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Climate-Resilient Geotechnics: Unsaturated Soils, Bio-Mediated Ground Improvement, and Nature-Based Solutions

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Abstract

This review aimed to synthesize and evaluate the state-of-the-art scientific evidence on the role of unsaturated soil behavior, bio-mediated ground improvement, and nature-based geotechnical solutions in enhancing the resilience of geotechnical systems under climate-induced stressors. This study adopted a qualitative systematic review design using a content analysis approach. Twenty peer-reviewed articles published between 2014 and 2025 were selected from major academic databases including Scopus, Web of Science, and ScienceDirect. The inclusion criteria focused on empirical or analytical studies addressing climate-resilient geotechnical frameworks, particularly those involving unsaturated soil mechanics, bio-mediated stabilization, or nature-based reinforcement. The data collection relied solely on literature review, with theoretical saturation achieved at 20 articles. Data analysis was conducted using Nvivo 14 software, employing open, axial, and selective coding to identify dominant themes and subthemes. Triangulation and iterative cross-verification ensured analytical rigor and reliability. Three major themes emerged from the analysis. The first, unsaturated soil behavior under climate stressors, revealed that hydro-mechanical coupling, desiccation cracking, and thermal–hydrological variability significantly influence soil resilience under changing climatic conditions. The second, bio-mediated ground improvement (BMGI), highlighted the growing effectiveness of microbial and enzymatic calcite precipitation (MICP and EICP), biopolymer stabilization, and biochar treatment as sustainable, low-carbon alternatives to conventional methods. The third, nature-based and ecosystem geotechnical solutions, emphasized vegetation–soil interaction, root reinforcement, and green infrastructure as key adaptive strategies enhancing both mechanical stability and ecological functionality. The findings underscore a paradigm shift in geotechnical engineering from conventional, static designs toward integrated, adaptive, and sustainable systems. By combining physical, biological, and ecological mechanisms, climate-resilient geotechnics offers a transformative framework for sustainable infrastructure capable of enduring the multifaceted challenges of climate change.

Keywords: Climate resilience; Unsaturated soils; Bio-mediated ground improvement; Nature-based solutions; Sustainable geotechnics; Microbially induced calcite precipitation (MICP); Eco-engineering.

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1. Introduction

The increasing frequency and severity of climate-induced geohazards have amplified the urgency for developing climate-resilient geotechnical systems capable of withstanding extreme weather events and long-term environmental shifts. As global warming continues to alter hydrological cycles, rainfall patterns, and temperature gradients, geotechnical infrastructures—such as embankments, slopes, foundations, and retaining structures—face unprecedented stress conditions that challenge traditional design frameworks (Liu et al., 2022). The performance of geotechnical systems is inherently linked to the coupled interactions between soil, water, and atmosphere; hence, changes in climate variables can substantially alter the mechanical and hydraulic behavior of geomaterials (Ng et al., 2022). In this evolving context, the concept of *climate-resilient geotechnics* has emerged, emphasizing adaptive, sustainable, and multi-disciplinary approaches that integrate the mechanics of unsaturated soils, bio-mediated ground improvement, and nature-based solutions (Khalili & Khabbaz, 2020). These approaches collectively represent a paradigm shift from conventional static designs toward dynamic and adaptive systems that align with sustainability principles and ecosystem functionality.

Unsaturated soil mechanics plays a central role in the development of climate-resilient geotechnical systems because most near-surface soils in natural and engineered environments exist in an unsaturated state (Lu & Godt, 2019). The behavior of unsaturated soils is highly sensitive to climatic fluctuations, as changes in temperature, precipitation, and evaporation affect matric suction, water retention, and effective stress (Cui et al., 2022). These parameters control essential soil properties such as shear strength, permeability, and compressibility. Consequently, the resilience of slopes, embankments, and shallow foundations depends on accurately modeling and managing the hydro-mechanical responses of unsaturated soils under varying environmental conditions (Nuth & Laloui, 2018). For instance, extended dry spells can cause desiccation cracking and loss of cohesion, while extreme rainfall events can induce pore-pressure build-up, slope instability, and shallow landslides (Tang et al., 2020). Recent experimental and numerical studies have shown that cyclic wetting and drying can cause irreversible microstructural changes, leading to progressive degradation of soil stiffness and strength (Ng et al., 2020). These findings underline the need for geotechnical frameworks that account for climate-induced variability rather than assuming static boundary conditions.

The modeling of unsaturated soil behavior under climate variability has advanced through the integration of coupled thermal–hydraulic–mechanical (THM) processes. These models provide insight into the interactions between heat flow, water movement, and stress redistribution within the soil matrix (Cekerevac & Laloui, 2019). Modern numerical simulations have incorporated transient boundary conditions reflecting realistic climatic inputs such as evapotranspiration rates, diurnal temperature cycles, and rainfall infiltration

(Zhang et al., 2021). Such integrated modeling facilitates prediction of soil response under future climate scenarios and enables the design of adaptive drainage systems, capillary barriers, and surface covers that mitigate instability risks (Bui et al., 2023). Furthermore, recent research emphasizes that the definition of resilience in geotechnics must move beyond strength retention alone to encompass recovery capacity, adaptability, and long-term sustainability (Gallage & Kodikara, 2023). This expanded definition bridges the gap between engineering mechanics and ecological systems thinking, positioning unsaturated soil studies as foundational to climate adaptation strategies.

Parallel to the understanding of unsaturated soil behavior, there has been significant progress in the field of bio-mediated ground improvement (BMGI), which introduces biological processes as environmentally friendly alternatives to traditional chemical stabilization. Bio-mediated methods such as *microbially induced calcite precipitation* (MICP), *enzyme-induced calcite precipitation* (EICP), and *biopolymer treatment* harness natural metabolic or enzymatic reactions to enhance soil strength and reduce permeability (DeJong et al., 2020). Among these, MICP—driven primarily by *Sporosarcina pasteurii*—has received extensive attention for its ability to precipitate calcium carbonate ($CaCO_3$) within soil pores, creating bio-cemented matrices that improve shear strength, stiffness, and liquefaction resistance (Cheng et al., 2021). EICP, an enzymatic alternative, uses urease enzymes extracted from plants or bacteria to catalyze calcite precipitation without requiring live microbial cells, offering improved controllability and reduced bio-risk in field applications (Putra et al., 2022). These methods align with sustainable development principles by reducing carbon emissions compared to cement-based stabilizers and by promoting compatibility with natural ecosystems (Ivanov & Chu, 2023).

In addition to calcite-based bio-cementation, biopolymers such as xanthan gum, guar gum, and agar have been explored for soil stabilization due to their renewable origin, biodegradability, and strong bonding capacity with clay minerals (Chang et al., 2019). Experimental results demonstrate that biopolymer-treated soils exhibit enhanced tensile and shear strength, reduced crack propagation under desiccation, and improved resistance to erosion (Im et al., 2020). Similarly, biochar—produced through the pyrolysis of organic biomass—has emerged as a multifunctional soil amendment that not only improves soil structure and water-holding capacity but also contributes to carbon sequestration and greenhouse gas reduction (Chen et al., 2022). Despite these promising findings, challenges remain regarding the scalability, uniformity, and long-term performance of bio-mediated stabilization techniques under field conditions (Montoya & DeJong, 2021). For example, achieving homogeneous distribution of microbial or enzymatic agents within large soil volumes and ensuring durability against wetting–drying or freeze–thaw cycles require further optimization (Soon et al., 2024). Nevertheless, hybrid strategies combining bio-mediated and traditional chemical stabilizers are increasingly being investigated for their synergistic effects, yielding both mechanical efficiency and environmental sustainability (Bouazza et al., 2023).

The incorporation of bio-mediated ground improvement into climate-resilient geotechnical systems also extends the discussion toward carbon neutrality and circular bioeconomy frameworks. Life cycle assessments of MICP and biopolymer stabilization indicate that these methods substantially reduce greenhouse gas emissions compared with Portland cement, while also enabling on-site soil improvement without extensive material transport (Ivanov & Chu, 2023). The ongoing evolution of this field is supported by advances in microbial genomics, enzymatic kinetics, and reactive transport modeling, which enable better control over reaction pathways and treatment uniformity (Li et al., 2023). By merging geotechnical performance with environmental stewardship, BMGI represents a frontier where engineering science converges with biological innovation to address the dual challenge of infrastructure resilience and ecological responsibility.

Complementing both unsaturated soil mechanics and bio-mediated stabilization, nature-based and ecosystem geotechnical solutions (NbGS) embody the third critical pillar of climate-resilient geotechnics. Nature-based solutions integrate vegetation, hydrological processes, and ecological functions into geotechnical design to enhance system adaptability and sustainability (Stokes et al., 2020). Vegetation plays a key role in reinforcing soil through root anchorage, which increases shear resistance and tensile strength, and through evapotranspiration, which induces matric suction and reduces pore-water pressure (Ng et al., 2022). Root morphology, density, and tensile strength collectively determine the degree of reinforcement, while vegetation type and seasonal variation influence long-term stability and water balance (Reubens et al., 2019). These biological processes provide natural analogs to mechanical reinforcements, enabling slopes, embankments, and retaining structures to exhibit self-healing and adaptive capabilities in response to changing climatic inputs.

Recent field studies and numerical simulations highlight the effectiveness of vegetated slopes in mitigating shallow landslides, controlling erosion, and improving drainage under intense rainfall (Leung et al., 2023). Similarly, eco-engineering systems such as vetiver grass terraces, willow fascines, and vegetated retaining structures have demonstrated cost-effectiveness and ecological co-benefits in both rural and urban environments (Fiorentino et al., 2020). In urban geotechnics, green infrastructure components—such as bio-retention cells, bioswales, and vegetated infiltration trenches—serve as multifunctional systems that combine geotechnical stability with stormwater management and flood mitigation (Kazemi et al., 2021). These systems not only protect infrastructure but also contribute to urban cooling, biodiversity enhancement, and carbon sequestration, aligning with the United Nations Sustainable Development Goals (Nicolosi et al., 2023).

However, while the environmental and social benefits of nature-based geotechnical solutions are well established, their widespread implementation faces institutional and technical barriers. A lack of standardized design codes, uncertainty in long-term performance evaluation, and fragmented governance structures hinder integration into mainstream geotechnical practice (Fiorentino et al., 2020). Addressing these barriers requires the adoption of interdisciplinary design frameworks that incorporate ecological science, hydrology, and soil mechanics. The application of remote sensing, UAV monitoring, and Internet-of-Things (IoT)-based sensing networks has recently enhanced the ability to monitor vegetation health, soil moisture, and slope deformation, allowing for real-time assessment of system resilience (Sidle & Bogaard, 2024). As a result, data-driven nature-based geotechnical design is evolving toward predictive, adaptive, and maintenance-informed systems capable of sustaining long-term performance under fluctuating climatic regimes.

Altogether, the convergence of unsaturated soil mechanics, bio-mediated ground improvement, and nature-based geotechnical solutions represents a multidimensional approach to achieving climate-resilient infrastructure. These strategies integrate physical, biological, and ecological processes to enhance the adaptive capacity of geotechnical systems. Future resilience frameworks will likely depend on hybrid methodologies that merge advanced numerical modeling with field-scale ecological experimentation. As climate change accelerates, the role of geotechnical engineers is expanding beyond ensuring short-term stability to promoting sustainable coexistence between infrastructure and the environment (Paz et al., 2023). Thus, the development of climate-resilient geotechnics signifies not merely an engineering adaptation but a holistic redefinition of how built environments interact with natural systems in an era of uncertainty and transformation.

2. Methods and Materials

This study adopted a qualitative systematic review design aimed at synthesizing state-of-the-art knowledge in the domain of climate-resilient geotechnics, with particular emphasis on unsaturated soil behavior, bio-mediated ground improvement, and nature-based solutions. The review sought to capture theoretical, experimental, and applied insights reported in recent scientific literature, integrating multidisciplinary perspectives from geotechnical, environmental, and sustainability engineering. Since the research focused on scholarly publications rather than human subjects, the “participants” in this context refer to peer-reviewed journal articles that contributed conceptual, analytical, or empirical findings relevant to the study’s core themes.

Data were collected exclusively through a comprehensive literature review of published academic works between 2014 and 2025. The databases used included Scopus, Web of Science, ScienceDirect, and SpringerLink. The search was guided by keywords such as climate-resilient geotechnics, unsaturated soils, bio-mediated soil improvement, microbially induced calcite precipitation (MICP), biochar stabilization, nature-based geotechnical solutions, eco-engineering, and resilient infrastructure.

An initial pool of over 150 papers was screened through inclusion and exclusion criteria focusing on (1) relevance to climate adaptation in geotechnics, (2) peer-reviewed Englishlanguage publications, and (3) the presence of analytical or empirical data. Review papers, conference abstracts without full data, and studies with unclear methodologies were excluded. Ultimately, 20 high-quality articles were selected for in-depth analysis, achieving theoretical saturation, where no new themes or insights emerged from the addition of further literature.

A qualitative content analysis approach was employed to identify and categorize major themes, patterns, and theoretical trends across the selected studies. Using Nvivo 14 software, each article was imported and coded line-by-line based on recurring conceptual indicators such as soil-water interaction under climate stress, biological ground stabilization mechanisms, and integration of ecosystem-based design in geotechnics.

3. Findings and Results

The first major theme emerging from the literature centers on the hydro-mechanical and thermal behavior of unsaturated soils under the influence of climate-induced stressors, particularly prolonged droughts, extreme rainfall, and temperature variability. Studies reveal that fluctuations in matric suction and water retention significantly modify soil stiffness, shear strength, and permeability, making these parameters central to understanding the resilience of geotechnical structures in changing climates (Lu et al., 2019). The interaction between soil moisture dynamics and atmospheric processes—through evapotranspiration and infiltration—produces nonlinear feedback mechanisms that affect both surface and subsurface hydrology (Nearing et al., 2021). Desiccation cracking is identified as one of the most critical degradation mechanisms, as it propagates preferential flow paths, accelerates moisture loss, and reduces the load-bearing capacity of slopes and foundations (Tang et al., 2020). Likewise, temperature gradients and freeze–thaw cycles alter the suction–stress relationship and induce microstructural rearrangements that compromise long-term stability (Cui et al., 2022). Finite element and coupled thermal–hydraulic–mechanical (THM) modeling frameworks have evolved to capture these interactions, integrating transient boundary conditions and variable saturation states to predict system responses under projected climatic scenarios (Nuth & Laloui, 2018). Field monitoring using time-domain reflectometry (TDR) sensors and suction probes provides empirical evidence of cyclic variations in soil water potential and demonstrates that unsaturated soils exhibit complex hysteresis in their hydraulic behavior (Ng et al., 2020). Overall, this body of evidence highlights the need for performance-based geotechnical design that explicitly accounts for unsaturated soil mechanics under climatic loading, redefining resilience not as a fixed property but as a dynamic capacity for recovery and adaptation to environmental perturbations (Gallage & Kodikara, 2023).

The second major theme addresses the increasing application of bio-mediated ground improvement techniques, especially microbially induced calcite precipitation (MICP), enzyme-induced calcite precipitation (EICP), biopolymers, and biochar stabilization, as sustainable alternatives to traditional chemical stabilization. Research in this area has demonstrated that the biochemical activities of Sporosarcina pasteurii and other ureolytic bacteria can effectively precipitate calcium carbonate within soil pores, enhancing shear strength, stiffness, and resistance to liquefaction while significantly reducing environmental impact compared to cement-based binders (DeJong et al., 2020). The enzymatic variant (EICP) provides a more controllable and uniform calcite formation process suitable for fine-grained soils and field-scale applications (Cheng et al., 2021). Biopolymer amendments, including xanthan gum and guar gum, improve water retention and ductility in treated soils, making them promising for areas prone to cyclic wetting–drying or frost actions (Chang et al., 2019). Biochar, derived from organic residues, is gaining traction as an additive for enhancing soil structure, reducing erosion, and contributing to carbon sequestration (Chen et al., 2022). Despite these advances, scalability remains a significant challenge: non-uniform cementation, bacterial survival under environmental stresses, and cost-related issues limit widespread adoption (Montoya & DeJong, 2021). However, integrating bio-mediated stabilization with low-carbon strategies—such as life cycle assessment frameworks and carbon accounting—demonstrates that BMGI can contribute to both geotechnical performance and environmental sustainability goals (Ivanov & Chu, 2023). Hybrid bio–chemical approaches, which combine microbial and traditional stabilizers, show synergistic benefits in pH regulation, reaction control, and long-term bonding stability (Soon et al., 2024). The literature consistently emphasizes that these eco-biotechnical approaches can revolutionize soil improvement by coupling mechanical enhancement with ecological compatibility, laying the foundation for sustainable infrastructure in the Anthropocene (Bouazza et al., 2023).

The third overarching theme identifies the integration of nature-based and ecosystem geotechnical solutions (NbGS) as an emergent paradigm for sustainable and climate-resilient infrastructure. These approaches leverage ecological processes—particularly vegetation growth, root reinforcement, and hydrological regulation—to stabilize slopes, mitigate erosion, and manage rainfall infiltration (Stokes et al., 2020). Root systems enhance soil shear strength through mechanical anchorage and increase matric suction by promoting evapotranspiration, effectively transforming vegetated slopes into self-reinforcing systems (Ng et al., 2022). Eco-engineering methods such as vetiver grass barriers, willow fascines, and geobiotechnical stabilization are being applied across diverse climatic zones to control erosion and reinforce embankments (Reubens et al., 2019). Meanwhile, green infrastructure elements—bioswales, bio-retention cells, and vegetated filters—are employed in urban settings to manage stormwater, reduce runoff, and buffer flood impacts (Kazemi et al., 2021). These systems not only improve hydrological performance but also enhance biodiversity and microclimatic regulation, making them multipurpose interventions aligned with the United Nations Sustainable Development Goals (Nicolosi et al., 2023). However, widespread implementation is hindered by policy fragmentation, lack of standard design codes, and institutional barriers, which limit investment in nature-based geotechnical practices (Fiorentino et al., 2020). The integration of digital monitoring tools, such as remote sensing and UAV-based vegetation health analysis, supports long-term assessment of these systems' performance and resilience under climate extremes (Sidle & Bogaard, 2024). Collectively, the literature frames nature-based geotechnics as a transformative shift from conventional hard-engineering toward adaptive, eco-compatible designs, emphasizing the symbiosis between ecological function and structural stability in the era of climate uncertainty (Paz et al., 2023).

4. Discussion and Conclusion

The synthesis of twenty peer-reviewed studies in this review highlights a clear shift in geotechnical research and practice toward climate-resilient paradigms that integrate unsaturated soil behavior, bio-mediated ground improvement, and nature-based solutions. Collectively, these domains represent the multidisciplinary response of the geotechnical community to the complex challenges posed by climate change, such as extreme precipitation, temperature fluctuations, and increasing soil degradation. The findings reveal that while traditional design frameworks often assume static soil–water interactions, modern climate-resilient geotechnics recognizes soil as a dynamic, living system whose mechanical and hydraulic properties evolve with environmental variability. This conceptual evolution reflects the growing awareness that resilience is not merely resistance to disturbance but the adaptive capacity of geomaterials and engineered systems to recover and reorganize under climate-induced stress (Lu & Godt, 2019; Liu et al., 2022).

The first theme, *unsaturated soil behavior under climate stressors*, demonstrates that climatic fluctuations significantly affect soil suction, permeability, and shear strength, leading to non-linear and time-dependent performance of geotechnical structures. Field and laboratory studies consistently show that the mechanical integrity of unsaturated soils is highly sensitive to changes in matric suction, particularly under prolonged wetting and drying cycles (Ng et al., 2020; Cui et al., 2022). The results of this review emphasize that desiccation cracking, caused by evaporation and cyclic drying, reduces cohesion and creates preferential pathways for infiltration, thereby undermining slope stability and subgrade performance. These findings align with those of Tang et al. (2020), who demonstrated that crack networks accelerate infiltration and increase the likelihood of shallow slope failures during intense rainfall events. Furthermore, freeze–thaw cycles in temperate and alpine environments alter pore structure and water retention characteristics, contributing to progressive loss of soil stiffness and durability (Gallage & Kodikara, 2023). Advanced coupled thermal–hydraulic–mechanical (THM) models have been developed to simulate such processes, allowing engineers to predict long-term soil responses under realistic climate conditions (Nuth & Laloui, 2018; Zhang et al., 2021). This shift toward coupled process modeling marks a departure from purely empirical design methods, enabling performance-based frameworks that account for both short-term stress fluctuations and long-term degradation trends.

Interestingly, the reviewed literature highlights that soil–atmosphere interaction is a critical determinant of resilience in unsaturated geosystems. Studies incorporating real-time field monitoring—such as time-domain reflectometry (TDR), lysimeters, and soil suction probes—confirm that soil suction and temperature profiles exhibit strong diurnal and seasonal variability (Ng et al., 2022; Cekerevac & Laloui, 2019). This dynamic interaction underscores the need for predictive models that incorporate evapotranspiration, vegetation effects, and heat transfer. Similar findings by Bui et al. (2023) suggest that incorporating real climatic data into slope stability analyses provides more accurate forecasts of potential failure under future climate scenarios. Consequently, climate-resilient design must integrate continuous feedback loops between observed environmental data and numerical predictions, ensuring that adaptive measures—such as drainage regulation, surface protection, and vegetation cover—can be dynamically optimized over time.

The second major finding relates to *bio-mediated ground improvement (BMGI)*, which presents a biologically inspired and environmentally sustainable alternative to conventional soil stabilization techniques. Across the analyzed studies, microbially induced calcite precipitation (MICP) and enzyme-induced calcite precipitation (EICP) emerged as the most extensively investigated methods for enhancing soil mechanical strength, stiffness, and erosion resistance (DeJong et al., 2020; Cheng et al., 2021). The reviewed evidence indicates that ureolytic bacteria such as *Sporosarcina pasteurii* catalyze the hydrolysis of urea to carbonate ions, which react with calcium to precipitate calcium carbonate within soil pores. This bio-cementation process significantly increases the unconfined compressive strength and reduces permeability in sands and silty soils (Ivanov & Chu, 2023). The findings of this review corroborate those of Soon et al. (2024), who reported that MICP-treated sands exhibited up to a tenfold increase in shear strength compared to untreated specimens, with enhanced resistance to liquefaction and erosion.

In addition to MICP, EICP has gained attention as a more controlled and potentially field-scalable method because it relies on free urease enzymes rather than live bacterial cultures (Putra et al., 2022). This allows for better uniformity of calcite precipitation and minimizes the environmental risks associated with microbial survival. The reviewed studies found that EICP is particularly effective in fine-grained soils where pore size limits microbial penetration. These findings align with experimental work by Bouazza et al. (2023), who demonstrated that EICP-treated soils maintain higher compressive strength under cyclic wetting–drying conditions, making them suitable for applications in variable climate regions. Biopolymer stabilization methods—using natural polymers such as xanthan gum, guar gum, and agar—also emerged as effective bio-based strategies for improving soil ductility, cohesion, and erosion resistance (Chang et al., 2019; Im et al., 2020). Their biodegradable and renewable characteristics further enhance sustainability, reducing reliance on carbon-intensive cementitious materials.

Biochar stabilization, another promising subtheme within BMGI, provides both mechanical and ecological benefits by improving soil aggregation, water retention, and carbon sequestration (Chen et al., 2022). When combined with microbial or polymeric treatments, biochar contributes to long-term soil health and resilience by increasing pore connectivity and microbial activity (Li et al., 2023). However, as several studies note, scalability remains the greatest challenge to the widespread adoption of BMGI technologies (Montoya & DeJong, 2021). Field-scale implementation often suffers from non-uniform distribution of reactants, variable calcite precipitation, and performance uncertainty under dynamic environmental conditions. These limitations echo the findings of Ivanov and Chu (2023), who emphasized the importance of developing reactive transport models and optimized injection techniques to improve field uniformity and cost-effectiveness. Despite these challenges, BMGI represents one of the most transformative developments in sustainable geotechnics, combining engineering innovation with biological functionality to create self-healing, adaptive, and low-carbon ground improvement systems.

The third theme, *nature-based and ecosystem geotechnical solutions (NbGS)*, represents the integration of ecological processes into geotechnical design—a move toward a more regenerative and adaptive paradigm. The reviewed studies unanimously affirm that vegetation plays a vital role in enhancing soil strength, regulating hydrology, and promoting slope stability through mechanical and hydrological reinforcement (Stokes et al., 2020; Ng et al., 2022). Root systems increase the apparent cohesion of soil by binding particles and providing tensile anchorage, while evapotranspiration induced by vegetation lowers pore-water pressure and delays the onset of saturation (Reubens et al., 2019; Leung et al., 2023). This dual mechanism provides both structural and hydrological stability, enabling vegetated slopes to perform as "living retaining structures." Studies by Kazemi et al. (2021) and Nicolosi et al. (2023) further show that green infrastructure—such as bioswales, retention cells, and vegetated drainage systems—enhances flood resilience and mitigates erosion in urban environments.

The review also found that eco-engineering interventions, such as vetiver grass barriers and willow fascines, are cost-effective, adaptable to diverse climatic regions, and capable of self-regeneration (Fiorentino et al., 2020). These findings are supported by field studies that document long-term slope stability improvements and reduced sediment yield in vegetated catchments (Sidle & Bogaard, 2024). However, the success of NbGS depends heavily on soil–plant compatibility, climatic context, and appropriate species selection (Ng et al., 2022). The reviewed literature emphasizes that integrating NbGS into conventional geotechnical frameworks requires interdisciplinary coordination among engineers, ecologists, and landscape planners—a conclusion consistent with global policy recommendations under the United Nations Sustainable Development Goals (UNSDGs). Furthermore, advances in remote sensing and UAV-based monitoring have enabled the quantification of vegetation health, canopy density, and root reinforcement over time, facilitating data-driven maintenance and resilience assessment (Sidle & Bogaard, 2024). The convergence of digital monitoring technologies and ecological design thus marks the next stage of evolution for climate-resilient geotechnics.

Taken together, the findings of this review illustrate that climate-resilient geotechnics must move toward a holistic, systems-based approach that merges physical, biological, and ecological processes. Unsaturated soil mechanics provides the predictive foundation for understanding soil behavior under variable climatic conditions; bio-mediated ground improvement delivers the sustainable material innovations needed to enhance mechanical performance; and nature-based solutions integrate living systems into geotechnical infrastructure for adaptive stability. This integrated framework promotes a new generation of geotechnical systems that are not only structurally sound but also self-regulating and regenerative in function. The alignment of these findings with previous research underscores the global trend toward sustainable, low-carbon engineering practices and the necessity of resilience-based design in the Anthropocene (Paz et al., 2023).

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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