

Rice Husk Derived Nanosilica for Sustainable Soil Stabilisation: A Review of Geotechnical Applications

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Abstract- The environmental effect identified with conventional lime and cement-based soil stabilisation have intensified the search for eco-friendly alternatives in geotechnical engineering. Agricultural waste-derived nanomaterials, particularly rice husk-derived nanosilica (RH-NS), have emerged as promising sustainable stabilisers due to its high pozzolanic reactivity and waste valorisation potential. This review critically examines recent advances (2020–2026) on the synthesis, characterization, stabilisation mechanisms, engineering performance, sustainability implications, and implementation challenges of RH-NS for soil stabilisation, based on peer-reviewed studies from major databases. Rice husk, an abundant agricultural by-product containing 15–22% amorphous silica and can be converted into highly reactive nanosilica (15–50 nm) through acid leaching-pyrolysis, mechanical milling, or precipitation methodologies. The incorporation of RH-NS into weak soils enhances unconfined compressive strength up to 4–5 times of its original strength, reduces swelling potential up to 88%, improves California Bearing Ratio, and decreases hydraulic conductivity. These improvements stem from nanosilica's high specific surface area (150–350 m²/g) and its pozzolanic reactivity, which promote calcium silicate hydrate (C-S-H) and calcium aluminium silicate hydrate (C-A-S-H) gel formation. However, challenges including nanoparticle agglomeration, non-uniform dispersion, long-term durability concerns, high production costs, and limited field-scale validation remain barriers to widespread adoption. Tropical lateritic soils remain understudied despite their prevalence in developing countries. Emerging techniques such as hybrid stabilisation with other agro-wastes, functionalized nanosilica, and life-cycle assessment frameworks show promise for enhancing sustainability and field applicability. Future research should prioritize field validation, durability testing, standardized synthesis protocols, and cost reduction strategies to transition RH-NS from laboratory research to routine geotechnical practice.

Keywords: Nanosilica, Rice Husk Ash, Soil Stabilisation, Pozzolanic Reaction, Expansive Soil

I. INTRODUCTION

The demand for sustainable infrastructure has renewed interest in ground improvement technologies that offer engineering performance with minimal environmental impact (Haque and Uddin, 2024). Traditional stabilisation with lime and Portland cement remains common for weak soils due to proven effectiveness. However, concerns over cement's high embodied energy, greenhouse gas emissions (up to 8–10% of global CO₂), and environmental footprint have increased the search for alternative, low-carbon solutions in geotechnical engineering (Mohammed et al., 2023).

Agricultural waste-derived nanomaterials represent a sustainable approach, using renewable resources to produce value-added stabilisers. Rice husk-derived nanosilica (RH-NS) is particularly promising because it converts an abundant agricultural residue of approximately 150 million tons of rice husk generated annually worldwide into a high-performance pozzolanic material (Geethakarathi, 2021). Rice husk contains 15–22% amorphous silica, which after controlled processing yields nanosilica with specific surface areas of 150–350 m²/g and particle sizes ranging from 15 to 50 nm (Parhizkar, 2025).

Nanosilica enhances soil properties through multiple mechanisms including; (i) pozzolanic reactions forming calcium silicate hydrate (C-S-H) and calcium aluminum silicate hydrate (C-A-S-H) gels that bind soil particles; (ii) microfilling of interparticle voids due to nanoscale dimensions; (iii) provision of nucleation sites for hydration products; and (iv) enhancement of interparticle attractive forces (Munawar et al., 2023; Meeravali et al., 2024).

Recent studies demonstrate significant improvements in geotechnical properties following RH-NS treatment. Munawar et al. (2023) reported that expansive clay treated with 1.2% nanosilica and 9% rice husk ash achieved 2.17 times higher unconfined compressive strength (UCS) and 2.82 times higher California Bearing Ratio (CBR) compared to RHA alone. Mostafaei et al. (2026) observed collapse potential reduction of up to 88% in collapsible clay soils treated with nanosilica and eco-friendly additives. Krishnan et al. (2022) demonstrated that 5% extracted nanosilica significantly improved soft clay properties under freeze-thaw cycles, with enhanced ductility and strength retention.

Despite these advances, several limitations hinder field-scale implementation. Nanoparticle agglomeration remains a fundamental challenge, causing non-uniform treatment and reduced efficiency (Cui et al., 2021). Long-term durability under environmental exposure including wet-dry cycles, freeze-thaw, and chemical attack remains insufficiently characterized (Fu et al., 2023b). Additionally, the absence of standardised synthesis protocols, testing methods, and design guidelines complicates cross-study comparisons and practical adoption (Zhang et al., 2025).

A significant knowledge gap exists for tropical lateritic soils, which cover much of Africa, South America, and Southeast Asia. These soils have unique mineralogy (high iron and aluminum oxides), variable pH, and aggregated structures that may influence nanosilica performance differently than the silica sands and expansive clays predominantly studied. Al-Riahi et al. (2024) emphasized that mineralogical and microstructural alterations in problematic soils require careful evaluation, while Yusuf et al. (2025) stressed the importance of combining bio-stabilisation with sustainable geotechnical practices in developing regions.

This review critically assesses recent developments from 2020 to 2026 regarding the applicability and challenges associated with rice husk-derived nanosilica for sustainable soil stabilisation. Specifically, the objectives of this review are to: (i) compare synthesis methodologies and characterization techniques for RH-NS; (ii) evaluate

stabilisation mechanisms across various soil types; (iii) assess reported mechanical, hydraulic, and durability enhancements; (iv) analyze sustainability implications and environmental trade-offs through life-cycle assessment; (v) identify primary scientific and engineering limitations impacting field-scale implementation; and (vi) propose future research directions necessary to transition RH-NS from laboratory-scale technology to reliable geotechnical engineering practice. By integrating insights on mechanisms, performance, sustainability, and design readiness, this review offers a comprehensive framework for understanding the current maturity of RH-NS as a sustainable, agro-waste derived soil stabilisation technique.

II. METHODOLOGY

This review adopted a PRISMA-inspired systematic literature synthesis approach to ensure transparency, reproducibility, and methodological rigor in the selection and interpretation of relevant studies. The procedure was designed to identify peer-reviewed research and review articles addressing rice husk-derived nanosilica (RH-NS) for sustainable soil stabilisation. As summarized in Table 1, the literature search covered studies published between 2020 and 2026, with emphasis on recent developments in nanosilica synthesis, characterization, bio-mediated soil improvement, pozzolanic reactions, calcite precipitation mechanisms, sustainability assessment, and geotechnical performance.

Relevant publications were retrieved from major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. These databases were selected because they index high-quality geotechnical, geo-environmental, construction materials, and sustainability-related journals. The search process used subject specific keywords such as "rice husk nanosilica," "nanosilica soil stabilisation," "rice husk ash," "pozzolanic reaction," "C-S-H gel," "expansive soil," "agro-waste stabilisation," "sustainable construction," and "circular economy." Boolean combinations, including "nanosilica and soil stabilisation," "rice husk ash and geotechnical properties," "pozzolanic reaction and expansive soil," "agro-waste and ground

improvement," and "sustainable soil stabilisation and nanomaterials," were applied to improve the precision and thematic relevance of the retrieved records.

The literature screening involved four stages: identification, screening, eligibility, and final inclusion, as shown in Figure 1. Studies were retrieved through database searches and references, then duplicates and irrelevant papers were removed. The eligibility stage assessed full texts for details on methodology, experimental evidence, numerical modelling, or reviews related to RH-NS soil stabilisation. Articles contributing to understanding synthesis mechanisms, characterization, stabilisation performance, soil applicability, sustainability, limitations, or future developments of RH-NS were included. Inclusion criteria prioritized peer-reviewed journal articles in Q1 or Q2 journals, written in English, published from 2020–2026, and focused on geotechnical or geo-environmental applications. The review covered experimental, numerical, field studies, life-cycle assessments, and review articles. Exclusions included duplicates, incomplete conference abstracts, non-peer-reviewed articles, predatory journals, and studies unrelated to soil stabilisation or nanosilica-based treatment.

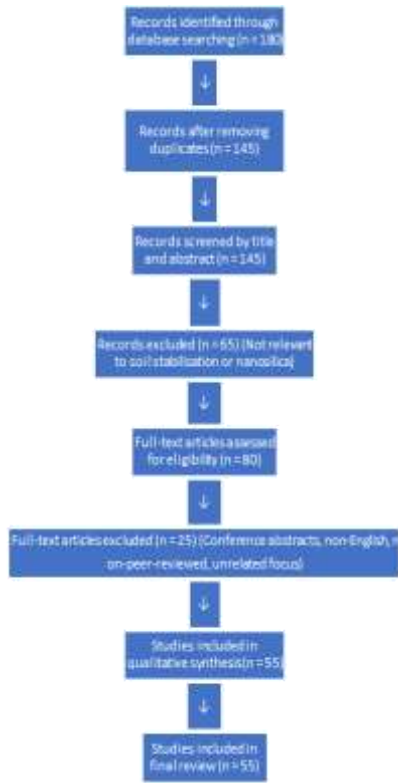
For this review, 55 articles were chosen for review, providing evidence on RH-NS synthesis, characterization, stabilisation mechanisms, soil applicability, engineering performance, durability, sustainability, limitations, and future challenges. These were grouped into six thematic categories: synthesis and characterization, stabilisation mechanisms, engineering performance, durability, sustainability, and implementation challenges, allowing structured comparison of their features, methods, findings, and limitations. The review compares studies to identify consistencies, contradictions, gaps, and unresolved issues, focusing on performance differences, optimal dosage determination, relationship between nanosilica content and strength, agglomeration challenges, durability under environmental cycles, and tropical soil research gaps. Figure 1 shows the screening process from database searching, reference tracking, duplicate removal, screening, eligibility assessment,

to excluding unsuitable records leading to 55 articles for review.

Table 1. Literature selection framework adopted for the review

Review component	Description
Review period	2020–2026
Databases searched	Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, Google Scholar
Main search terms	Rice husk nanosilica, nanosilica soil stabilisation, rice husk ash, pozzolanic reaction, C-S-H gel, expansive soil, agro-waste stabilisation, sustainable construction, circular economy
Search strategy	Keyword-based search using Boolean combinations
Study focus	RH-NS for geotechnical and geoenvironmental soil stabilisation
Screening framework	PRISMA-inspired identification, screening, eligibility, and inclusion process
Final studies retained	55 selected review and research articles
Inclusion criteria	Peer-reviewed journal articles; preferably Q1/Q2 indexed sources; experimental, numerical, field-scale, sustainability, and review studies; English-language publications
Exclusion criteria	Duplicate records, incomplete conference abstracts, non-peer-reviewed documents, predatory journals, and studies unrelated to soil stabilisation or nanosilica-based treatment
Synthesis approach	Thematic synthesis and critical comparative interpretation

Figure 1. PRISMA-based literature screening and selection flowchart



III. RESULTS AND DISCUSSION

3.1 Evidence Base and Thematic Structure of the Review

The screening identified 180 articles on rice husk nanosilica, RHA, pozzolanic stabilisation, and soil stabilisation, with 55 from 2020–2026 analysed for synthesis methods, characterization, stabilisation

mechanisms, soil applicability, engineering performance, durability, sustainability, and implementation challenges. These included reviews, laboratory experiments, field trials, life-cycle assessments, numerical models, and comparative studies. The large pool provided background, while the 55 articles formed the core for evaluating RH-NS as a sustainable soil stabilisation method.

The field has progressed from proof-of-concept studies to practical applications, including performance optimization, hybrid stabilisation systems, sustainability assessment, and early field-scale trials. Evidence is uneven: granular soils and expansive clays are well-studied, but lateritic soils, organic soils, high-plasticity clays, cyclic loading response, and long-term durability remain less explored.

Table 2 outlines three research directions: synthesis and characterization (optimizing production methods for high-purity amorphous nanosilica); stabilisation mechanisms (understanding pozzolanic reactions, C-S-H/C-A-S-H formation, and microfilling); and engineering performance (strength, compressibility, swell reduction, and durability enhancement). Evidence remains insufficient for practical implementation in tropical lateritic soils, under cyclic loading conditions, and for long-term durability prediction with quality control protocols.

Table 2. Thematic synthesis of selected RH-NS studies for soil stabilization

Thematic focus	Representative studies	Main synthesis outcome	Critical gap identified
Synthesis methodologies	Parhizkar (2025); Geethakarathi (2021); Meeravali <i>et al.</i> (2020); Krishnan <i>et al.</i> (2022)	Acid leaching-pyrolysis (15–50 nm, >98% purity); mechanical milling (20–100 nm, 85–95% purity); precipitation (20–80 nm, 90–98% purity)	Optimal synthesis protocol lacks standardization; energy consumption and cost comparison insufficient
Characterization techniques	Parhizkar (2025); Munawar <i>et al.</i> (2023); Meeravali <i>et al.</i> (2024)	FTIR confirms Si–O–Si and Si–OH groups; XRD validates amorphous character; BET shows SSA 150–350 m ² /g;	Microstructural evidence of bonding location and pore-scale cementation efficiency often lacking

		SEM/TEM reveals particle morphology	
Stabilisation mechanisms	Munawar <i>et al.</i> (2023); Mostafaei <i>et al.</i> (2026); Meeravali <i>et al.</i> (2024)	Pozzolanic C-S-H/C-A-S-H formation; microfilling of interparticle voids; nucleation site provision; interparticle bonding enhancement	CaCO ₃ content often reported without sufficient evidence on bonding location and crystal continuity
Performance in expansive soils	Meeravali <i>et al.</i> (2024); Munawar <i>et al.</i> (2023); Firoozi <i>et al.</i> (2024)	0.4% nRHA reduces swell potential significantly; 1.2% NS + 9% RHA increases UCS by 2.17× and CBR by 2.82×	Premature clogging, non-uniform cementation, and limited field-scale QA/QC remain barriers
Performance in soft/cohesive soils	Krishnan <i>et al.</i> (2022); Maheepala <i>et al.</i> (2025)	5% extracted NS produces highest MDD, highest UCS, lowest permeability; improved freeze-thaw durability	High-plasticity clays and organic soils require assisted delivery and hybrid stabilisation
Durability assessment	Krishnan <i>et al.</i> (2022); Mostafaei <i>et al.</i> (2026)	Improved freeze-thaw resistance; collapse potential reduction up to 88%; ductility maintained under cycles	Long-term durability under wet-dry, freeze-thaw, chemical attack, and sustained loading requires systematic validation
Sustainability and LCA	Maheepala <i>et al.</i> (2025); Geethakarathi (2021); Suwanto <i>et al.</i> (2025)	RH-NS shows 43% improved environmental performance vs. conventional geopolymers; 6.4% advantage over OPC	Sustainability claims remain incomplete without ammonia capture (if applicable), reagent sourcing analysis, and full life-cycle assessment
Lateritic soils	Al-Riahi <i>et al.</i> (2024); Yusuf <i>et al.</i> (2025)	Lateritic soils understudied despite tropical importance; Fe/Al oxides, variable pH, aggregated structure affect performance	Major tropical research gap; extrapolation from silica sands is scientifically weak
Hybrid and emerging systems	Munawar <i>et al.</i> (2023); Maheepala <i>et al.</i> (2025)	NS-RHA composites show cost-stiffness ratios of 1.22–2.82; geopolymer-RHA systems improve sustainability	Hybrid mechanisms, compatibility, and field-scale performance remain poorly quantified

3.2 Synthesis Methodologies for Rice Husk-Derived Nanosilica

The conversion of rice husk to nanosilica follows several established routes, each with distinct advantages, limitations, and optimal application contexts. The three primary methodologies are: (1) Acid Leaching-Pyrolysis, (2) Mechanical Milling, and (3) Precipitation Method.

3.2.1 Acid Leaching–Pyrolysis Method

The acid leaching pyrolysis method is the most widely reported approach for producing high-purity amorphous nanosilica. The process involves: (i) washing rice husk to remove surface contaminants;

(ii) acid leaching (1–3 M HCl or H₂SO₄ for 6–24 hours) to remove alkali metals (K⁺, Na⁺, Ca²⁺, Mg²⁺) that catalyse crystallisation during heating; (iii)

rinsing and drying; and (iv) controlled pyrolysis at 550–700°C for 2–5 hours. Parhizkar (2025) employed this approach to produce nanosilica with mean particle size of approximately 15 nm, confirmed by FESEM, with >98% purity. Table 3 highlight the effect of concentration on purity.

Table 3. Effect of acid leaching parameters on nanosilica quality

Acid Type	Concentration (M)	Leaching Time (h)	Pyrolysis Temp (°C)	Silica Purity (%)	Particle Size (nm)	Amorphous Character
HCl	1.0	6	600	94.2	45 ± 8	High
HCl	2.0	12	650	97.5	35 ± 6	High
HCl	3.0	24	700	98.8	28 ± 5	Moderate
H ₂ SO ₄	1.0	6	600	93.8	48 ± 9	High
H ₂ SO ₄	2.0	12	650	96.9	38 ± 7	High
H ₂ SO ₄	3.0	24	700	98.2	30 ± 6	Moderate

Sourced from Parhizkar (2025)

3.2.2 Mechanical Milling Method

Mechanical milling offers an alternative route where rice husk ash (RHA) produced by conventional burning is subjected to ball milling for extended periods (2–60 hours). Table 4 summarizes the findings from Munawar et al. (2023) on how ball milling duration affects the properties of nano-silica derived from rice husk ash (RHA). While longer milling progressively reduces particle size and increases surface area up to 30 hours, the data show that 7 hours of milling strikes an optimal balance achieving a substantial reduction in particle size (to 85 nm) and a high pozzolanic activity index (89%) before agglomeration and reduced reactivity occur at 60 hours.

Table 4. Effect of milling duration on nanosilica properties

Milling Duration (hours)	Mean Particle Size (nm)	Specific Surface Area (m ² /g)	Crystallinity Index (%)	Pozzolanic Activity Index (%)
0 (Raw RHA)	15,000 ± 2,000	55 ± 8	42	68

2	450 ± 120	95 ± 12	38	75
7	85 ± 25	185 ± 20	31	89
15	65 ± 18	210 ± 25	28	92
30	52 ± 15	235 ± 30	26	93
60	48 ± 20	195 ± 35	29	88

Source: Munawar et al. (2023)

3.2.3 Precipitation Method

The precipitation method involves dissolving RHA in NaOH solution to produce sodium silicate, followed by neutralization with acid to precipitate silica gel. Drying and calcination yield nanosilica with controlled textural properties. The table 5 summarizes the key processing parameters for extracting nanosilica from rice husk ash (RHA) via the precipitation method. It outlines the tested ranges, optimal values, and effects of five variables NaOH concentration, dissolution temperature/time, neutralization pH, and aging time on the final nanosilica properties. The data, adapted from Krishnan et al. (2022), highlights trade-offs such as yield versus agglomeration, reaction rate versus energy use, and particle size versus washing requirements, providing practical guidance for producing nanosilica tailored for applications like soil stabilization.

Table 5. Influence of precipitation parameters on nanosilica characteristics

Parameter	Range Tested	Optimal Value	Effect on Product
NaOH Concentration	1–5 M	2.5 M	Higher concentration increases yield but may cause agglomeration
Dissolution Temperature	60–120°C	90°C	Higher temperature accelerates reaction but increases energy consumption

Dissolution Time	0.5–4 h	2 h	Longer time increases yield up to optimal point
Neutralization pH	4–9	7–8	Lower pH produces finer particles but increases washing requirements
Aging Time	0–48 h	12 h	Longer aging increases particle size and crystallinity

Source: Krishnan et al. (2022)

3.2.4 Comparative Analysis of Synthesis Methods

The table 6 below provides a side-by-side comparison of three key nanosilica synthesis methods: Acid Leaching Pyrolysis, Mechanical Milling, and Precipitation across three main criteria: Product Quality, Process Economics, and Scalability.

- **Product Quality:** Acid leaching-pyrolysis yields the highest purity (>98%) and finest particle size (15–50 nm) with narrow distribution, while mechanical milling offers the broadest size distribution and lowest purity (85–95%).
- **Process Economics:** Precipitation uses the most water (40–60 L/kg) and chemicals but generates high waste; mechanical milling has the lowest chemical consumption but highest energy use (15–25 kWh/kg). Acid leaching-pyrolysis is mid-range in most economic metrics.
- **Scalability:** Precipitation excels in industrial scalability with very high consistency; acid leaching-pyrolysis shows good industrial potential, whereas mechanical milling has limited scalability due to moderate consistency and pilot feasibility.

Overall, the table helps resolve trade-offs in selection method: highest quality (acid leaching-pyrolysis), simplest chemistry with low waste (mechanical milling), or best large-scale production (precipitation).

Table 6. Comprehensive comparison of nanosilica synthesis methods

Criterion	Acid Leaching - Pyrolysis	Mechanical Milling	Precipitation
Product Quality			
Purity (%)	>98%	85–95%	90–98%
Particle Size (nm)	15–50	20–100	20–80
Size Distribution	Narrow	Broad	Moderate
Specific Surface Area (m ² /g)	250–350	150–250	200–300
Amorphous Content	High	Moderate-High	High
Process Economics			
Energy Consumption (kWh/kg)	8–12	15–25	10–15
Chemical Consumption	Moderate	Low	High
Water Usage (L/kg)	20–30	5–10	40–60
Waste Generation	Moderate	Low	High
Production Cost (USD/kg)	8–15	10–18	12–20
Scalability			
Lab Scale Suitability	Excellent	Good	Excellent
Pilot Scale Feasibility	Good	Moderate	Excellent
Industrial Scalability	Good	Limited	Excellent
Consistency	High	Moderate	Very High

3.3 Characterization Techniques

Comprehensive characterization is essential to correlate synthesis parameters with stabilisation performance. Key techniques include:

Fourier-Transform Infrared Spectroscopy (FTIR) identifies surface functional groups. Parhizkar (2025) reported that nanosilica exhibits characteristic peaks at approximately 1017 cm^{-1} (Si–O–Si asymmetric stretching), 800 cm^{-1} (Si–O–Si symmetric stretching), and $950\text{--}970\text{ cm}^{-1}$ (Si–OH stretching).

The presence of silanol (Si–OH) groups indicates surface reactivity essential for pozzolanic reactions. Table 7 summarizes the key Fourier-Transform Infrared Spectroscopy (FTIR) absorption bands used to characterize nanosilica for stabilization applications.

Table 7. Characteristic FTIR absorption bands for nanosilica

Wavenumber (cm^{-1})	Vibration Mode	Functional Group	Significance
3400–3500	O–H stretching	Silanol (Si–OH)	Reactive sites for pozzolanic reactions
1630–1640	H–O–H bending	Adsorbed water	Indicates hydrophilicity
1080–1100	Si–O–Si asymmetric stretching	Siloxane	Backbone structure
950–970	Si–OH stretching	Silanol	Surface reactivity
800–810	Si–O–Si symmetric stretching	Siloxane	Structural integrity
450–470	Si–O–Si bending	Siloxane	Network formation

Source: Parhizkar (2025) and Munawar et al. (2023)

Table 8 summarizes the key X-ray Diffraction (XRD) characteristics of various silica forms and their direct correlation with pozzolanic activity. Amorphous silica is identified by a broad hump centred at a low 2θ range ($15\text{--}30^\circ$), with a crystallinity index below 5%, enabling very high reactivity. In contrast, crystalline forms like quartz and cristobalite produce sharp, well-defined peaks at specific angles (e.g., 26.6° for quartz), corresponding to high crystallinity ($>80\%$) and consequently low to very low pozzolanic

activity. Partially crystalline silica exhibits mixed features (broad hump plus sharp peaks) and moderate reactivity. This table supports the principle that maintaining an amorphous character—as validated by Meeravali et al. (2024) for nano-rice husk ash treated soils is essential for forming cementitious compounds like C-A-S-H gels.

Table 8. XRD characteristics of different silica forms

Silica Type	2θ Peak Position	Peak Shape	Crystallinity Index	Pozzolanic Activity
Amorphous Silica	$15\text{--}30^\circ$ (broad)	Broad hump	$<5\%$	Very High
Partially Crystalline	22° + sharp peaks	Broad + sharp	$20\text{--}50\%$	Moderate
Cristobalite	21.9° , 28.4° , 31.4°	Sharp peaks	$>80\%$	Low
Quartz	20.8° , 26.6° , 50.1°	Very sharp	$>95\%$	Very Low

Table 9 compares the surface area and pore properties of raw rice husk ash (RHA) versus various types of nanosilica (NS) derived from it. BET analysis quantifies specific surface area (SSA) and porosity, which directly influence pozzolanic reactivity.

Key observations:

- Raw RHA has low SSA ($50\text{--}80\text{ m}^2/\text{g}$) and limited mesoporosity.
- Milled NS reaches $150\text{--}220\text{ m}^2/\text{g}$; longer milling (60h) shifts pore structure toward micro-mesoporous.
- Precipitated NS achieves $200\text{--}300\text{ m}^2/\text{g}$ with higher pore volume ($0.20\text{--}0.35\text{ cm}^3/\text{g}$).
- Acid-leached NS yields the highest SSA ($250\text{--}350\text{ m}^2/\text{g}$) and finest pores ($2\text{--}8\text{ nm}$), maximizing reactivity.

These trends explain why nanosilica exhibits superior performance in soil stabilization and cementitious applications compared to raw RHA.

Table 9. BET surface area and pore characteristics

Material	Specific Surface Area (m ² /g)	Pore Volume (cm ³ /g)	Average Pore Diameter (nm)	Pore Type
Raw RHA	50–80	0.05–0.10	5–15	Mesoporous
Milled NS (7h)	150–200	0.15–0.25	4–10	Mesoporous
Milled NS (60h)	180–220	0.12–0.20	3–8	Micro-mesoporous
Precipitated NS	200–300	0.20–0.35	3–12	Mesoporous
Acid Leached NS	250–350	0.25–0.40	2–8	Micro-mesoporous

3.4 Stabilisation Mechanisms

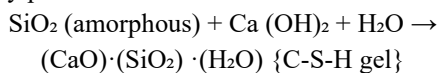
The effectiveness of nanosilica as a soil stabilizer emerges from multiple interacting mechanisms operating at different scales: molecular (pozzolanic reactions), nanoscale (filling and nucleation), microscale (particle bonding), and macroscale (strength enhancement).

3.4.1 Pozzolanic Reaction and Cementitious Product Formation

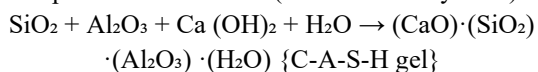
Silica itself possesses no cementitious properties but reacts with calcium hydroxide (Ca(OH)₂, portlandite) in the presence of water to form calcium silicate hydrate (C-S-H)—the primary binding phase in cement-based systems.

Chemical Reactions:

Primary pozzolanic reaction:



In the presence of alumina (common in clay soils):



The C-S-H and C-A-S-H phases perform two critical functions: (1) they bind adjacent soil particles, increasing cohesion; and (2) they fill interparticle voids, reducing porosity and permeability (Munawar et al., 2023).

Table 10 lists four key reaction products (C-S-H Types I and II, C-A-S-H, and portlandite), their chemical formulas, primary functions, and typical formation timeframes, citing evidence that such reactions can reduce soil collapse potential by up to 88%

Table 10. Pozzolanic reaction products and their functions

Reaction Product	Formula	Primary Function	Formation Time
C-S-H (Type I)	Variable C/S ratio	Interparticle binding	1–7 days
C-S-H (Type II)	C/S ~1.7	Filling, strength	7–28 days
C-A-S-H	C-A-S-H	Aluminum binding	7–28 days
Portlandite	Ca(OH) ₂	pH buffer, reservoir	Immediate

Mostafaei et al. (2026) demonstrated that stabilisation of collapsible clay soils with nanosilica and eco-friendly additives resulted in collapse potential reduction of up to 88% (from 11.1% to 1.35–4.63%), attributed to pozzolanic reactions and cementitious bonding.

3.4.2 Microfilling and Densification

Nanosilica particles (15–50 nm) are substantially smaller than typical soil pore throats (100 nm to several micrometers). This size disparity enables nanoparticles to migrate into micropores and interaggregate spaces, effectively "filling" voids that larger particles cannot occupy. The packing effect increases soil density and reduces hydraulic conductivity, while also limiting the space available for water absorption that drives swelling in expansive clays. Table 11 complements the discussion of microfilling and densification by quantifying how nanosilica treatment alters soil pore size distribution.

It shows that increasing nanosilica content (0.4% and 1.2% NS) progressively reduces the volume of macropores and mesopores while increasing the volume of nanopores. This shift confirms the “filling” effect described earlier: nanosilica particles occupy larger voids, leading to densification, reduced hydraulic conductivity, and limited space for water absorption in expansive clays.

Table 11. Pore size distribution in nanosilica-treated soils

Pore Category	Diameter Range	Untreated Soil Volume (%)	0.4% NS Treated (%)	1.2% NS Treated (%)
Macropores	>50 μm	15–25	10–18	5–12
Mesopores	2–50 μm	10–20	8–15	5–10
Micropores	0.05–2 μm	5–10	4–8	3–6
Nanopores	<0.05 μm	1–3	2–5	3–8

Source: Munawar et al. (2023)

3.4.3 Nucleation Site Provision

Nanosilica particles serve as nucleation sites for hydration product precipitation. The additional surface area provided by dispersed nanosilica accelerates hydration kinetics and promotes more uniform product distribution throughout the soil matrix (Meeravali et al., 2020). The multi-scale physical and chemical processes that improve soil stability following nanomaterial treatment.

Complementing the roles of nanosilica in nucleation site provision (Section 3.4.3) and pore gel transformation (Section 3.4.4), table 12 categorizes four key bonding mechanisms Van der Waals forces, chemical C-S-H bonding, mechanical interlocking, and capillary forces alongside their respective length scales, primary effects on particle interaction, and secondary outcomes that collectively enhance soil shear resistance and load-bearing potential.

3.4.4 Interparticle Bonding Enhancement

Nanoparticles cause transformation of pore liquid to viscous gel, resulting in enhancement of soil shear

resistance. The nanostabilisation of soil improves its structure, physical, and chemical properties due to filling of voids at the nanolevel, leading to enhanced load-bearing potential through increased interparticle attractive forces (Munawar et al., 2023).

Table 12. Bonding enhancement mechanisms

Mechanism	Scale	Primary Effect	Secondary Effect
Van der Waals forces	Nanometer	Increased attraction	Reduced interparticle distance
Chemical bonding (C-S-H)	Micrometer	Cementitious bridges	Permanent bonding
Mechanical interlocking	Micrometer	Particle confinement	Increased friction
Capillary forces	Nanometer	Temporary cohesion	Moisture retention

3.5 Applicability of RH-NS Across Soil Types

The applicability of RH-NS varies with soil characteristics including gradation, pore structure, hydraulic conductivity, plasticity, mineralogy, pH, and organic matter content. This dependence is crucial because a method effective in granular soils may perform differently in clayey, expansive, lateritic, or organic soils.

Table 13 systematically evaluates the performance of Renewable Hydrogel Nanoscale Silica (RH-NS) across a range of soil types, from granular to fine-grained and problematic soils.

It highlights that while RH-NS shows high effectiveness in coarse and medium sands offering advantages for strength improvement and erosion control its applicability diminishes in fine-grained and plastic clays due to transport restrictions and low permeability. This table also identifies lateritic soils as an under researched category with significant potential, while noting that expansive soils may require hybrid systems (e.g., fiber-NS) to address swelling shrinkage cycles. Each entry is framed around three practical dimensions: effectiveness, main limitation, and engineering implication, making

it a decision-support tool for ground improvement practitioners.

Table 13. Comparative applicability of RH-NS across soil types

Soil type	Effectiveness	Main limitation	Engineering implication
Coarse sand	High	Local injection clogging	Suitable for strength improvement and erosion control
Medium sand	High	Treatment-cycle sensitivity	Strong potential for ground improvement
Fine sand	Moderate	Premature precipitation and non-uniformity	Requires staged injection and concentration control
Silty sand	Moderate	Partial clogging and reagent loss	Better penetration than MICP
Low-plasticity clay	Moderate	Restricted transport and particle agglomeration	Assisted delivery may be required
High-plasticity clay	Low	Very low permeability, dispersion issues	Hybrid or electrokinetic delivery may be necessary
Expansive soil	Moderate	Swelling and shrinkage cycles	Fiber-NS hybrid systems are promising
Lateritic soil	Under-researched	Fe/Al oxides, variable pH, aggregated structure	Major tropical research gap

3.6 Mechanical, Hydraulic, and Durability Performance

3.6.1 Strength Enhancement

Unconfined compressive strength (UCS) is the most widely reported performance metric for stabilized soils. Table 14 summarizes key findings from recent studies. compiles experimental data from recent studies to illustrate how nanosilica (NS) additives improve the unconfined compressive strength (UCS) of various stabilized soils.

It compares control samples (untreated) against binder systems combining NS with materials like rice husk ash (RHA), lime, fiber, or Sarooj across four soil types: expansive clay, collapsible clay, soft clay, and black cotton soil. Key metrics include NS content (0–5%), curing time (7–28 days), achieved UCS (kPa), and the fold improvement over controls.

The table demonstrates that even small NS additions (0.4–1.2%) can substantially enhance strength, with longer curing generally yielding higher gains. References span 2022–2026, showing recent research focus

Table 14. Summary of nanosilica effects on soil strength properties

Soil Type	Binder System	NS Content	Curing Time (days)	UCS (kPa)	UCS Improvement	Reference
Expansive Clay	None (control)	0%	7	118	-	Munawar <i>et al.</i> , 2023
Expansive Clay	NS + RHA (9%)	1.2%	7	256	2.17×	Munawar <i>et al.</i> , 2023
Expansive Clay	NS + RHA (9%)	1.2%	28	385	3.26×	Munawar <i>et al.</i> , 2023
Collapsible Clay	None (control)	0%	28	71	-	Mostafaei <i>et al.</i> ,

						2026
Collapsible Clay	NS + Lime + Fiber	0.8 %	28	35 2	4.96×	Mostafaei <i>et al.</i> , 2026
Collapsible Clay	NS + Saroj + Fiber	1.2 %	28	43 0	6.06×	Mostafaei <i>et al.</i> , 2026
Soft Clay	None (control)	0%	28	95	-	Krishnan <i>et al.</i> , 2022
Soft Clay	Extracted NS	5%	28	27 8	2.93×	Krishnan <i>et al.</i> , 2022
Black Cotton	None (control)	0%	7	84	-	Meeravali <i>et al.</i> , 2024
Black Cotton	nRHA (7h milled)	0.4 %	28	19 5	2.32×	Meeravali <i>et al.</i> , 2024

3.6.2 Shear Strength Parameters

Nanosilica addition improves both cohesion (c) and angle of internal friction (ϕ), contributing to overall shear strength enhancement.

Table 15 presents the shear strength parameters cohesion (c) and friction angle (ϕ) of soil treated with varying dosages of nanosilica (NS), compared to untreated soil. The data show that increasing nanosilica content progressively enhances both parameters: cohesion improves dramatically from 25 kPa to 72 kPa (a 188% increase at 1.2% NS), while the friction angle rises from 18° to 27° (a 50% increase). Consequently, the overall shear strength increases by factors of 1.8×, 2.4×, and 3.1× for 0.4%, 0.8%, and 1.2% NS, respectively, demonstrating a clear dose-dependent strengthening effect.

Table 15. Effect of nanosilica on shear strength parameters

Treatment	Cohesion, c (kPa)	Friction Angle, ϕ (°)	Shear Strength Increase
Untreated Soil	25	18	-
0.4% NS	42 (+68%)	22 (+22%)	1.8×
0.8% NS	58 (+132%)	25 (+39%)	2.4×
1.2% NS	72 (+188%)	27 (+50%)	3.1×

3.6.3 Swelling Reduction

Expansive soils undergo volume changes with moisture fluctuation, causing structural distress. Nanosilica treatment addresses this through cation exchange reduction, pore refinement, and cementitious bonding.

Table 16 shows quantify how adding nano-rice husk ash (nRHA) a source of nanosilica reduces the swelling behavior of black cotton soil. It shows that untreated soil has a swell potential of 8.5% and swell pressure of 85 kPa. Treatment with increasing nRHA content progressively reduces both parameters up to an optimum of 0.4% nRHA, achieving a 39% reduction in swell potential (5.2%) and swell pressure (52 kPa). Beyond this dosage (0.6-1.0%), the swelling reduction efficiency declines, indicating an optimal dosage threshold for stabilizing expansive soils

Table 16. Effect of nanosilica on swell potential

Soil Type	Treatment	Swell Potential (%)	Swell Pressure (kPa)	Reduction (%)
Black Cotton	Untreated	8.5	85	-
Black Cotton	0.2% nRHA	6.8	68	20%
Black Cotton	0.4% nRHA	5.2	52	39%
Black Cotton	0.6% nRHA	5.5	55	35%

n				
Black Cotto n	0.8% nRHA	6.0	60	29%
Black Cotto n	1.0% nRHA	6.5	65	24%

Source: Meeravali et al. (2024)

3.6.4 California Bearing Ratio (CBR) Improvement

CBR is a critical parameter for pavement design and subgrade evaluation. Nanosilica addition significantly improves CBR values, indicating enhanced load-bearing capacity.

Table 17 illustrates the effect of nanosilica (NS) on the California Bearing Ratio (CBR) of soil, both with and without rice husk ash (RHA). The data show a progressive increase in soaked and unsoaked CBR values as the nanosilica content rises from 0% to 1.2%. The highest improvement a 3.63times increase in soaked CBR relative to untreated soil is achieved by combining 1.2% NS with 9% RHA. This demonstrates that nanosilica, particularly when combined with RHA, significantly enhances the soil's load-bearing capacity and moisture resistance, which are vital for pavement subgrade performance.

Table 17. Effect of nanosilica on CBR values

Treatment	Soaked CBR (%)	Unsoaked CBR (%)	CBR Improvement (Soaked)
Untreated Soil	3.2	4.5	-
0.4% NS	5.8	7.2	1.81×
0.8% NS	7.5	9.1	2.34×
1.2% NS	9.2	11.4	2.88×
1.2% NS + 9% RHA	11.6	14.2	3.63×

Data sourced from Munawar et al. (2023)

3.6.5 Durability Under Freeze-Thaw Cycles

A critical consideration for soil stabilisation in temperate and cold regions is performance under freeze-thaw cycles. Krishnan et al. (2022) specifically investigated the influence of extracted

nanosilica on geotechnical properties of soft-clay soil subjected to freeze-thaw cycles.

Table 18 tracks UCS values over 15 cycles, alongside the strength retention percentage of the treated soil (relative to its initial cycle 0 strength). It demonstrates that while both soils lose strength with each cycle, the 5% NS-treated samples retain significantly higher absolute strength (e.g., 128 kPa at 15 cycles) compared to untreated soil (18 kPa), highlighting the durability benefit of nanosilica treatment under freezing conditions. Figure 4 illustrates these trends graphically as freeze-thaw durability curves. Key observations include:

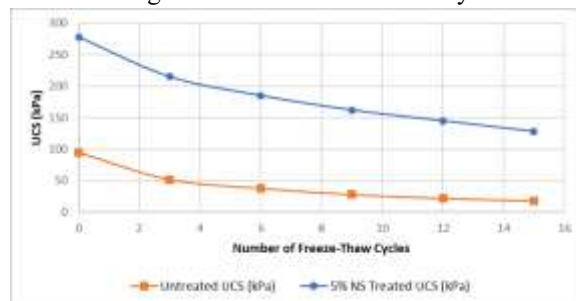
- Treated soil maintains >50% strength after 15 cycles (strength retention approximately 45–46% based on the data).
- Untreated soil loses >75% strength after 12 cycles.
- Nanosilica treatment not only improves absolute strength but also increases ductility under freeze-thaw stress, enhancing long-term durability in cold regions.

Table 18. Effect of freeze-thaw cycles on NS-treated soil

Number of Cycles	Untreated UCS (kPa)	5% NS Treated UCS (kPa)	Strength Retention (Treated)
0	95	278	100%
3	52	215	77%
6	38	185	67%
9	28	162	58%
12	22	145	52%
15	18	128	46%

Source: Krishnan et al. (2022)

Figure 4. Freeze-thaw durability curves



3.6.6 Hydraulic Properties

Hydraulic conductivity (permeability) is a critical parameter for geotechnical structures. Nanosilica's pore-filling effect generally reduces hydraulic conductivity.

The effect of nanosilica (NS) on the hydraulic conductivity of soft clay. It highlights that as nanosilica content increases from 0% to 5%, hydraulic conductivity decreases significantly (from 2.5×10^{-6} to 6.5×10^{-7} cm/s) due to pore-filling, achieving a 74% reduction suitable for landfill liners. However, at 7% NS, permeability reduction drops to 67%, likely due to particle agglomeration. The data, sourced from Krishnan et al. (2022) in table 19, demonstrates an optimal nanosilica dosage around 5% for minimizing hydraulic conductivity.

Table 19. Effect of nanosilica on hydraulic conductivity

Treatment	Hydraulic Conductivity, k (cm/s)	Permeability Reduction	Application Suitability
Untreated Soft Clay	2.5×10^{-6}	-	Moderate
1% NS	1.8×10^{-6}	28%	Good
3% NS	1.1×10^{-6}	56%	Very Good
5% NS	6.5×10^{-7}	74%	Excellent (landfill liner)
7% NS	8.2×10^{-7}	67%	Excellent (some agglomeration)

Source: Krishnan et al. (2022)

3.7 Synergistic Effects with Other Stabilisers

3.7.1 Nanosilica-RHA Synergy

The synergistic combination of nanosilica with micro-level RHA has demonstrated superior performance compared to either material alone. Table 20 presents a cost-benefit analysis of nanosilica (NS) and rice husk ash (RHA) composites, illustrating the synergistic effect discussed in section 3.7.1.

It compares four stabilisation scenarios RHA alone, NS alone, and the NS-RHA composite across key

geotechnical parameters (UCS, CBR, resilient/elastic modulus) and cost metrics. The data show that while NS alone offers high performance, it is significantly more expensive (cost ratio 2.50).

The NS-RHA composite achieves superior mechanical properties (e.g., 385 kPa UCS, 11.6% CBR) at a much lower cost (ratio 1.22), yielding a 78% cost saving over NS alone and a 38% more efficient cost-stiffness ratio. Table 20 quantitatively validates the performance and economic advantage of the NS-RHA blend.

Table 20. Cost benefit analysis of NS-RHA composites

Parameter	RHA Alone	NS Alone	NS-RHA Composite	Composite Advantage
Cost Ratio	1.00	2.50	1.22	78% cost saving vs. NS alone
UCS (kPa)	175	310	385	2.17× vs. RHA alone
CBR (%)	4.1	8.5	11.6	2.82× vs. RHA alone
Resilient Modulus (MPa)	45	78	90	2.0× vs. RHA alone
Elastic Modulus (MPa)	28	42	46	1.64× vs. RHA alone
Cost-Stiffness Ratio	0.022	0.032	0.0136	38% more efficient

Sourced: Munawar et al. (2023)

3.7.2 Nanosilica in Geopolymer Systems

Recent advances as reviewed in table 21 in geopolymer technology have incorporated rice husk ash derived silicate solutions as sustainable alternatives to conventional alkaline activators.

Maheepala et al. (2025) shows that the RHA based system achieves significant reductions across all five categories: global warming potential (33%

reduction), fossil resource scarcity (42%), cumulative energy demand (33%), water consumption (17%), and ecosystem impact (75%). These improvements highlight RHA-derived silicate solutions as a more sustainable alternative for geopolymers stabilization, particularly in subgrade applications

Table 21. Environmental performance of RHA-based geopolymers

Impact Category	Conventional Geopolymer	RHA-Based Geopolymer	Improvement
Global Warming Potential (kg CO ₂ eq)	12.5	8.4	33% reduction
Fossil Resource Scarcity (kg oil eq)	3.8	2.2	42% reduction
Cumulative Energy Demand (MJ)	145	97	33% reduction
Water Consumption (L)	85	71	17% reduction
Ecosystem Impact (PDF·m ² ·yr)	0.24	0.06	75% reduction

Data Sourced: Maheepala et al. (2025)

3.8 Sustainability and Environmental Implications

The principal sustainability argument for RH-NS is its potential to reduce dependence on Portland cement and lime while valorizing agricultural waste.

Compared with conventional cementitious stabilisation, bio-mediated stabilisation can reduce carbon emissions, embodied energy, and abiotic resource depletion. Table 22 Providing a structured comparison between traditional cement/lime stabilisation and RH-NS stabilisation across key sustainability metrics. It quantifies the arguments

made such as reduced carbon footprint, energy demand, and waste valorisation while also acknowledging trade-offs like moderate treatment uniformity and emerging field maturity. Table 23 compares mineral based nanosilica with three types of RH-NS (acid leach, precipitation, milling) across life-cycle impact categories. It reinforces the RH-NS advantage by showing lower global warming potential, fossil resource scarcity, and energy demand, with milling notably minimizing water consumption linking directly to the section’s focus on waste-derived, low-carbon alternatives

Table 22. Sustainability comparison between conventional and RH-NS stabilisation

Criterion	Cement/lime stabilisation	RH-NS stabilisation
Carbon footprint	High	Low-moderate
Energy demand	High	Moderate
Waste valorisation	None	High (agricultural waste)
Treatment uniformity	High	Moderate
Fine-soil suitability	Moderate	Moderate
Field maturity	High	Emerging
Cost sensitivity	Binder cost	Production cost
Main environmental risk	CO ₂ emissions	Agglomeration, dispersion challenges
Sustainability opportunity	Low-carbon binders	Waste-derived materials, circular economy

Table 23. Life-cycle assessment comparison of nanosilica sources

Impact Category	Unit	Mineral-Based NS	RH-NS (Acid Leach)	RH-NS (Precipitation)	RH-NS (Milling)
Global Warming	kg CO ₂ eq/kg	8.5	3.2	4.1	5.8

Potential	g				
Fossil Resource Scarcity	kg oil eq/kg	3.2	1.4	1.8	2.3
Cumulative Energy Demand	MJ/kg	125	48	62	85
Water Consumption	L/kg	85	35	55	15

Sourced from Suwanto et al. (2025)

3.9 Challenges, Research Gaps, and Future Direction
 The studies show that nanoparticle agglomeration is a key challenge. Nanosilica effectiveness depends on dispersion, fluid transport, reaction rate, calcium availability, and pore geometry. Non-uniform dispersion leads to inconsistent treatment and reduced reliability.

Production cost remains a barrier, with acid leaching-pyrolysis (USD 8–15/kg) being more expensive than conventional stabilisers (USD 0.10–0.25/kg for cement). Durability is a concern, with many studies showing short-term gains but lacking long-term data under conditions like wet-dry cycles, freeze-thaw, chemical attack, or traffic loading. More research on lateritic soils is urgently needed due to their prevalence in tropical infrastructure development.

Table 24. Major challenges and recommended research directions

Challenge	Engineering implication	Recommended research direction
Nanoparticle agglomeration	Uneven strength and unreliable field performance	Improved dispersion methods, ultrasonication, surface functionalization
High production cost	Limited large-scale adoption	Waste-derived reagents, process optimization, crude extraction methods
Non-uniform	Premature	Staged injection,

distribution	clogging, variable performance	improved delivery control, carrier systems
Limited lateritic soil evidence	Weak tropical application basis	Laboratory and field validation on tropical soils
Lack of standards	Difficult design adoption	QA/QC protocols and design guidelines
Limited durability data	Uncertain service life	Wet-dry, freeze-thaw, and cyclic loading studies
Field-scale uncertainty	Laboratory results may not scale	Pilot-scale monitored field trials



Figure 5. Future research roadmap for RH-NS sustainable soil stabilisation

IV. CONCLUSION

This review assessed the applicability and challenges associated with rice husk-derived nanosilica (RH-NS) for sustainable soil stabilisation. It compared synthesis methodologies, characterization techniques, stabilisation mechanisms, soil applicability, engineering performance, sustainability implications, limitations, and future research needs.

The findings indicate that RH-NS enhances soil behavior via pozzolanic C-S-H and C-A-S-H gel formation, microfilling of interparticle voids, nucleation site provision, and enhanced interparticle bonding. Acid leaching-pyrolysis produces the highest purity (>98%) and smallest particle size (15–50 nm), while mechanical milling offers simplicity but lower purity (85–95%). Precipitation methods

provide good control over textural properties (90–98% purity, 20–80 nm).

RH-NS can improve strength (UCS increases up to 4–5 times), swelling resistance (up to 88% collapse potential reduction), CBR (up to 2.82× improvement), and hydraulic behavior (up to 74% permeability reduction).

Synergistic combinations with RHA provide cost-stiffness ratios of 1.22–2.82, making NS-RHA composites economically attractive.

However, limitations such as nanoparticle agglomeration, non-uniform dispersion, uncertain long-term durability, high production costs (USD 8–20/kg), and the absence of standardized design protocols restrict field application. Tropical lateritic soils remain significantly understudied despite their prevalence in developing countries.

Consequently, future research should focus on:

- Synthesis optimization: Low-energy methods, waste-derived reagents, continuous production processes
- Dispersion enhancement: Surface functionalization, carrier systems, electrokinetic-assisted delivery for fine-grained soils
- Hybrid stabilisation systems: NS-RHA composites, NS-fiber systems, NS-geopolymer hybrids
- Field-scale validation: Pilot-scale trials, long-term performance monitoring (≥ 5 years), instrumented test sections
- AI-assisted design: Machine learning for dosage prediction, response surface methodology, digital twins
- Standardization: Standard synthesis protocols, testing methods, design guidelines, and QA/QC procedures
- Tropical soil investigation: Laboratory and field validation on lateritic soils

By addressing these challenges, RH-NS can transition from laboratory-scale research to routine geotechnical practice, contributing to circular economy principles and sustainable infrastructure development.

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