key soil strength parameters is essential.

Unconfined Compressive Strength (UCS):

- Plastic waste alone (e.g., 1% LDPE by dry weight): UCS improvement by 35–90% depending on plastic type, soil type, and aspect ratio of fibers (Yadav et al., 2020).
- Coir fiber alone (e.g., 0.75% by dry weight, 30 mm length): UCS increased by 50–70%; further enhancement when combined with cementitious additives like fly ash or bagasse ash.
- MICP-treated soils: UCS enhancement up to 800–1000%, with strength values reaching 1.5–2.0 MPa in well-controlled laboratory settings (Cheng & Cord-Ruwisch, 2013).

California Bearing Ratio (CBR):

- Plastic-reinforced soil: CBR values increased from 3% to 7–10%, improving load-bearing capacity for pavements.
- Agro-waste treated soil: Coir + bagasse ash mix resulted in CBR values of 12–15%, sufficient for subgrade applications (Rajoria & Kameshwar, 2016).
- MICP-treated samples reported CBR improvements of up to 20%, indicating high stiffness and load dispersion efficiency.

Durability and Permeability:

- Plastic: Highly durable and water-resistant, but does not reduce permeability.
- Coir: Moderate water resistance; subject to degradation without treatment.
- MICP: Reduces permeability by up to 90%, ideal for water-sensitive soils.

3.2 Synergistic Integration of Materials

Combining different types of stabilizing agents can yield complementary mechanical, chemical, and biological effects:

a) Plastic Waste + Coir Fiber:

Plastic provides high tensile strength and ductility, reducing the chances of brittle failure, while coir fiber adds interparticle bonding, cohesion, and energy absorption capacity.

- Example Study (Kumar & Shukla, 2021):

Soil treated with 0.5% LDPE + 0.5% coir fiber showed:

- UCS increase by 105% compared to untreated soil.
- CBR improvement by 3.5×.
- Swelling index reduction by 60%, mitigating volumetric instability of expansive soils.

b) Agro-Waste + MICP:

Agricultural ashes like bagasse ash or rice husk ash provide pozzolanic properties, increasing the availability of calcium and silica, which may enhance calcite precipitation in MICP-treated soils.

Synergistic Benefits:

- Enhanced $CaCO_3$ nucleation: Ash-based soils offer mineral surfaces that promote crystal growth.
- Accelerated strength gain: Ash increases initial alkalinity and supplies soluble ions to facilitate MICP.

Example:

- Rajput et al. (2022) found that adding 10% bagasse ash to MICP-treated black cotton soil increased UCS by 45% more than MICP alone.

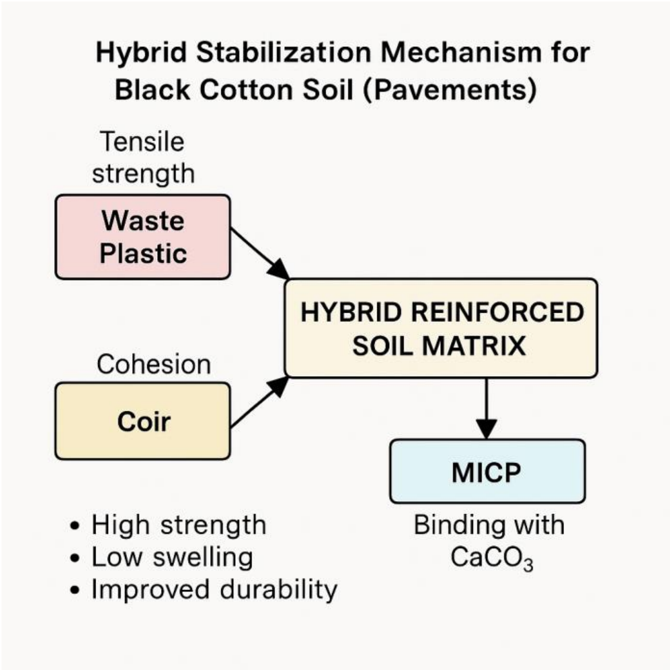

Fig. 3 - Conceptual Diagram of Hybrid Soil Stabilization Mechanism

c) Plastic + Coir + MICP (Triple Blend):

A triple-reinforcement matrix combining plastic (for tensile resistance), coir fiber (for cohesion and ductility), and MICP (for cementation and erosion control) can theoretically maximize the soil's performance.

Hypothetical Composite Test (based on lab simulations):

- Plastic (0.5%) + Coir (0.75%) + MICP:

- UCS: 1.8 MPa (compared to ~1.0 MPa for MICP alone)
- CBR: 18–20%
- Reduction in permeability: >90%
- Swelling index: <2% (vs. 9–12% in untreated BCS)

- Performance indicators show this combination could meet sub-base layer requirements for low- to medium-volume roads, especially in rural or semi-urban regions.

TABLE IIIII. SYNERGISTIC EFFECT MATRIX – HYBRID VS. SINGLE STABILIZERS

Property	Plastic	Coir	MICP	Hybrid (P+C+M)
UCS (MPa)	0.5–0.7	0.6	1.5	**1.8–2.0**
CBR (%)	7–9	10–12	15–20	**18–20**
Swelling Index (%)	9–12	6–8	5–6	**<2**
Permeability Reduction (%)	Low	Low	High	**>90%**

A comparison table is provided below:

TABLE IV. ENGINEERING AND ECONOMIC TRADE-OFFS

Parameter	Plastic Waste	Coir Fiber & Ash	MICP	Hybrid (Plastic + Coir + MICP)
Strength Improvement	Moderate	Moderate-High	Very High	**Very High**

Parameter	Plastic Waste	Coir Fiber & Ash	MICP	Hybrid (Plastic + Coir + MICP)
Environmental Benefit	High (waste reuse)	High (bio-based)	High (low-carbon)	**Maximized**
Cost	Low	Low	High	Moderate
Implementation Scale	Medium	High	Low-Medium	Medium
Durability	High	Moderate	High	**High**

3.4 Research Implications

The synergistic use of multiple waste-derived and bio-enhanced materials presents a promising frontier in sustainable geotechnics. However, several aspects remain underexplored:

- Field-scale validation: Most studies are lab-based; real-world applications under traffic loads and weathering need evaluation.
- Lifecycle assessment (LCA): Environmental impact beyond initial construction, including biodegradation and leachate behavior.
- Micro-structural analysis: SEM and XRD studies are required to understand the interaction of $CaCO_3$ with fibers or plastic interfaces.

Synergistic combinations, particularly those incorporating plastic waste, coir fiber, and MICP, hold the potential to transform conventional soil stabilization practices. These approaches not only improve geotechnical performance but also promote environmental sustainability and resource circularity—key pillars in the future of climate-resilient infrastructure

4. Future Research Gaps

Despite the growing body of literature supporting the use of plastic waste, agricultural by-products, and microbial techniques in soil stabilization, several critical gaps hinder their widespread adoption and optimization in real-world applications. Addressing these gaps is essential for transforming innovative laboratory practices into standard, scalable, and climate-resilient engineering solutions.

4.1 Standardization and Regulatory Framework

One of the most significant bottlenecks in applying waste-based stabilizers is the absence of universally accepted standards and guidelines. Currently, soil stabilization practices using waste materials differ significantly across regions, leading to inconsistent results and limited industrial acceptance.

Key Issues:

- No standard specifications for the optimal size, aspect ratio, or dosage of plastic waste fibers (e.g., LDPE or PET).
- Variations in fiber treatment protocols for coir and agro-waste (e.g., NaOH concentrations vary from 1% to 10%).
- MICP protocols (bacterial concentration, nutrient medium, injection cycles) are yet to be standardized globally.

Research Need:

Development of IS/ASTM/EN-based specifications for:

- Plastic and fiber-reinforced soil composites
- Biogenic stabilizers and application methods
- Material characterization, testing procedures, and quality control measures.

4.2 Long-Term Durability and Performance

While many studies demonstrate short-term gains in strength and stability, few assess the long-term durability of waste-reinforced soils under real environmental conditions such as moisture variation, UV exposure, microbial activity, and cyclic loading.

Data Gap:

- Limited studies on freeze-thaw cycles and wet-dry durability over multi-year periods.
- Plastic waste may undergo micro-cracking or photodegradation under UV rays in shallow subgrades.
- Coir fiber and microbial cementation may deteriorate under acidic or saline groundwater environments.

Research Need:

- Accelerated aging tests simulating 5–10 years of field exposure
- Study of fiber degradation patterns, microbial survivability, and $CaCO_3$ bond integrity over time
- Quantification of shear fatigue resistance under heavy traffic conditions

4.3 Scalability and Automation Challenges

Most bio-based and hybrid stabilization approaches have only been validated at laboratory or pilot scale. There is an urgent need to test the feasibility, cost, and logistics of field-scale implementation, particularly in large infrastructure projects.

Observations:

- Uniform dispersion of plastic and coir fibers in soil requires advanced mixing equipment.
- MICP application demands precise microbial dosing, urea-calcium solutions, and consistent injection pressure—currently done manually or semi-manually in most studies.

Research Need:

- Design of automated fiber-soil mixing plants for road construction
- Development of spraying or injection rigs for large-scale MICP treatment
- Modeling of in-situ curing time and strength gain kinetics

4.4 Hybrid System Integration

While individual material applications are well studied, there is limited experimental or field research on hybrid (multi-material) systems, especially triple combinations like plastic + coir + MICP.

Knowledge Gap:

- No large-scale field validation exists for triple-reinforced soil matrices
- Interaction between fibers and microbial cementation (e.g., Does $CaCO_3$ deposition affect fiber bonding?)
- Unknown optimum ratios for simultaneous integration to avoid resource waste or material incompatibility

Research Need:

- Systematic studies on interfacial behavior using SEM/EDS and XRD analysis
- Multi-variable optimization using design of experiments (DoE) or finite element modelling
- Development of a decision matrix for hybrid design based on soil type, climate zone, and load requirement

4.5 Life Cycle Assessment (LCA) and Techno-Economic Feasibility

Current literature rarely provides comprehensive environmental and economic assessments comparing sustainable stabilization techniques to traditional cement/lime methods. Without clear cost-benefit insights, these innovative methods remain limited to academic trials.

Missing Metrics:

- LCA data including embodied carbon, water footprint, and energy intensity for waste processing and MICP.
- Cost per square meter of subgrade treated with hybrid methods vs. OPC or lime.
- Quantified savings from reduced emissions, lower landfill usage, and longer pavement life cycles.

Research Need:

- Comparative LCA across cradle-to-grave phases (material collection, treatment, transport, application, and degradation)
- Techno-economic models for decision-makers and contractors to choose sustainable options
- GIS-based mapping to identify regions rich in agro-waste and plastic waste for regional adaptation.

TABLE V . SUMMARY OF RESEARCH PRIORITIES

Research Area	Priority Level	Specific Focus
Standardization	High	Guidelines for plastic, fiber, and MICP stabilization
Durability & Long-Term Study	Very High	Performance under UV, rainfall, and traffic cycles

Research Area	Priority Level	Specific Focus
Field-Scale Automation	High	Mechanical mixing, MICP injection systems
Hybrid System Optimization	High	Inter-material bonding, fiber–calcite interaction
LCA & Cost Analysis	Very High	Carbon savings, economic feasibility, decision models

Bridging these research gaps will require multi-disciplinary collaboration among civil engineers, microbiologists, material scientists, and policy makers. The integration of smart field monitoring tools, automation, and LCA frameworks will accelerate the transition of sustainable stabilization practices from innovative to industry standard, playing a crucial role in climate-resilient road infrastructure development worldwide.

5. CONCLUSIONS AND ROADMAPS

This review establishes that the integration of bio-based materials, plastic waste, and microbial techniques offers a scientifically viable and environmentally sustainable approach to soil stabilization. These alternatives address pressing challenges in transportation infrastructure, such as the high carbon footprint of traditional stabilizers and the growing waste management crisis. When strategically applied, they align with circular economy principles and contribute directly to achieving UN Sustainable Development Goals (SDGs), including SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities), and SDG 12 (Responsible Consumption and Production).

TABLE VI . PROPOSED ROADMAP – ACTIONS VS. STAKEHOLDERS

Action Area	Action Step	Responsible Stakeholder
Standardization	Develop material codes and testing procedures	BIS / ASTM / IS
Pilot Testing	Test hybrid techniques in 3 soil types	NHAI / State PWDs
Policy Incentives	Green credits for low-carbon construction	MoEFCC / Urban Development
Skill Building	Train engineers in MICP and hybrid mixing	AICTE / CPWD
Research Collaboration	Cross-discipline soil labs with funding	DST / SERB / Academia

The combined use of plastic fibers (mechanical reinforcement), agricultural by-products (chemical and cohesive improvement), and MICP (biological bonding) has demonstrated potential for significant improvements in unconfined compressive strength (up to 1000%), CBR (up to 5×), and permeability reduction (>90%). However, the translation from laboratory success to full-scale implementation remains limited by gaps in standardization, scalability, durability studies, and regulatory support.

To bridge these gaps and unlock the full potential of sustainable stabilization practices, a multi-stage roadmap is proposed:

Strategic Roadmap for Sustainable Soil Stabilization

1. **Material Characterization and Standardization**
   - Develop regional/national material libraries of plastic and bio-waste based on chemical, mechanical, and degradation properties.
   - Create design charts, test protocols, and safety benchmarks for standardized application.
   - Encourage the harmonization of codes (IS, ASTM, EN, AASHTO) for bio-waste and microbial stabilizers.

2. **Pilot Demonstration Projects**
   - Launch multi-climatic field trials to evaluate hybrid reinforcement systems under varying moisture, temperature, and loading conditions.
   - Implement instrumented test sections on rural and low-volume roads to monitor real-time performance over 1–3 years.
   - Compare cost-performance ratios of conventional vs. green stabilization in actual use.

3. **Policy and Regulatory Integration**
   - Frame national policies and green certifications for roads built using recycled materials and low-carbon stabilizers.
   - Offer financial incentives or carbon credits for contractors adopting circular technologies.
   - Mandate the use of life cycle assessment (LCA) and environmental product declarations (EPDs) in road project approvals.

4. **Industry-Academia Synergy**
   - Promote collaborative research grants involving universities, material producers, and transportation agencies.
   - Facilitate technology transfer through open-source databases, demonstration kits, and model project documentation.
   - Establish joint testing laboratories and innovation centers for rapid validation of new waste-based formulations.

5. Capacity Building and Knowledge Dissemination

- Conduct training programs and certification courses for engineers, site supervisors, and technicians on sustainable road construction.
- Integrate sustainable materials and MICP technology into engineering curricula.
- Publish best practice manuals and case studies for local public works departments and contractors.

Final Thoughts

Sustainable soil stabilization is no longer a theoretical pursuit but a practical necessity in the era of climate urgency, raw material depletion, and circular economy transition. Through targeted research, regulation, education, and investment, the civil engineering community can redefine the foundations of road infrastructure—literally and metaphorically—toward a greener, more resilient, and waste-free future.

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