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Systematic Review

Improvement of Expansive Soils: A Review Focused on Applying Innovative and Sustainable Techniques in the Ecuadorian Coastal Soils

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Abstract

Traditional stabilization techniques, such as lime and cement, widely used for their effectiveness, albeit with economic and environmental limitations, are leading to the search for sustainable approaches that utilize agricultural and industrial waste, such as rice husk ash, bagasse, and natural fibers. These have been shown to improve key geotechnical properties, even under saturated conditions, significantly. In particular, the combination of rice husk ash and recycled ceramics has shown notable results in Ecuadorian coastal soils. The article emphasizes the importance of selecting techniques that balance effectiveness, cost, and sustainability and identifies existing limitations, such as the lack of long-term data (ten years) and predictive models adapted to the Ecuadorian climate. From a bibliographic perspective, this article analyzes the challenges posed by expansive soils in the western coastal region of Ecuador, whose high plasticity and instability to moisture negatively affect civil works such as roads and buildings. The Ecuadorian clay contained 30% kaolinite and only 1.73% CaO, limiting its chemical reactivity compared to soils such as Saudi Arabia, which contained 34.7% montmorillonite and 9.31% CaO. Natural fibers such as jute, with 85% cellulose, improved the soil's mechanical strength, increasing the UCS by up to 130%. Rice husk ash (97.69% SiO_2) and sugarcane bagasse improved the CBR by 90%, highlighting their potential as sustainable stabilizers. All of this is contextualized within Ecuador's geoenvironmental conditions, which are influenced by climatic phenomena such as El Niño and La Niña, as well as global warming. Finally, it is proposed to promote multidisciplinary research that fosters more efficient and environmentally responsible solutions for stabilizing expansive soils.

Keywords: expansive soils; soil stabilization; sustainable techniques; geotechnical innovation; soil improvement

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1. Introduction

Expansive soils are materials characterized by their remarkable capacity for volume change (swelling and shrinking processes), mainly related to variations in moisture content [1–7]. These materials represent a significant global geotechnical challenge worldwide due to their behavior, which can cause severe damage and costly interventions in infrastructure, such as building foundations, roads, and pavement bases [2–4,6,8,9]. Soil stabilization may solve these problems, becoming a crucial technique to improve soil behavior and its engineering properties and mitigating volume change issues [2,7,10,11].

Damage caused by expansive soils is significant worldwide, and it can have a greater impact than other natural disasters [12,13]. Annual damage costs are estimated in billions of dollars in several countries, e.g., over $15.0 billion in the US and over $3.7 billion in the UK [12]. However, construction in areas with expansive soils is often complex and challenging to avoid [6].

Expansive soils contain high proportions of clay mineral such as montmorillonite, illite, and vermiculite [12,13]. The structure of those clay minerals is found in sheets and layers [14], which allows them to exhibit an important volume change when moisture varies [12]. These minerals possess a net electronegative ionic arrangement and an extraordinary capacity to absorb water [13]. Water enters between the clay sheets, separating them and causing swelling [14], ultimately affecting the soil structure and reducing its resilient capacity. Swelling depends on the particles' total internal and external area [6,14].

Stabilization seeks to improve the soil geotechnical properties, such as the soil's bearing capacity, while controlling or reducing its swelling potential. Thermal stabilization uses heat treatment to alter expansive soil's mineralogical properties, inducing transformative changes in clay minerals [15]. Chemical stabilization methods with additives such as lime and cement have been traditionally used [6,7,9,14,16–19]. However, the high cost and growing environmental concerns related to their production and use have driven the search for more sustainable alternatives [6,7,9,14,18,19]. That has led to a growing interest in innovative techniques that use industrial and agricultural waste materials and other non-traditional additives [4,6–10,14,18,20–25], seeking more economical and ecological solutions. Materials such as fly ash [7–9,20–22,26], agricultural waste (rice husk ash, sugarcane bagasse) [10,11,20,21,27], expanded polystyrene (EPS), sand and jute fibers [1], recycled plastics [20,28], nanomaterials [29,30], and rubber particles obtained from end-of-life tires [31] are being investigated for their potential.

Although significant improvements in properties such as uniaxial compressive strength (UCS), California bearing ratio (CBR), and swelling reduction were achieved [1,8–11,18,26,28,32], the effectiveness of stabilizers may vary depending on the specific composition of the expansive soil. Another challenge is the lack of clear standards for applying stabilization techniques [2,7]. Furthermore, long-term durability under various environmental conditions and potential environmental risks (leaching) requires further research [6,7,9,22,32,33].

The main objective of this paper is conducting a review on the innovative and sustainable techniques available for improving expansive soils, focusing on those techniques with potential applications in Ecuadorian coastal soils. Figure 1 shows Ecuador's general classification of soils, based on their predominant composition. Blue areas correspond to areas where clayey soils predominate, while red areas represent other soil types. According to regional reports and previous geotechnical studies, the dashed black line delimits an approximate region within which clayey soils exhibit expansive characteristics. This information identifies areas with greater susceptibility to seasonal expansion and contraction, justifying the need to apply appropriate stabilization techniques. It should be noted that Figure 1 is a schematic representation for illustrative purposes, based on cartographic data and national geotechnical background. Emerging materials and techniques and the different stabilization mechanisms are analyzed in the paper, and the resulting engineering properties are highlighted.

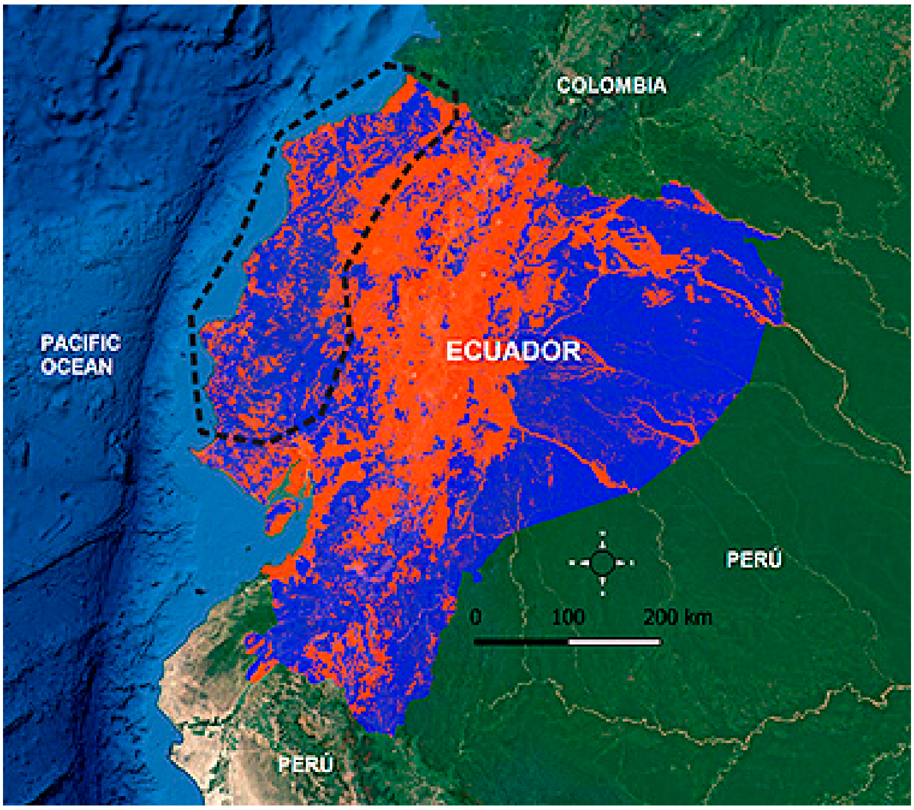


Figure 1. A general classification of the Ecuadorian soils. The clayed type soils are in blue, and the rest are in red. In a dashed black line, the area where the clayed soil presents expansive characteristics. Modified from Google Earth Pro (www.google.es, accessed on 10 May 2025).

In this work, a systematic review was adopted by a qualitative-descriptive approach, complemented by technical evaluation criteria and a structured search strategy in scientific databases. Results were limited to publications containing key terms from this study.

During the review process, the techniques were classified according to their nature into four main categories: chemical stabilization, physical-mechanical stabilization, thermal stabilization, and sustainable stabilization. Due to the research approach integrating the latter, it receives greater attention by integrating biological action mechanisms. Each technique was analyzed considering its geotechnical variables.

The work conducted suggests that the use of additives from waste materials can substantially improve the properties of expansive soils [9,14,20,34]. However, more detailed studies on their long-term performance and environmental impact are needed for their widespread and sustainable implementation [6,7,9,22,32,33]. Special attention was paid in this work to studies that incorporate agro-industrial waste to analyze their adaptability to Ecuador.

2. Research Methods

Expansive soil stabilization techniques fall primarily into two broad categories: (i) physical or mechanical methods, which seek to alter the physical properties of the soil, including modifying gradation and solidity and (ii) chemical methods, which add chemically active materials to the soil, those ones being the most popular stabilization techniques [35].

Other classifications include methods such as thermal stabilization, which involves heat or cooling treatment [35]; electrical treatments, such as electroosmosis [35]; biostabilization techniques, which use biological processes, including microorganism-induced calcium carbonate precipitation (MICP) [36]; and sustainable techniques, which prioritize recycled materials or waste [37].

This work uses a qualitative-descriptive systematic review design, complemented by technical evaluation criteria, to identify and analyze innovative and sustainable techniques for improving expansive soils, particularly in coastal environments such as those in the Manabí province in Ecuador. The methodological approach was structured to ensure academic rigor and relevance to geoengineering practices on the Ecuadorian coast.

Based on the established criteria, this study follows a methodological approach structured in four main stages, aiming to identify, classify, and analyze the most relevant, sustainable, and innovative expansive soil improvement techniques applicable in coastal regions of Ecuador, as shown in Figure 2.

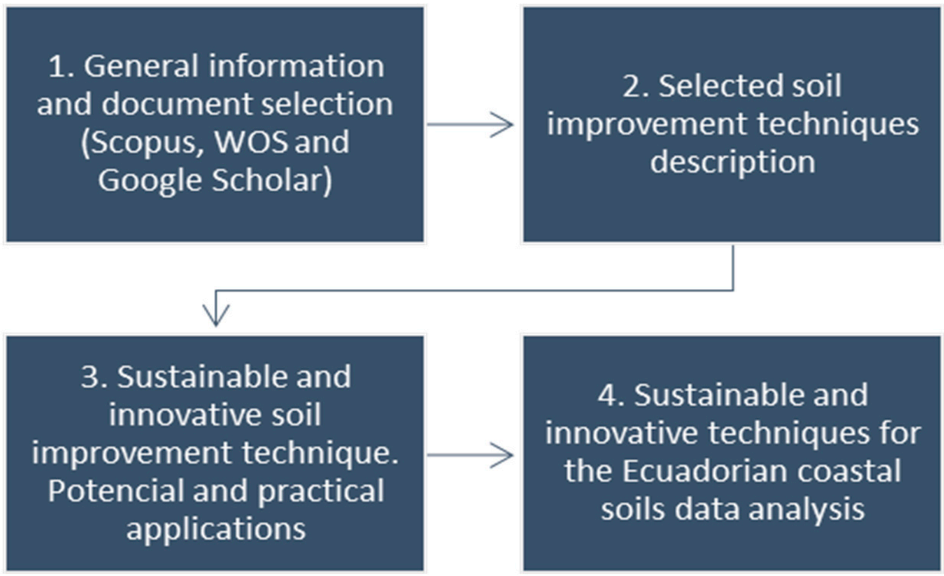


Figure 2. The four stages applied to the methodological approach (WOS meaning Web of Science).

2.1. Gathering General Information and Selecting Documents

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was followed to ensure the research work's transparency and reproducibility. The search strategy was implemented in internationally recognized scientific databases such as Scopus (www.scopus.com, accessed on 5 March 2025), Web of Science—WOS (www.webofscience.com, accessed on 5 March 2025), and Google Scholar (www.scholar.google.com, accessed on 5 March 2025). No publication period restrictions were applied, but languages were limited to English and Spanish. Search strings with the following keywords were used: "expansive soils", "soil stabilization", "sustainable techniques", "geotechnical innovation", "soil improvement", and "Ecuador", using the Boolean operators AND/OR, as shown in Table 1.

In the PRISMA selection process, 510 records were identified through databases. Eleven additional records were obtained through cross-referencing, i.e., by reviewing the bibliographic lists of previously selected articles and locating relevant studies that had not been retrieved in the initial search. After removing 275 duplicates, 246 records were evaluated. From them, 78 were excluded after title/abstract review. A total of 168 articles were then evaluated, from which 20 were excluded due to not meeting the inclusion criteria and 13 due to presenting a high risk of bias. Ultimately, 135 relevant studies were included.

The inclusion criteria considered the following:

- Studies related to the stabilization of expansive soils.
- Publications addressing sustainable or innovative techniques in geotechnics.
- Papers referring to the geotechnical context in tropical or similar areas to Ecuador.
- Studies with sufficient methodological description.

Table 1. Boolean operators that are applied in the scientific papers and publications search.

Basic Keywords	Boolean Operator	Keywords to Combine	Search Results
state of the art, expansive soil, stabilization techniques	AND	review AND of AND the AND state AND of AND the AND art AND in AND expansive AND soil AND stabilization AND techniques	9
expansive soil, stabilization, waste materials, review	AND	expansive AND soil AND stabilization AND using AND waste AND materials: AND a AND review	22
innovative chemical, stabilization, expansive soils	AND	innovative AND chemical AND stabilization AND of AND expansive AND soils	11
application of recycled materials, expansive soil stabilization	AND	application AND of AND recycled AND materials AND for AND expansive AND soil AND stabilization	9
expansive soil, expansive clay, stabilization, improvement, sustainable, innovative	OR/AND	("expansive soil*" OR "expansive clay*") AND ("stabilization" OR "improvement") AND ("sustainable" OR "innovative")	73
expansive soil, swelling soil, problematic soil, soil improvement, soil stabilization, ground improvement, geopolymer, lime stabilization, sustainable technique, innovative method, coastal soil, tropical soil, Ecuador	OR/AND	("expansive soil*" OR "swelling soil*" OR "problematic soil*") AND ("soil improvement" OR "soil stabilization" OR "ground improvement") AND ("geopolymer*" OR "lime stabilization" OR "sustainable technique*" OR "innovative method*") AND ("coastal soil*" OR "tropical soil*" OR "Ecuador*")	11
		Total scientific articles found	135

The exclusion criteria considered the following:

- Duplicates or publications without full access.
- Non-scientific sources (e.g., journals without peer review).
- Papers with unclear methodologies or without verifiable results.
- Studies with a high risk of bias, which are determined through qualitative assessment based on criteria such as lack of experimental control, absence of peer review, or undeclared conflicts of interest.

Figure 3 shows the PRISMA flow diagram for this investigation, where the process used for identification, screening, and included registers can be seen.

Based on the filtered results, a bibliometric analysis was performed using VOSviewer software [38], which facilitates the construction and visualization of bibliometric networks. In this case, keyword co-occurrence analysis was chosen, a bibliometric technique that identifies and visualizes the frequency with which two terms appear together in documents.

This methodology allows the discovery of thematic relationships and conceptual structures within a field of study [38].

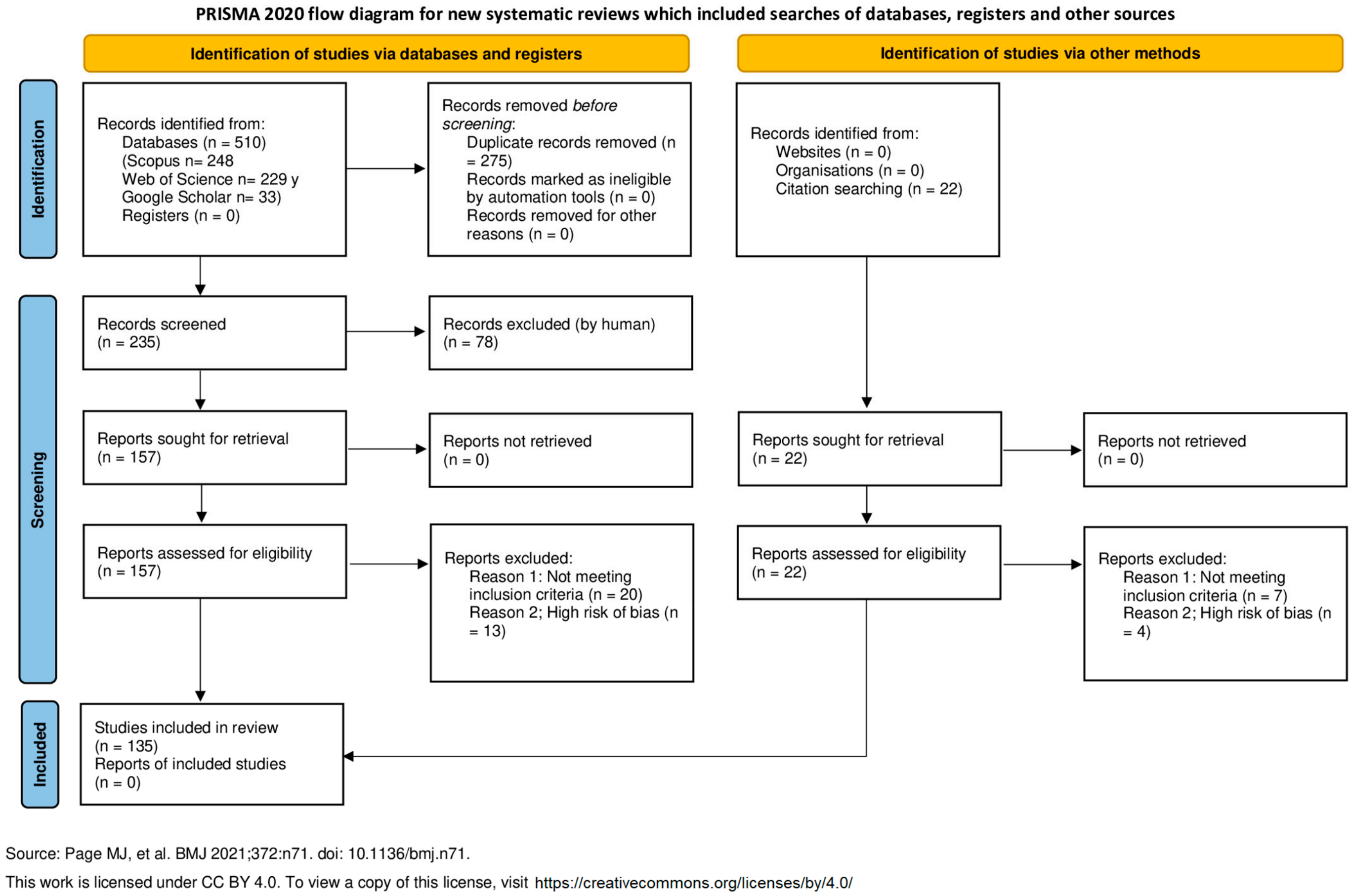


Figure 3. PRISMA 2020 flow diagram. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D., et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. https://doi.org/10.1136/bmj.n71 [39].

Figure 4 represents a keyword co-occurrence network extracted from scientific articles on stabilizing expansive soils using sustainable and innovative materials. Each node (circle) is a keyword, and the lines represent co-occurrences (words that appear together in articles). The minimum co-occurrence threshold used to include terms in the cluster analysis was five. The colors group the terms into thematic clusters that reflect research subfields. Table 2 identifies the five thematic clusters identified in the keyword co-occurrence network.

Evidently, "soil stabilization" is the most central and frequent term on the co-occurrence map, indicating that it is the central thematic axis, while "fly ash" is closely connected to engineering and sustainability clusters, demonstrating its transversal use.

The network reflects a growing interdisciplinarity, connecting environmental sustainability, geotechnical properties, and recycled materials.

In the fifth search string, the occurrences of keywords in scientific articles obtained from the search string with the terms {"expansive soil" OR "expansive clay"} AND {"stabilization" OR "improvement"} AND {"sustainable" OR "innovative"} were studied. The result of the previous process was the relationships between the keywords and the conceptual structure of the research, as shown in Figure 5.

Figures 4 and 5 suggest that modern approaches combine engineering criteria with environmental objectives, this being the key for developing stabilization techniques of use in regions such as the Ecuadorian coast.

Table 3 identifies the two thematic clusters of keyword co-occurrence network for the fifth search string.

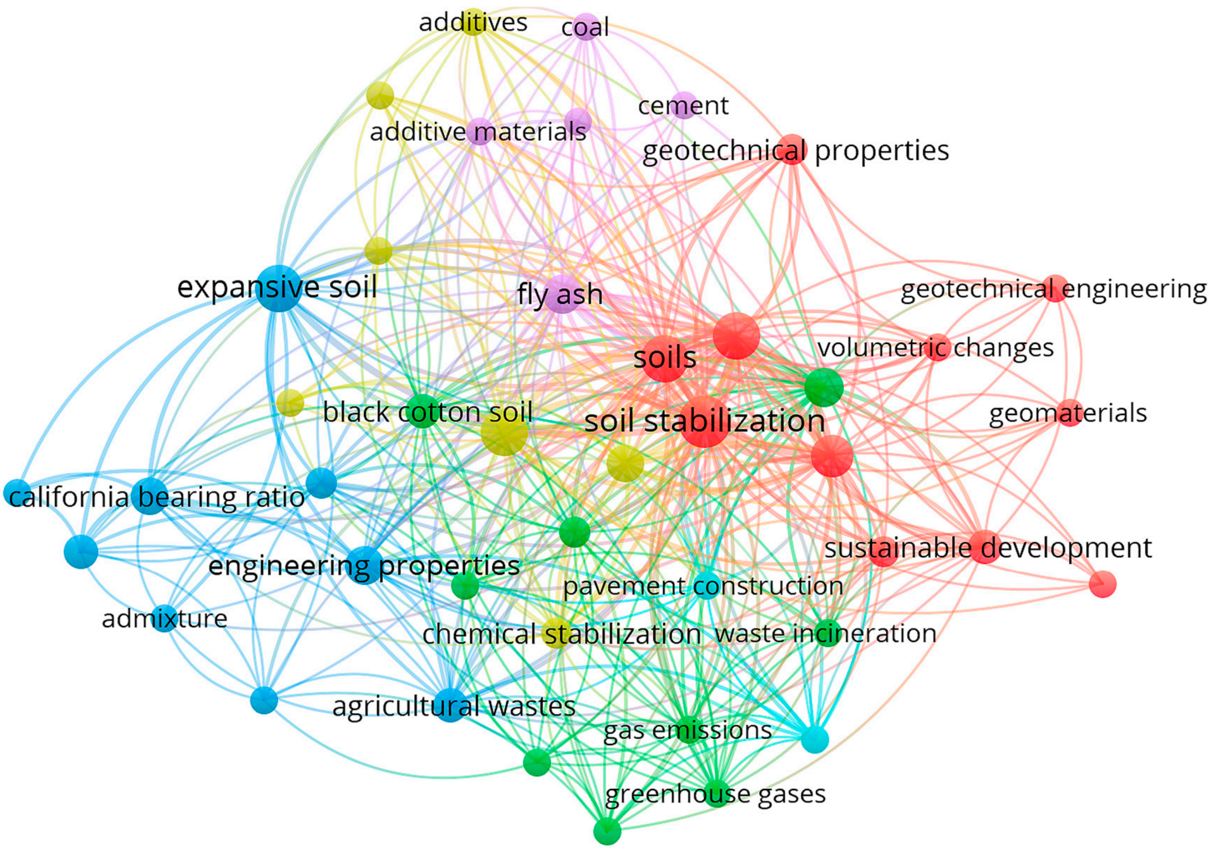


Figure 4. Keyword of the co-occurrence analysis map.

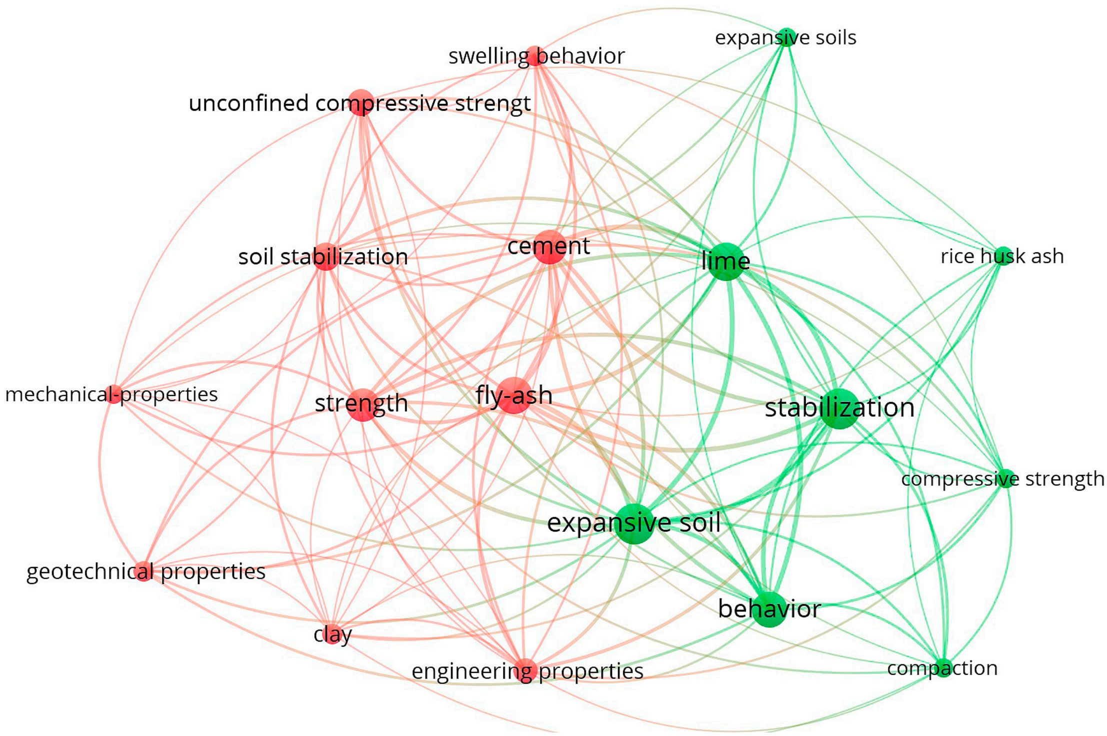


Figure 5. Keywords connection of the co-occurrence analysis map in the fifth search string.

Table 2. Identification of thematic clusters from the second search string.

Description	Cluster Color and Explanation	Practical Implications
Words: soils, soil stabilization, geotechnical properties, sustainable development, volumetric changes This group brings together the core concepts of the study of soil mechanical behavior and its relationship to sustainable practices.	Red—Geotechnical conceptual approach and sustainability	Highlights the fundamental understanding required to integrate sustainability into geotechnical design, particularly relevant for infrastructure projects in Ecuador.
Words: expansive soil, engineering properties, California bearing ratio, admixture This set focuses on how expansive soils' mechanical and physical properties are modified and evaluated.	Blue—Engineering properties of expansive soils	It supports targeted interventions in expansive soils by linking types of additives with performance metrics such as CBR and UCS, which is helpful for local road subgrades.
Words: agricultural waste, greenhouse gases, gas emissions, waste incineration Represents the environmental focus of research, emphasizing the use of organic and industrial waste as stabilizing additives.	Green—Sustainable stabilization and waste	It promotes environmentally friendly and cost-effective solutions through the reuse of waste materials, aligning with the circular economy's goals and utilizing local agricultural by-products.
Words: black cotton soil, fly ash, additive materials Focused on specific types of problematic soils (such as black clays) and common additives (such as fly ash).	Yellow—Specific materials used	It facilitates the selection of additive types for "black cotton" soils in some areas of Ecuador, contributing to field-level stabilization planning.
Words: cement, lime, coal, additives Represents the traditional approach to stabilization with cementitious materials.	Purple—Conventional materials	It serves as a reference for comparing traditional methods with innovative approaches in terms of durability, cost, and carbon footprint.

Table 3. Identification of thematic clusters from the fifth search string.

Description	Cluster Color and Explanation	Practical Implications
Words: soil stabilization, cement, fly ash, unconfined compressive strength, mechanical properties, strength, clay, geotechnical properties, swelling behavior This group represents the traditional approach to stabilization using materials such as cement and fly ash, aimed at improving properties such as mechanical strength, swelling behavior, maximum dry density, and other geotechnical and structural aspects. It reflects a strong interest in quantitative evaluation through tests such as the UCS test	Red—Traditional soil stabilization with cementitious materials	It provides a solid quantitative basis for evaluating the performance of traditional stabilizers, helpful in establishing comparisons with alternative materials in Ecuadorian coastal soils.

Table 3. *Cont.*

Description	Cluster Color and Explanation	Practical Implications
Words: lime, stabilization, expansive soil, rice husk ash, compaction, compressive strength, behavior, engineering properties The group reflects the trend toward more sustainable and innovative approaches to expansive soil stabilization. Using lime and agricultural residues such as rice husk ash suggests a growing focus on economical, environmentally responsible, and low-impact techniques. The approach also focuses on analyzing general soil behavior and compaction properties.	Green—Sustainable and innovative stabilization with alternative additives	It reflects the potential of sustainable, low-impact techniques for improving expansive soils, promoting agricultural waste as a viable alternative in local contexts with limited resources.

2.2. Description of Selected Soil Improvement Techniques

After analyzing the scientific literature obtained for a global context on conventional expansive soil improvement techniques and highlighting the concept of clay mineralogy to understand the nature of these expansive soils, the main soil improvement techniques are briefly described below.

The considerable volumetric changes (swelling and shrinkage) of expansive soil, in response to variations in moisture content, cause movements that can cause severe structural damage. Various stabilization techniques are used to mitigate the adverse effects of these soils, one of which is physical-mechanical stabilization [2,7].

Alsabhan and Hamid [15] refer to the performance evaluation of chemically treated soils, which complements the description of physical-mechanical techniques by emphasizing the importance of increasing density to reduce swelling. They describe an aspect of mechanical behavior that these techniques seek to improve and highlight the critical environmental conditions (humidity cycles) that stabilization techniques must address to be effective.

The effects of heat treatment on soil properties are notable. Heat application significantly reduces soil plasticity, as measured by the liquid and plastic limits, and decreases its swelling and shrinkage potential [15]. For example, studies have shown that heating expansive soils to temperatures such as 400 °C for kaolin or 600 °C for bentonite can effectively convert them into non-expansive soils [15]. In addition, heating improves soil strength characteristics such as maximum dry density and CBR and increases compressive strength [15].

The literature review was extensive and intended to focus on sustainable and innovative techniques. The inclusion criteria prioritized the following:

- Application of innovative or unconventional materials;
- Sustainability potential (use of agricultural or industrial waste);
- Documented experimental validation;
- Applications in regions with geoenvironmental conditions similar to those of the Ecuadorian coast.

Chemical, physical-mechanical, and thermal stabilization are described in greater detail in the results section because they are more widely used. However, the sustainable techniques that are the focus of this work are included, detailing their chemical, physical-mechanical, and biological mechanisms of action. Those articles used to introduce and classify the techniques were classified to ensure a focused reading based on thematic sections.

2.3. Techniques in Sustainable Innovative Soil Improvement

Sustainable and innovative techniques use waste materials and industrial byproducts as additives to improve the properties of these soils. These methods improve strength, reduce volume change, and are more economical and environmentally sustainable alternatives to traditional stabilizers [6,13,21]. Waste materials are available in sufficient quantities to meet demand.

Practical applications of these techniques focus primarily on road subgrade stabilization and are also mentioned for foundations and light structures [6,14,18]. Using waste in these applications offers economic and environmental advantages by reducing costs and the need for landfills [6,14,18].

The practical relevance of each technique was evaluated based on case studies, experimental validations, and documented applications in real-life projects. Special attention was paid to those techniques that

- Have been implemented in low- or middle-income regions;
- Require local, low-cost materials; and
- Can be adapted to coastal environments with high humidity and climate variability (El Niño/La Niña effects).

This stage sought to bridge the gap between theoretical potential and field feasibility, identifying opportunities for scaling, replicability, and community adoption.

2.4. Data Analysis on Sustainable and Innovative Techniques for Soils on the Ecuadorian Coast

In the review of scientific literature, studies on expansive soils on the Ecuadorian coast and nearby regions, such as Peru, were selected. Information was scarce compared to global research. These studies analyze data on stabilization techniques for expansive soils in the coastal zone, evaluating physical properties such as particle size distribution and consistency limits and mechanical properties such as compaction and CBR [17,40–42]. The results are compared between natural soil and mixtures treated with innovative/sustainable additives such as volcanic ash, rice husk ash, ceramic waste, or molasses/vinasse [40–45]. That allows for determining the improvement in strength and reduction of expansion/plasticity following standards such as those of the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO) [40,42,44].

Additionally, the chemical and mineralogical composition is analyzed using techniques such as X-ray diffraction (XRD) and scanning electron microscopy (SEM) [41,44]. These data reveal the structural and compositional changes induced by the additives, providing a better understanding of the stabilization mechanisms [46].

The final analysis integrates the property, composition, and modeling test results to evaluate the technique's effectiveness and define optimal dosages [40,43,44]. The results are validated by comparing them with current regulations and previous studies. Finally, the applicability to specific coastal soils, economic viability, and environmental impact are considered to propose practical and sustainable solutions [17,41–44,46].

The data analysis is carried out in the Results section, where the materials used in sustainable and innovative techniques for improving expansive soils with chemical, physical-mechanical, and biological mechanisms of action are shown.

The conventional techniques mentioned in previous sections, such as chemical, physical-mechanical, and thermal, have been discarded. The techniques best suited to the Ecuadorian coastal context have also been highlighted, and a comparison is made with international best practices for their use in Ecuadorian coastal soils.

3. Results

3.1. General Information Gathering and Document Selection

The sample of 135 scientific documents consulted and obtained through the Scopus, Web of Science, and Google Scholar repositories was classified by similar topics according to their mechanisms of action about expansive soil improvement techniques and the materials typically used. The results are presented in Figure 6.

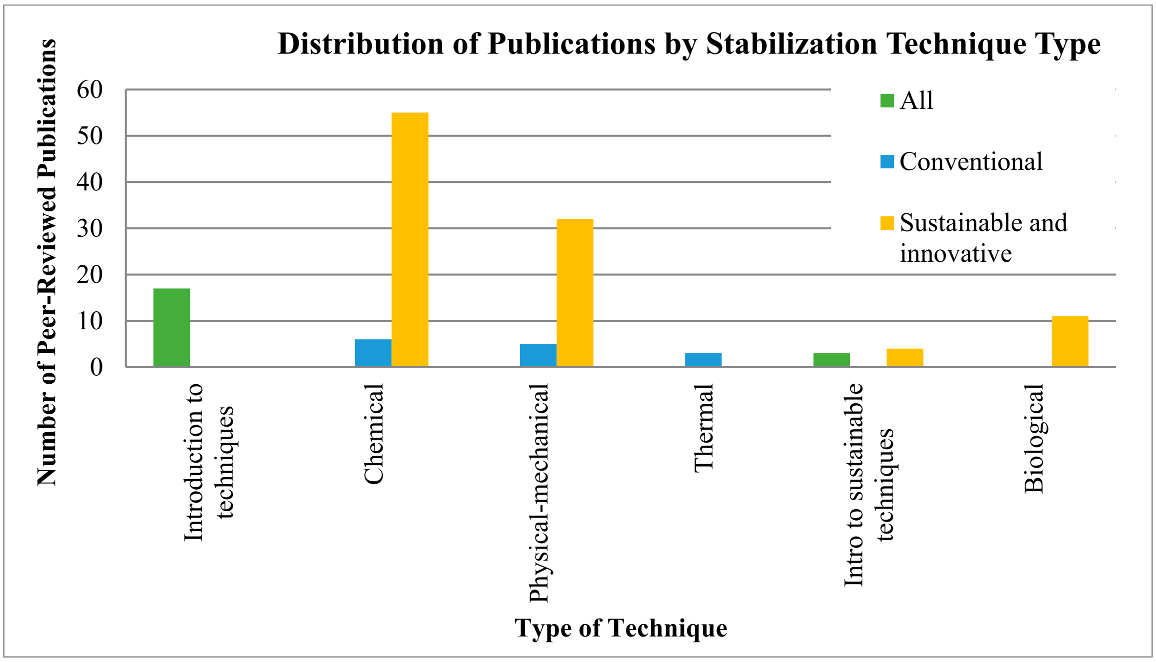


Figure 6. Comparative graph of the number of publications by mechanism of action and type of technique.

An interpretation of Figure 6, which compares the number of publications by mechanism of action and type of technique, highlights the following:

1. The chemical mechanism within sustainable and innovative techniques is the most studied (55 publications).
2. It is followed by the physical-mechanical mechanism and sustainable techniques (31 publications).
3. The biological category appears exclusively as a sustainable technique, with 11 publications.
4. Conventional techniques are much less represented in all categories.
5. The general theoretical introduction to the techniques is divided into the "All" and "Sustainable" categories.

Regarding the occurrence networks, the fifth search string was chosen because it contained over 54% of the scientific documents consulted. It is filtered using the keywords "expansive soil*", "expansive clay*", "stabilization", "improvement", "sustainable", and "innovative", as shown in Figure 5. The main findings are as follows:

- Presence of two thematic streams: The graph reflects two differentiated research streams, one focused on traditional materials and proven methods and the other oriented toward sustainable and innovative alternatives.
- Connection between clusters: The expansive soil node acts as a thematic bridge between both clusters, indicating that traditional and sustainable techniques focus on solving these soils' challenges.
- Importance of the term "soil stabilization": It occupies a central position with multiple connections, confirming its role as the thematic axis of the entire network.

- Emergence of alternative materials: The presence of rice husk ash alongside terms such as lime and compaction in a separate cluster demonstrates an emerging interest in residual and green materials with potential practical applicability.
- Relationship between geotechnical properties and admixture type: Key geotechnical properties such as strength, compressive strength, and swelling behavior are linked to the materials used, allowing for a comparative evaluation of the technical efficiency of each stabilization technique.

Regarding the documents that were consulted with the sixth search string that included the keywords ("expansive soil" OR "swelling soil" OR "problematic soil") AND ("soil improvement" OR "soil stabilization" OR "ground improvement") AND ("geopolymer" OR "lime stabilization" OR "sustainable technique" OR "innovative method") AND ("coastal soil" OR "tropical soil" OR "Ecuador"), results were obtained for Ecuador and its neighboring regions such as Peru and Colombia that present these expansive soils in some areas. However, the information was scarce and only in Spanish, with barely 11 scientific articles, which shows a potential topic for future lines of research.

3.2. Description of the Selected Soil Improvement Techniques

The techniques were selected based on a structured bibliographic search, applying six search strings shown in Table 1. They were systematically classified within the universe of 135 bibliographic sources into four main categories, according to their mechanism of action. In turn, the sustainable techniques that are the focus of this research were divided into three subcategories.

It should be clarified that chemical techniques using cement and lime are known as conventional, while those using agricultural or industrial byproducts with a pozzolanic effect have been considered sustainable and innovative. Among the conventional physical-mechanical techniques, the most common are dynamic or static compaction, granular fill, sand trenches or mattresses, controlled pre-hydration, piles, or deep foundations. Those improve the properties of expansive soil through changes in the physical structure or the application of mechanical reinforcement.

The thermal technique should be explained further since an article among the sources consulted presents the high energy requirement to reach the temperatures necessary to stabilize expansive soils and the high cost as a challenge. That is a significant limitation for large-scale applications, making the technique less economically feasible than traditional methods [15]. Furthermore, the environmental cost of large-scale heating may outweigh its benefits in some contexts. Consequently, it was not categorized as a sustainable technique as it is an emerging technique and is under study [15].

In the last decade, numerous investigations have been conducted on the use of industrial, agro-industrial, demolition, and construction waste, among others, which are characterized as sustainable. Therefore, it was considered to include them within sustainable techniques and sub-classify them according to their mechanism of action.

It is worth mentioning that there are combined techniques where the mechanism of action that provides greater soil reinforcement prevails. For example, a system composed of fly ash (chemical technique) and coconut fibers (physical-chemical-mechanical technique) was categorized within the physical-mechanical technique because it improved expansive soil.

3.2.1. Chemical Stabilization

Chemical stabilization is one of the various improvement techniques, and it can modify soil properties by adding chemically active materials [16,35].

Various materials act as chemical stabilizers, including calcium-based stabilizer materials (CSMs) [47]. CSMs exhibit pozzolanic properties. Widely used CSMs include lime, cement, fly ash (FA), ground granulated blast furnace slag (GGBS), and bottom ash (BA) [47]. Other reported materials include calcium sulfoaluminate (CSA) cement [48], alkali-activated binders (AABs) derived from precursors such as fly ash, slag, metakaolin, or quarry dust [35], calcium chloride ($CaCl_2$) [16], potassium chloride (KCl) [35], quarry dust [35,49], groundnut shell ash [47], and cement kiln dust (CKD) [17,49,50]. Choosing the right stabilizer is crucial for the sustainable construction of civil structures on expansive soils. This technique has been practiced for decades to mitigate problems related to expansive soils' swelling and shrinkage behavior [49].

The effects observed with these stabilizers include the following:

- Plasticity: The addition of CSMs and other stabilizers, such as lime and AABs, reduces soil plasticity, as evidenced by decreased liquid limit (LL) and plasticity index (PI) [16,17]. Lime is particularly suitable for materials with a PI greater than 10% to reduce plasticity [47].
- Compaction: Properties such as maximum dry density (MDD) and optimum moisture content (OMC) are evaluated [16,35]. Adding $CaCl_2$ and KCl increases MDD and decreases OMC, resulting in greater strength [16]. Depending on the precursor used, AABs can increase or decrease MDD and OMC [35]. Adjusting lime percentages is crucial to optimize stabilization without compromising soil compaction [17].
- Bearing Capacity and Strength: Improvements in bearing capacity (CBR) [16,17] and UCS [35,47,49] are observed. Cement provides the highest strength among the CSMs [47]. Fly ash has also been shown to increase the strength of expansive soils with a 10% addition [47]. The strength achieved depends on the amount of stabilizing agent incorporated and the type of material treated [47]. There is a positive relationship between proctor values and CBR [17].
- Volumetric Change (Swelling/Shrinkage): Chemical stabilization controls and decreases swelling properties [16,17,35,49]. A decrease in swelling is observed as the percentage of lime application increases [17]. AABs restrict expansive characteristics [35]. However, an increase in swelling has been identified, especially at lower levels of lime application, suggesting the need for a balanced approach to the quantity used [17]. It is important to carefully consider swelling in the design of lime mixes [17].

3.2.2. Physical-Mechanical Stabilization

Physical-mechanical techniques are fundamentally based on the physical modification or reconfiguration of soil structure. The purpose is to improve its engineering properties without inducing significant permanent chemical changes in the mineralogical composition of the clay, unlike chemical methods [7]. The main objective is to control water absorption, increase density, reduce plasticity, and minimize the potential for soil swelling and shrinkage [2].

Within this category, sources highlight several key strategies.

1. Deep Foundations: A common technique for managing expansive soils is using foundations that transfer structural loads to stable soil strata below the unstable active zone, where the most significant volumetric changes occur [3].
2. Compaction: This is a widely used physical-mechanical technique. It involves the application of mechanical energy to expel the air contained in soil voids [7]. This results in an increase in dry density and a reduction in the total void volume [2]. By decreasing the available void space, the amount of water the soil can absorb is limited, restricting its swelling potential [2,7]. The process seeks to achieve MDD at or near the OMC, determined by tests such as the Standard Proctor [7,51]. This technique

is fundamental in reusing expansive clayey soils in embankments, where rigorous execution and control procedures are applied, including layer compaction [51].

3. Soil Reinforcement: Incorporating fibrous or geosynthetic materials (such as geotextiles or geogrids) into the soil mass. These materials can be randomly distributed or specifically placed [7]. Reinforcement creates a three-dimensional network within the soil, improving its mechanical strength, such as shear strength and bearing capacity [2,7]. Although it does not eliminate the intrinsic expansivity of the soil, the presence of reinforcement can reduce the potential for swelling and shrinkage and control differential settlements [2].

3.2.3. Thermal Stabilization

Thermal stabilization has emerged as a promising and sustainable alternative to address the geotechnical engineering challenges of expansive soils, unlike conventional chemical methods such as lime and cement, which can raise environmental concerns due to the emissions associated with their production. Thermal stabilization leverages heat treatment to modify soil properties [15].

Scientifically, the thermal stabilization technique involves exposing expansive soils to elevated temperatures. This process induces fundamental, often irreversible, alterations in the soil's physical, chemical, and mineralogical properties [15]. At the microstructural level, heating causes transformative changes in clay minerals. For example, minerals such as kaolinite can collapse at certain temperatures, while montmorillonite undergoes modifications [15]. Research has shown that heating can transform clay minerals into an amorphous phase at elevated temperatures, which is crucial for understanding the mechanisms underlying soil improvement [15]. The escape of structural water and dehydroxylation during heating also induce chemical changes.

Historically, modifying clay properties through heat is not new; it dates back to ancient civilizations that employed clay firing at high temperatures (around 800 °C) to produce durable ceramics and building materials [15].

Modern thermal stabilization techniques include traditional approaches such as furnace heating or electrical resistance heating and emerging innovations such as microwave heating [15]. Microwave heating is particularly interesting because it can reach high temperatures and couples directly with water molecules, resulting in rapid and relatively uniform heating [15]. The application of microwaves has demonstrated a marked reduction in both the free-swell ratio and the vertical free-swell deformation with increasing heating duration [15].

3.2.4. Sustainable Stabilization (Chemical, Physical-Mechanical, and Biological Mechanism of Action)

Sustainable and innovative stabilization techniques are employed to improve expansive soils due to the high costs and environmental concerns associated with traditional stabilizers such as cement and lime [13,14]. Cement production, in particular, contributes significantly to CO_2 emissions and climate change issues [14,18]. Using processed waste is less expensive, more sustainable, and environmentally friendly, emitting significantly fewer greenhouse gases [14,18].

Various waste materials are employed, such as fly ash, bagasse ash, brick dust, GGBS, plastic waste, and fibers [6,14,18,21]. These additives improve the geotechnical properties of weak soils. They have been shown to significantly increase values such as the CBR and UCS [14,18,21].

The main applications of these techniques focus on subgrade stabilization to improve soil-bearing capacity [14,18]. They are crucial for road construction and are used in highway and airport engineering applications [14]. The objective is to improve the geotechnical properties of weak soils wherever possible.

Faced with the limitations of traditional stabilizers such as cement and lime (high cost, CO_2 emissions), industrial byproducts and waste offer sustainable alternatives. These are based on chemical mechanisms using ash from industrial or agro-industrial waste, physical-mechanical mechanisms using natural or synthetic fibers, granular waste particles, and biological mechanisms using plant extracts, organic waste, and microorganisms.

Each of the mechanisms of action analyzed in the scientific literature is detailed, filtering those that employ sustainable and innovative techniques for improving expansive soils, which is the focus of this study, and subsequently identifying those that would be most viable to apply on the Ecuadorian coast.

- Chemical mechanisms involve reactions between waste additives and the soil (see Table 1). The pozzolanic reaction is key: materials such as fly ash, granulated and GGBS [52], rice husk ash (RHA) [14,18], and brick dust form cementitious compounds (C-S-H, CH gel) [14] when they react with water, binding particles [6]. Cation exchange occurs when cations (e.g., from marble dust [6] or eggshell [18,21]) displace ions in the clays, reducing repulsion and causing flocculation and agglomeration [6]. That decreases plasticity and swelling potential [6], improving strength (UCS, CBR) [14,18]. Other materials include silica fume [6,18] and bagasse ash [6,18,21].
  Other agro-industrial materials are also being explored. That includes a variety of residues such as palm oil ash (POFA), eggshell dust, burnt olive residue, press mud, rice straw ash, coconut fiber, and wood ash, among others [6,21,53]. Their mechanisms of action often combine chemical and physical-mechanical aspects. For example, silica-rich materials, such as RHA, bagasse ash, and POFA, can participate in pozzolanic reactions by reacting with activators and soil water, forming cementitious compounds such as C-S-H gels that bind soil particles and improve strength [6].
  Calcium-containing waste, such as eggshell dust or burnt olive waste, can induce cation exchange and flocculation, reducing plasticity and swelling [6]. Using fibers like coconut fiber acts through physical reinforcement, providing tensile strength, controlling cracking, and increasing overall strength [6].
- Physical-Mechanical Mechanisms alter the physical structure of the soil. Reinforcement uses fibers (polypropylene, plastic [14] or recycled geotextiles [6,18]) to improve tensile strength and control cracks. Mechanical interlocking occurs when granular waste particles (GGBS, fly ash) are physically interlocked [6,14]. Dilution involves the addition of non-expansive materials. These methods improve strength (UCS, CBR) and reduce the expansion-contraction potential.
- Biological Mechanisms. Recent research promotes biological methods for stabilizing expansive soils, considering them economical, feasible, and environmentally friendly compared to traditional alternatives [54]. These approaches leverage plant extracts, organic residues, and, crucially, microorganisms to modify soil properties, for example, by decreasing the Cation Exchange Capacity (CEC) [54].
  One notable technique is MICP, particularly through biostimulation, which is based on the activity of microorganisms of native soil bacteria capable of precipitating $CaCO_3$ [36]. An interesting finding is that the success of this technique in clays with variable plasticity depends on the optimization of stimulation ("mellowing") and curing times [36].
  Bioenzyme-based soil stabilizers also promise significant improvements [55], although the exact mechanism of action remains a matter of debate among researchers [56]. It is hypothesized that enzymes are adsorbed by clays, reducing their affinity for water [55]. Microstructural evidence using μ-CT shows reduced small pores in treated

soils, suggesting a densification mechanism [56].

The use of natural biopolymers presents benefits. Xanthan gum, for example, has demonstrated superior mechanical results to lime, and its mechanism could involve direct bonding with clay particles [57].

Furthermore, research is exploring the potential of waste materials. Biochar derived from biomass, such as *Prosopis juliflora*, has been evaluated as a modifier, showing increased shear strength and decreased free swelling [58]. Agro-biogenic waste fibers, such as wool and banana peel, improve key geotechnical parameters and reduce swelling [59]. Incorporating agro-industrial waste such as vinasse has proven viable for stabilizing cohesive soils, achieving significant increases in CBR [40].

3.3. Sustainable and Innovative Soil Improvement Technique: Potential and Practical Applications

As a result of the previous sections, a specific analysis was conducted to assess the compatibility and adaptability of the most promising techniques to the Ecuadorian coastal zone's geotechnical, environmental, and socioeconomic conditions (see Tables 4–6). This analysis included the following:

- Review of soil classification reports and hydrological and climatic data.
- Estimation of local availability of materials and waste (e.g., rice husk ash, coffee ash).
- Assessment of regulatory and infrastructure frameworks.
- Identification of research gaps and field validation needs.

Scientific articles referring to sustainable techniques with a chemical mechanism of action were classified as shown in Table 4. It is worth noting that, as this is the most widely used technique, it has had the most stabilizing materials investigated worldwide, with 45 additives with a chemical effect for improving expansive soils.

The thematic classification process of the bibliography on sustainable techniques with a physical-mechanical action mechanism is repeated, as shown in Table 5. It is highlighted that it is the second technique with the highest number of scientific articles within this review, with 32 materials and elements with physical-mechanical action of improvement on expansive soils.

In the documentary organization on sustainable techniques with a biological mechanism of action, the compounds and their references were categorized as shown in Table 6. As a result, it is the third technique in the volume of scientific documentation compared to chemical and physical-mechanical mechanisms, with nine compounds and systems with a biological mechanism of action for improving expansive soils.

The reviewed documents highlight the value of sustainable techniques that leverage biological mechanisms to improve the properties of expansive soils. Methods such as MICP, the use of bio-enzymes, biopolymers such as xanthan gum and guar gum, agro-biogenic waste fibers, and biochar offer viable and environmentally friendly solutions to mitigate problems such as swelling, shrinkage, and cracking while improving soil strength and stiffness.

The most important applications of soil stabilization techniques in Colombia, Peru, and Ecuador, according to the provided source, include the following:

- In Ecuador, stabilization focuses on roads (such as Rocafuerte-Tosagua in Manabí) and civil works affected by expansive clays [44]. Lime, cement, volcanic ash, and rice husk ash pozzolan are used [42–45].
- In Colombia, 4G road projects (Puerta de Hierro, Conexión Norte) and linear parks in Cartagena use lime. It is applied in embankments, injections, and piles to improve plasticity and CBR [45,46].
- In Peru, it is used to improve subgrades for paving in various cities. The additives include coal ash, potato peel starch, and wood ash. Fly ash, scallop ash, and rice

husk ash are also used. Molasses and vinasse residues are also used for unpaved roads [40,41,43]

Table 4. Chemical materials used in sustainable and innovative expansive soil improvement techniques.

Chemical Materials	References
Fly ash	[4,5,15,16,22,27,43–48]
Rice husk ash [1]	[4,20,32,33,44,60–62]
Brick dust	[63]
Eggshell	[4,64–66]
Silica fume	[4,20]
Micro silica or silica fume (SF)	[33]
Copper slag (CS)	[33]
Bagasse ash [1]	[20,67–69]
Sugarcane straw ash [1]	[4]
Blast furnace slag and GGBS	[4,33,70,71]
Lime-induced calcite precipitation (LICP)	[72]
Sawdust ash	[5]
Coal bottom ash (CBA)	[73]
Municipal solid waste incineration (MSWI) ash	[26]
Kota stone sludge	[27]
Phosphogypsum (PG)	[33]
Nanomaterials	[29]
Recycled gypsum	[32,62]
Recycled cement and concrete	[74]
Lignosulfonate (lignin-derived)	[75–80]
Lignosulfonate-based composite (CA) admixture	[81]
Lime ash	[67]
Cement kiln ash (CKD)	[33]
Lime	[63,65,68,79,82,83]
Cement slag	[69]
Calcined clay	[84–88]
Enzyme-induced carbonate precipitation (EICP)	[66,89]
Basic oxygen furnace slag (BOF)	[90]
Banana leaf ash [1]	[91]
Coconut shell ash [1]	[20,92]
Bamboo leaf ash [1]	[93]
Volcanic ash	[45]
Coal ash	[43]
Calcium carbide waste	[20]
Red mud	[20]
MSWI fly-ash	[94]
Magnesite mine waste	[95]
Recycled ground glass (PWG)	[96]
Cement kiln dust	[20]
Biochar derived from the invasive weed species *Prosopis juliflora*	[58]
Biomass bottom ash	[97,98]
Teff straw ash	[99]
Microorganism-facilitated calcium carbonate precipitation	[36]
EICP	[89,100]
Digestate ash	[101]

[1] The most outstanding compatibility and adaptability techniques for the Ecuadorian coastal zone.

Table 5. Expansive soil improvement techniques with a physical-mechanical action mechanism.

Physical-Mechanical Action Mechanism	References
Fly ash columns (FAC)	[33,102]
Plastic waste	[20]
Peat and coconut fiber [1]	[20]
Coconut fiber [1]	[103]
Construction and demolition waste (CWD) [2]	[104,105]
Granite industrial waste	[93]
Quarry dust	[105,106]
Foundry waste sand	[93]
Crushed rubber	[31,94]
Biomedical waste	[107]
Jute and nylon fibers [1]	[25]
Geosynthetic fibers (nylon)	[108]
Artificial sand and clay mixtures	[109]
Recycled crushed plastic waste strips (PWS)	[28]
Recycled plastic and glass waste	[110]
Recycled ash and natural fibers	[34]
Flax fibers	[111]
Fly ash and crushed face masks (FA + FMs)	[112]
Crushed face mask chips (SFMC) and biopolymers	[113]
Polypropylene fiber (PP)	[114]
Pond ash and polypropylene fiber (PA + PP)	[115]
Sugarcane bagasse ash (SCBA) and nonwoven geotextile (NWG)	[116]
Granular pile anchor	[117]
Medical waste incineration ash, coal fly ash, and polyethylene terephthalate (PET) strips	[37]
Foundry sand waste	[118]
Ground wheat straw (WS) with minimal sieving and SF	[119]
Recycled Crushed Ceramic Rubble (RCCR)	[120]
Rice husk ash and banana fibers [1]	[41]
Ground rice husk and crushed ceramics [1]	[42]
Sand, EPS spheres, sand, and jute fibers	[1]
Bamboo charcoal (BC), quarry dust (QD), and lime (L)	[121]
Cellulose-based fiber additives	[122]

[1] The most outstanding compatibility and adaptability techniques for the Ecuadorian coastal zone. [2] CWD: Use of fine fractions of construction and demolition waste.

Table 6. Expansive soil improvement techniques with a biological action mechanism.

Biological Action Mechanism	References
Plant cellular compounds and microbial products	[54]
Compost-treated topsoils (CMTs)	[123]
Guar gum biopolymer	[124,125]
Enzymatic stabilization mechanism	[56]
Calcium carbonate precipitation facilitated by microorganisms	[57]
Enzymatic stabilization (expansive soils subjected to moisture fluctuations)	[59]
Xanthan gum	[40]
Wool and banana fiber [1]	[59]
Molasses and vinasse residues [1]	[40]

[1] The most outstanding compatibility and adaptability techniques for the Ecuadorian coastal zone. Ramos et al. [44].

3.4. Data Analysis on Sustainable and Innovative Techniques for Soils on the Ecuadorian Coast

With a focus on sustainable and innovative techniques for improving expansive soils, the main industrial and agro-industrial products on the Ecuadorian coast were investigated to gain insight into the waste generated and its use, as shown in Tables 4–6.

During 2024, the sector with the highest growth in gross value added (GVA) in Ecuador was agriculture, livestock, and forestry, with 3.1%, followed by real estate and financial activities. This growth in the agricultural sector is relevant for studies on the circular economy, as it generates large volumes of organic waste (rice husks, sugarcane bagasse, coffee waste, plant fibers), which can be used as natural stabilizers in expansive soils, contributing to sustainable construction practices. This approach represents a technical alternative for soil improvement, reducing dependence on traditional additives such as lime or cement.

On the other hand, industrial sectors such as non-food manufacturing (−5.7%) and construction (−7.8%) are experiencing a considerable decline, reflecting economic challenges and opportunities to redesign production processes toward more sustainable models (Figure 7) [126]. Byproducts such as slag, crushed ceramics, or waste from technical processes can stabilize soil. This utilization of waste mitigates its environmental impact and drives the development of geotechnical solutions with a lower carbon footprint, aligned with the principles of the circular economy and climate resilience.

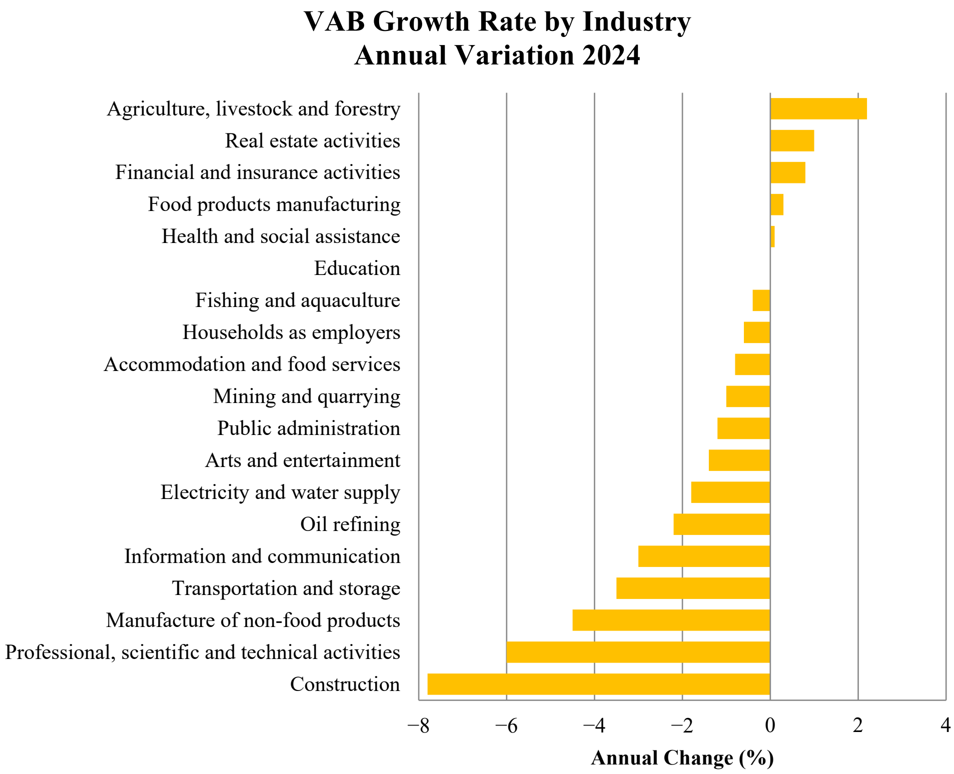
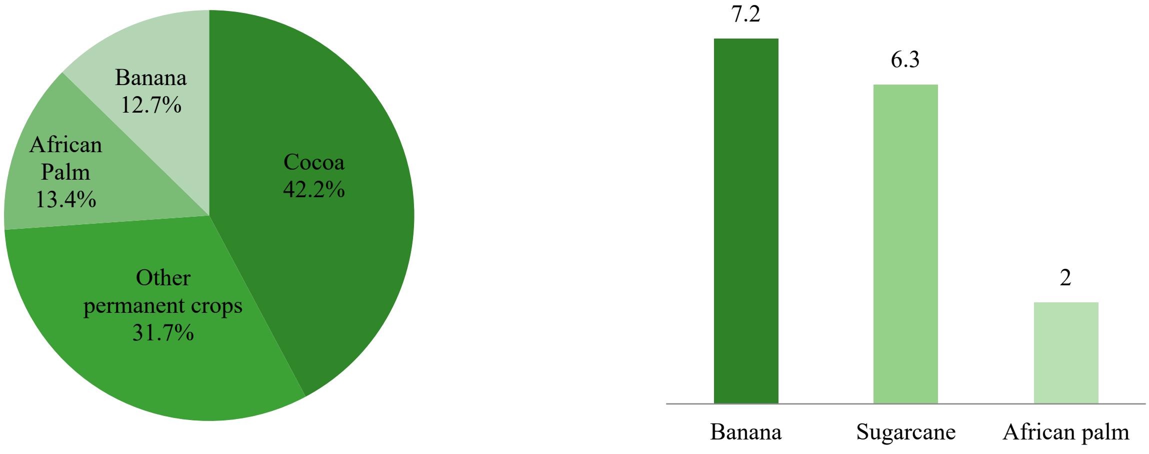


Figure 7. Rate of variation of gross value added by industry in 2024 (modified from Banco Central del Ecuador [126]).

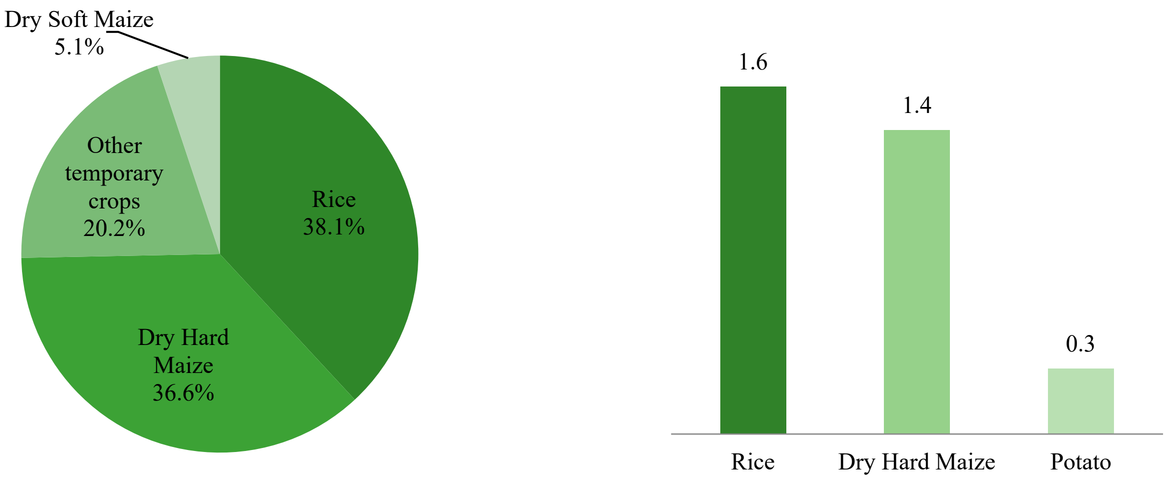
The latest national census in Ecuador showed that the area under permanent crops in 2023 was 1.4 million hectares. Regarding cocoa production, it represents 42.2% of the total planted area. In 2023, bananas, sugarcane, and African palm were the most produced crops nationwide (Figure 8a,b) [127].



(a) (b)

Figure 8. Area and production of permanent crops in Ecuador. (**a**) Share the total planted area. (**b**) Production of permanent crops (millions of tons). Modified from INEC [127].

The area planted with transitional crops in 2023 was 940,717 hectares. Rice accounts for 38.1% of the total planted area. In 2023, dry durum corn, paddy rice, and potatoes were the most widely produced crops nationwide (Figure 9a,b) [127].



(a) (b)

Figure 9. Area and production of transitional crops in Ecuador. (**a**) Share the total planted area. (**b**) Production of transitional crops (millions of tons). Modified from INEC [127].

The results indicate that the Ecuadorian coast is a region with a strong presence of agro-industrial activities, with products such as bananas, cocoa, coffee, rice, and African palm leading the production and export [127].

According to Riera et al. [128], agroindustry generates approximately 2.2 million tons of waste annually in Ecuador. This waste is mainly lignocellulosic or contains starch. Although there is no official data detailing the specific amount of each type of waste, it is known that the Ecuadorian agroindustry generates a large amount of potential raw material for new sustainable products.

However, in their research, Riera et al. [128] classify the waste generated by agroindustry, which varies according to its characteristics. Those of interest in the improvement of expansive soils have been selected as the following:

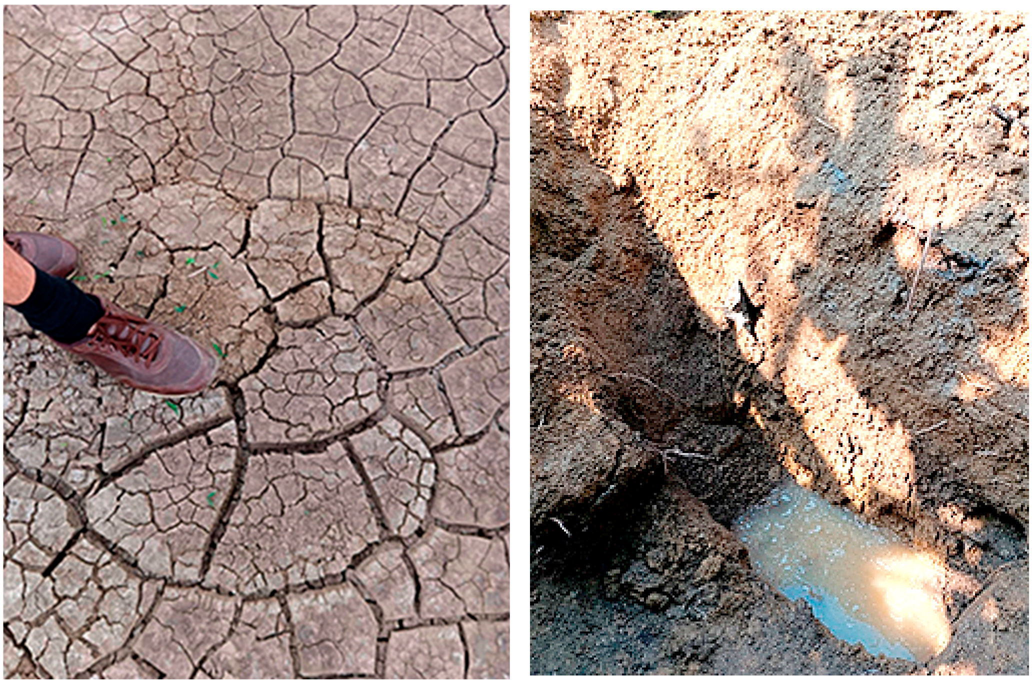
- Sugarcane: Sugarcane processing primarily produces green bagasse, which accounts for between 37 and 42% of the total, yielding between 580 and 630 kg of juice per ton processed.
- Banana and plantain: The raw material arrives at the factory as bunches containing the fruit attached to the stem. A bunch consists of 60% fruit, 25% peel, and 15% stem, from which the fruit is used. Although the banana plant is more robust than the plantain, the same percentages are used for both.
- Oil palm: Using the palm oil extraction process as a reference, it is found that for every ton of fresh fruit bunches, approximately 20 kg of dried sludge from drying beds, 220 kg of empty bunches, and between 0.8 and 1.0 m^3 of liquid effluent are generated. In this way, 760 kg per processed ton is utilized, with 24% of this being waste.
- Dry hard corn: Corn cultivation produces a large amount of biomass, of which 50% is the grain. Processing generates waste corresponding to the cob and leaves, representing just over 11.8% of the corn plant.
- Rice: This crop produces between 30% and 45% of rice straw, and rice husks are produced in large quantities during processing: 100 kg of rice produces 20 kg of husks. Rice processing waste accounts for an average of 20% of its production.
- Cocoa: Large amounts of significantly differentiated materials are wasted in the cocoa industry. Industrial waste includes the husk, and agricultural waste includes the shell and mucilage. The husk is obtained after drying, fermenting, and roasting the grain, representing about 12% of the seed.

From the research by Riera et al. [128], it is evident that residues such as sugarcane bagasse, banana and plantain leaves, oil palm, and rice have been used within the sustainable technique with a chemical action mechanism such as rice husk ash, sugarcane bagasse and straw ash, and plantain leaf ash, as shown in Table 4. Meanwhile, ground rice husk and plantain fibers have been used in the physical-mechanical mechanism, and the latter is also used within the biological action mechanism.

A cross-sectional analysis of the main industrial and agricultural products manufactured and generated in Ecuador highlights soil improvement techniques with a sustainable and innovative approach that is compatible with and highly adaptable to the coastal environment. For instance, the stabilization of plastic soils using ground rice husks and crushed ceramics to improve pavement subgrades has already been investigated in Ecuador [42], as well as the stabilization of expansive clays in the province of Manabí using pozzolan derived from rice husk ash [44]. These cases illustrate the potential to explore other agro-industrial and industrial by-products as sustainable alternatives for improving expansive soils along the Ecuadorian coast.

As part of the on-site investigation, sampling was conducted at three locations along the Rocafuerte-Tosagua-Chone Highway in the province of Manabí on the Ecuadorian coast. Expansive soils were found in this section, especially in the Rocafuerte canton, where future studies in this line of research will focus. The photographic record of the sampling shows the typical behavior of expansive soils on the Ecuadorian coast with their potential for contraction in the dry season and expansion in the rainy season (Figure 10a,b).

In Ecuador, expansive soils are found mainly in the coastal and Amazonian regions (Figure 1) [45]. The coastal provinces of Esmeraldas, Manabí, Guayas, and El Oro present a higher frequency of this phenomenon [129]. Topography and climate influence the presence of these soils. The climate of the study area in Manabí (Rocafuerte-Tosagua) is dry tropical during some months and humid tropical during the rest of the year [129]. Variation in soil moisture content is the "catalyzing" element of the expansion phenomenon [130]. The change in moisture content is influenced by climate, among other factors [130]. Seasonal fluctuations in humidity, cycles of rainfall and evaporation, and wet and dry seasons soften the soil and can cause failures [44–46]. Expansive clays are susceptible to these volumetric changes produced by variations in moisture content [44].



(a) (b)

Figure 10. Two examples of expansive soil in the coastal zone of Ecuador. (**a**) Dry condition. (**b**) Wet condition.

The sources consulted directly mention the El Niño phenomenon and its impact:

- In 1997 and 1998, the El Niño phenomenon drastically affected the country's roads, primarily the Rocafuerte and Tosagua highways in the Manabí Province of Ecuador [130]. This climatic trigger, coupled with a lack of prevention and maintenance, led to a dramatic state of the roads [130].
- Studies in other locations determined that soils are at high risk for landslides, which can occur during rainy seasons or anomalous events such as the El Niño phenomenon and earthquakes [43]. These massive movements destroy homes, crops, and access routes.
- Zambrano [129] mentions that between 1982 and 1983, exceptional rainfall occurred not only at the site of interest in Manabí but throughout the country, forming part of a phenomenon that occurred on a global scale [129]. Although not explicitly named, this description coincides with the impacts of the El Niño Phenomenon of 1982–1983.

In addition to the El Niño phenomenon, other climatic and environmental factors influence expansive soils:

- Climate variations generate wet seasons that cause soils to absorb water and swell, becoming soft and reducing their strength; in dry seasons caused by the La Niña phenomenon, which occurs approximately every 2 to 7 years, their volume is reduced by extreme evaporation [44]. These changes can be of natural origin (climate change) or artificial [44].
- The position and variations of the water table influence the potential for expansion [130]. In coastal areas with high water tables, these can be affected by climatic factors [44]. The active zone above the water table is highly susceptible to expansion and contraction during rainy and low-water (dry seasons) [44].

- Climatic variations that produce periods of drought predominantly over periods of rain contribute to the weathering of surface rocks [129], and long periods of drought make the soil more expansive [130]. The decrease in natural moisture content increases the percentage and stress of expansion [129].
- Even stabilized soils experience volumetric changes due to cycles of moisture changes [46]. It has been noted that pavements subjected to seasonal variations in moisture content tend to reach a stabilization point after several years [130].

4. Discussion

The findings presented in this review confirm that Ecuador's coastal expansive soils pose a serious challenge for civil engineering, especially for constructing road infrastructure and buildings on highly plastic soils [42,44,129–131]. This statement is consistent with previous studies conducted in other tropical and subtropical regions, such as India, Nigeria, and the southern United States, where the cyclic swelling and shrinkage behavior of these soils and their adverse structural effects have been documented [16,26,27,58,83,121,132].

The collection of general information and selection of documents demonstrated the paucity of literature on the topic addressed in this study in Ecuador, with only seven documents from the country and four from neighboring countries with expansive soils. That contrasts with the numerous international studies that study 86 materials as stabilizers for expansive soils. Of the sustainable soil improvement techniques consulted, those with a chemical mechanism (55 publications) are the most researched, followed by those with a physical-mechanical mechanism (31 publications) and biological mechanisms (11 publications), which opens up the possibility of research into the last two mechanisms of action.

In the bibliometric analysis of keyword co-occurrence in the fifth search string, two thematic research streams were observed: the first focused on traditional materials and proven methods, and the second oriented toward sustainable and innovative alternatives, a growing trend over the last decade.

El Niño and La Niña phenomena significantly influence soil behavior in Ecuador's coastal region, particularly in provinces such as Manabí, Guayas, Esmeraldas, and El Oro. [129] El Niño events, especially those of 1982–1983 and 1997–1998, caused extreme rainfall that triggered widespread landslides and severe damage to road infrastructure, such as on the Rocafuerte–Tosagua highway in Manabí [129,130]. The prolonged phases of humidity associated with El Niño saturate expansive soils, reduce their shear strength, and increase the likelihood of landslides, directly affecting homes, agricultural areas, and access roads [44–46]. Furthermore, La Niña events are often associated with prolonged drought conditions, influencing soil behavior in this region [44].

The alternating cycles of humidity and drought caused by El Niño and La Niña directly affect the volumetric stability of expansive clays. During wet periods, soils absorb water and expand; during dry phases, they lose moisture and contract, generating cracks, differential settlements, and loss of bearing capacity [44,130]. This behavior is especially critical in soils with high plasticity and low initial moisture content, which can absorb up to 35% of water, aggravating structural damage [45,130]. Furthermore, fluctuations in the water table intensify these effects, particularly in the active upper soil layer, which is highly susceptible to seasonal cycles of expansion and contraction.

The description of soil improvement techniques included conventional techniques such as chemical, physical-mechanical, and thermal, as well as sustainable techniques with their chemical, physical-chemical, and biological mechanisms of action.

Chemical stabilization is an effective technique for mitigating the problems associated with expansive soils by altering their properties through key chemical reactions. The proper selection and dosage of stabilizers are essential to achieve optimal improvements in soil plasticity, compaction, strength, and volumetric change behavior while also considering sustainability aspects. Physical-mechanical techniques address the behavior of expansive soils by modifying their physical structure (compaction, reinforcement) to limit water ingress and restrict volumetric changes or by diverting loads through problematic layers to more stable strata (deep foundations).

Thermal stabilization transforms expansive soils by altering their mineralogy and structure through heat, reducing plasticity and swelling, and improving strength. While the technique faces practical implementation challenges, its scientific basis in fundamentally modifying clay properties positions it as a valuable approach for managing problematic soils.

The materials used in sustainable enhancement techniques improve the geotechnical properties of expansive soil, such as increasing UCS and the CBR and reducing swell-shrink potential and plasticity.

These sustainable waste-based techniques offer economic and environmental advantages, reducing costs and CO_2 emissions. However, research is needed on their long-term durability and other impacts.

Unlike traditional chemical methods, biological approaches are often more economical and contribute to sustainability using renewable resources and byproducts. Although laboratory research has provided a fundamental understanding of their mechanisms and demonstrated significant improvements, large-scale implementation and evaluation of their long-term durability under diverse field conditions are crucial for their widespread adoption in sustainable geotechnical engineering.

Based on the working hypothesis that sustainable improvement techniques can offer viable solutions with lower environmental impact compared to traditional ones (lime and cement), the results fully support this premise, as observed in Figure 6 (comparative graph of the number of publications by mechanism of action and type of technique) and Tables 4–6 (sustainable techniques by mechanism of action). It was shown that alternative materials such as rice husk ash, bagasse ash, sugarcane straw ash, banana leaves, rice husks, bamboo leaves, peat and coconut fiber, jute fibers, banana fibers, crushed ceramics, wool and banana fibers, molasses, and vinasse residues, have high stabilizing potential and applicability on the Ecuadorian coast, both in their natural and chemically activated forms, significantly improving properties such as plasticity, free swelling, moisture retention and mechanical strength. These observations are consistent with recent research by the authors referenced in Tables 4–6, who demonstrated the positive impact of these agro-industrial residues on expansive clay soils.

The inclusion of industrial byproducts (granulated blast furnace slag, lignosulfonate, lime, and calcined clay) in stabilization also coincides with global trends toward waste valorization, showing that their application not only improves geotechnical properties but also reduces the carbon footprint associated with traditional methods (Table 4).

The mineralogical composition of expansive soils has been studied in depth (Table 7). Thus, the high-plasticity clay of Ecuador presents a composition with a high content of kaolinite (30%) and minerals such as quartz, plagioclase, and diopside, in contrast to the soils of Saudi Arabia, which are dominated by montmorillonite (34.7%) and quartz (46.1%). This difference is significant since montmorillonite is the main mineral responsible for extremely expansive behavior. Table 7 shows that although Ecuadorian soils have high plasticity, their swelling potential is likely lower than that of soils with more montmorillonite, directly influencing the choice of stabilization techniques.

Table 7. Mineralogical composition of expansive soils in percentage for high plasticity clays.

Location	Quartz	Montmorillonite	Kaolinite	Feldspar	Plagioclase	Diopside	Others	Reference
Ecuador	16	2	30	-	13	12	28	[44]
Saudi Arabia	46.1	34.7	11.4	3.1	-	-	4.7	[91]

Furthermore, Ecuadorian soil's more diverse mineral content suggests greater geological heterogeneity, which may open up the possibility of using more versatile techniques. That reinforces the need to adopt sustainable solutions, especially those considering mineralogical type and proportion as key variables. Compared to countries like Saudi Arabia, where minerals with greater swelling activity predominate, Ecuador could benefit from less aggressive and more environmentally friendly treatments.

Table 8 shows that Ecuadorian clay contains 57.13% SiO_2, similar to Indian soil (56%) and slightly lower than Saudi Arabian clay (59.34%). However, it differs due to its lower Al_2O_3 and Fe_2O_3 content, indicating lower reactivity in chemical activation processes, a crucial aspect for techniques such as geopolymerization. For example, its low lime content (CaO = 1.73%) limits pozzolanic reactions compared to India (3.28%) and Saudi Arabia (9.31%), which may affect the effectiveness of traditional stabilizers such as lime. In contrast to the lower Al_2O_3 and Fe_2O_3 contents of Ecuadorian clay and its low CaO content, the low presence of reactive oxides in the Ecuadorian soil suggests that the use of alternative stabilizers, such as highly reactive agricultural byproducts (rice husk ash, silica, etc.), could be more effective (Table 8). This difference justifies the article's focus on using innovative and sustainable materials that provide the chemical compounds necessary for stabilizing Ecuadorian coastal soils.

Table 8. Chemical composition of expansive soils in percentage for high plasticity clays.

Location	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	Na_2O	TiO_2	K_2O	CO_2	SO_3	Others	Reference
Ecuador	57.13	17.63	6.89	-	1.73	1.71	1.96	0.68	1.74	-	-	0.11	[44]
Saudi Arabia	59.34	23.42	-	9.31	3.07	1.94	-	1.78	0.71	-	-	0.43	[91]
India	56.00	19.00	7.80	-	3.28	2.63	5.20	0.21	-	-	-	0.23	[60]
Malasia	75.84	12.09	3.47	-	0.72	1.33	1.13	0.68	1.51	-	-	0.09	[133]
India [1]	33.55	22.31	19.40	-	-	2.07	-	-	16.71	3.65	1.98	0.11	[134]
Irak [2]	51.30	33.10	1.40	-	1.60	0.60	-	-	-	-	-	12.00	[135]

[1] In lateritic soils. [2] For kaolinitic clay.

Table 9 shows that coconut and jute fibers have a high proportion of cellulose, with jute fiber (85%) significantly exceeding coconut fiber (43–44%). This high cellulose content is associated with improved soil mechanical reinforcement, especially regarding tensile strength and crack control. In Ecuador, where natural fibers such as plantain and abaca are produced at a high rate, an opportunity arises to study their performance as sustainable reinforcement.

Table 9. Chemical analysis of natural fibers (in percentage).

Type	Cellulose	Lignin	Water Soluble	Hemicellulose	Pectin and Similar	Wax	References
Coconut	44.00	48.00	6.00	-	-	-	[133]
Coconut	43.44	45.84	5.25	0.25	3.00	-	[134]
Jute	60.50	13.00	-	12.00	-	-	[135]
Jute	85.00	13.00	-	-	-	0.60	[136]

In Table 10, agricultural byproducts such as rice husk ash show high silica contents (up to 97.69%), which give them outstanding pozzolanic properties, ideal for stabilizing

CaO-poor soils such as those along the Ecuadorian coast. Sugarcane bagasse ash also shows good concentrations of SiO_2 and CaO, making it useful in chemically activated mixtures. These materials are present in Ecuador and could be used locally, replacing traditional stabilizers such as lime or cement.

Table 10. Chemical composition of additives for improving expansive soils (industrial and agricultural byproducts in percentage).

Additive	SiO_2	Al_2O_3	CaO	MgO	FeO_3	K_2O	TiO_2	Na_2O	SO_3	P_2O_5	BaO	P_2O_3	MnO	LOI [1]	Mn_2O_3	Others	Reference
Fly ash	59.12	18.30	12.07	1.49	3.87	1.02	0.49	1.17	1.65	0.39	0.12	-	-	-	-	-	[20]
Fly ash	59.83	30.48	1.74	0.86	-	-	6.91	-	-	-	-	-	-	-	-	0.18	[60]
Fly ash	57.47	15.36	3.32	-	4.71	-	-	-	-	-	-	-	-	-	-	-	[133]
Bagasse or sugarcane ash	66.70	9.24	10.07	4.60	1.53	2.51	0.25	1.30	-	-	-	1.55	0.05	2.21	-	-	[20]
Rice husk ash	93.1	0.30	1.50	0.60	0.20	2.30	0.03	0.06	-	-	-	-	-	0.80	-	-	[20]
Rice husk ash	97.69	-	0.29	-	0.22	-	-	0.41	-	-	-	-	-	-	-	-	[60]
Rice husk ash	88.18	31.00	0.60	0.10	4.10	0.90	1.63	0.05	0.12	-	-	-	-	-	-	-	[137]
Rice husk ash	73.86	1.96	5.77	0.98	1.23	-	-	-	-	-	-	-	-	-	-	16.20	[41]
Cement kiln ash	14.30	7.10	58.10	9.20	5.70	0.40	1.40	0.70	1.30	-	-	0.60	-	-	1.20	-	[20]
Silica fume	87.00	1.15	0.80	0.70	1.42	0.90	-	-	-	-	-	-	-	8.00	-	-	[20]
Banana leaf ash	17.54	4.08	47.31	1.47	3.87	16.92	-	-	2.69	3.14	-	-	-	0.28	-	2.70	[91]

[1] Loss on ignition (LOI) for volatile elements.

Although Ecuador does not yet report specific data on local fibers in the tables presented, the analysis suggests untapped potential. A comparison with fibers used in Iraq, India, and Bangladesh shows that implementing fibers with high tenacity and low lignin content could be replicated in the region. That encourages future lines of research applied to native Ecuadorian fibers for stabilizing expansive soils.

Table 10 shows that compared to industrial materials such as fly ash or silica fume, Ecuadorian industrial and agricultural byproducts show potential competitiveness if their composition is valorized. These ashes have already been successfully tested in India and Malaysia. Therefore, the results in this table reinforce the article's focus: There is a technical justification for promoting the use of Ecuadorian agro-industrial waste as a viable and sustainable alternative for improving expansive soils. In the sustainable techniques, a comparative matrix of sustainable materials used to improve expansive soils on the Ecuadorian coast was developed (see Table 11). A comparison index (*Ic*) was used to quantify the influence of the improvement methods on the geotechnical properties of the soil: MDD, OMC, UCS, and observations of the CBR. The *Ic* index was calculated by dividing the value of the improved soil geotechnical property by the unimproved soil geotechnical property.

The Ecuadorian case (see Table 11) stands out for using 10% rice husks and 40% recycled ceramics, increasing CBR from 8.92 to 34.6 under saturated conditions. This increase is comparable to that of countries such as Pakistan (CBR up to 15.4 with combined fibers) or Saudi Arabia (CBR of 40 with banana leaf ash and nano-silica), demonstrating that Ecuador can achieve competitive results with local waste.

This finding suggests that it is unnecessary to resort to imported industrial additives to achieve significant improvements. Furthermore, it is noted that Ecuador has not yet reported UCS or MDD data, unlike countries such as India or Iran. That highlights a pending line of research that must be developed to complement the strength and dry density results with techniques adapted to Ecuadorian coastal soils.

Table 11. Comparison of sustainable materials used to improve expansive soils on the Ecuadorian coast (see text for abbreviations).

Soil Type	Location	USCS	LL (%)	LP (%)	PI (%)	Improve	Fiber Length (mm)	Dosis (%)	Ic MDD	Ic OMC	Ic UCS	Observations	Reference
Lateritic soil	India	MH	53	31	22	Coconut fiber	15–280	1	Increasing from 1.84 to1.98	Decreasing from 13.00 to 11.95	Increasing from 0.34 to 0.43	CBR increased from 5.0 to 9.7 (wet) and 14.0 to 19.1 (dry)	[134]
Silty sand	India	SM	44	NP		Fly ash	-	43	Decreasing from 1.94 to 1.74	10.00 to 14.25	0.61 to 1.04	-	[138]
70% silty sand + 30% fly ash	India	SM	44	NP		Coconut fiber	80	1	-	-	1.94 to 2.65	-	[138]
Clay soil	Malaysia	CH	57–72	32–40	25–37	5% lime + 1%coconut fiber	50–200	-	-	31.0 to 35.0	2.04 to 12.13	28 days of lime curing	[133]
Clay soil	Malaysia	CH	57–72	32–40	25–37	60% fly ash + alkaline activator 10 molar (KOH) + 1% coconut fiber	50–200	-	-	31.0 to 22.4	2.04 to 80.56	28 days of lime curing	[133]
Silty sand soil	Iran	SM		NP		Palm fiber	20	2	-	-	0.32 to 3.95	CBR increased from 18 to 37 1.5% fiber (saturated) and 25 to 40 (wet)	[139]
Silty sand soil	Iran	SM		NP		Palm fiber	40	2	-	-	0.32 to 5.04	CBR increased from 18 to 44 1.5% fiber (saturated) and 25 to 47 (wet)	[139]
Kaolinitic clay	Iraq	CH	61	28	33	Jute fiber	200	2	1.73 to 1.63	18.40 to 23.82	0.40 to 1.70	-	[135]
Kaolinitic clay	Iraq	CH	61	28	33	Jute fiber	400	2	1.73 to 1.61	18.40 to 24.10	0.40 to 0.92	-	[135]
Clay loam	Bangladesh	CL	24.82	17.87	6.95	Jute fiber	15	1.2	1.93 to 1.86	11.20 to 13.20	-	CBR from 5.22 to 7.56	[136]
Clay loam	Bangladesh	CL	24.82	17.87	6.95	Jute fiber	30	1.2	1.90 to 1.82	12.40 to 15.50	-	CBR from 5.22 to 10.56. Fiber diameter has no impact on CBR (4 and 8 mm)	[136]

Table 11. *Cont.*

Soil Type	Location	USCS	LL (%)	LP (%)	PI (%)	Improve	Fiber Length (mm)	Dosis (%)	Ic MDD	Ic OMC	Ic UCS	Observations	Reference
High plasticity clay	Pakistan	CH	77	36	41	Wool fiber	23–31	0.6	-	-	0.49 to 0.67	Diameter 0.136 to 0.214 mm. CBR from 3.4 to 7.5 (saturated)	[20]
High plasticity clay	Pakistan	CH	77	36	41	Banana fiber	28–46	1.2	-	-	0.49 to 0.58	Diameter 0.245 to 0.311 mm. CBR from 3.4 to 5.7 (saturated)	[20]
High plasticity clay	Pakistan	CH	77	36	41	0.6% wool fiber + 1.2% banana fiber	23–31 wool and 28–46 banana	-	-	-	0.49 to 1.30	CBR from 3.4 to 15.4 (saturated)	[20]
High plasticity clay	Saudi Arabia	CH	74	39	35	15% leaf banana ash + 1.2% nano silica	200–300	-	-	27.4 to 28.9	4.59 to 18.35	CBR 5 to 40 wet samples. 28 days of curing	[91]
High plasticity clay	India	CH	84	29	55	Fly ash	-	30	1.58 to 1.42	25.0 to 23.0	2.04 to 5.40	28 days of curation. Better behavior between 7 and 28 days	[60]
High plasticity clay	India	CH	84	29	55	Husk rice ash	-	30	1.58 to 1.35	25.0 to 29.4	2.04 to 3.47	28 days of curation. Better behavior between 7 and 28 days	[60]
Soft clay	Indonesia	CH	75	33.96	41.05	75% cement + 25% bamboo leaf ash	-	30	1.28 to 1.35	29.0 to 35.0	-	CBR from 5 to 55 (without wet)	[93]
High plasticity silt	Philippines	MH	64.78	46.85	18.64	Recycled gypsum	-	15	1.22 to 1.29	42.42 to 37.17	0.51 to 10.20	28 days of curing	[62]
High plasticity clay	Philippines	MH	64.78	46.85	18.64	5% recycled gypsum + 10% husk rice ash	-	-	1.22 to 1.36	42.42 to 34.28	0.51 to 12.24	28 days of curing	[62]
High plasticity clay	Ecuador	CH	91	38	53	10% husk rice + 40% recycled ceramic	-	-	-	-	-	CBR from 8.92 to 34.6 (saturated)	[42]
Cohesive soil	Peru	CL	37.38	19.55	17.83	4% molasse	-	-	-	-	-	CBR from 6.61 to 10.20 (saturated)	[40]
Cohesive soil	Peru	CL	37.38	19.55	17.83	10% vinasse	-	-	-	-	-	CBR from 6.61 to 11.04	[40]
High plasticity clay	Peru	CL	36.24	21.31	14.93	Husk rice ash	-	10	1.91 to 1.67	15.14 to 18.31	-	CBR from 5.05 to 7.10	[41]
High plasticity clay	Peru	CL	36.24	21.31	14.93	10% husk rice ash + 0.5% banana fiber	-	-	1.91 to 1.82	15.14 to 17.18	-	CBR from 5.03 to 10.07	[41]

UCS is achieved by combining fly ash, alkaline activator, and coconut fiber. The maximum CBR was achieved with a mixture of cement and bamboo ash. Natural fibers alone primarily improved CBR and moderately improved UCS, while ash alone had a greater impact on UCS, especially after curing. That indicates that combinations of chemical additives and natural fibers are more effective than either alone. Combinations show the greatest overall improvement, especially in UCS and CBR.

Most studies use dosages between 1% and 2% of the soil's dry weight. The greatest improvements were observed with 2% jute and palm fiber and 1% coconut fiber. The recommended dosage is 1–2% of the soil's dry weight.

Natural fibers increase soil strength and ductility, making them useful for subgrade layers in sustainable road infrastructure.

The Maximum Soil Density shows a decreasing compression ratio. Several authors agree that replacing soil particles with fibers decreases the weight of the soil matrix since the density of the fibers is lower than the density of the soil particles. An increasing compression ratio is observed regarding optimal moisture content, given that fibers have a greater water absorption capacity.

The length of the natural fibers used with amendment materials (coconut, palm, and jute) ranges from 15 to 280 mm.

The effect of ash from agricultural and industrial byproducts shows increases in the UCS of up to 80.56 kg/cm^2 in mixtures with activators and fibers. In CBR, increases of up to 55% in combination with cement or waste. In MDD, the effect is slightly lower and helpful in lightweight soils or with weight restrictions. In OMC, the increase is moderate, requiring adjustments in the compaction water content.

These applications reinforce the vision of sustainability outlined in the Sustainable Development Goals (SDGs), particularly regarding waste management and resilient infrastructure. The 17 SDGs relate to goals 9, 11, 12, and 13: industry, innovation, and infrastructure; sustainable cities and communities; responsible consumption and production; and climate action.

However, key limitations are identified that must be addressed. First, there is a paucity of long-term (ten years) studies evaluating the durability of soils treated with these residues under variable climatic conditions, such as those affecting the Ecuadorian coast (the influence of El Niño and La Niña). Furthermore, developing localized predictive models that integrate variables such as temperature, relative humidity, and changes in the water table is necessary to predict the actual performance of the improved soil.

Future lines of research within this study area are highlighted:

- Full-scale validation: Implementation of pilot tests on road sections or foundations on soils stabilized with agro-industrial and industrial byproducts, with long-term monitoring.
- Development of predictive geo-environmental models: Integrating climate data and local soil characteristics to evaluate the performance of each technique in specific Ecuadorian contexts.
- Life cycle assessment (LCA): Of alternative stabilizing materials to quantify environmental benefits and compare their impact versus lime and cement.
- Microbiological and biochemical studies: Evaluating the impact of natural and agro-industrial stabilizers on soil biota and fertility.

5. Conclusions

The innovative and sustainable soil improvement techniques that have shown the greatest potential and practical applications in Ecuadorian expansive soils are those based on chemical mechanisms (such as rice husk ash, bagasse ash, sugarcane straw ash, banana leaf ash, rice husk ash, and bamboo leaf ash), physical-mechanical mechanisms (e.g., peat and coconut fiber, jute fibers, banana fibers, crushed ceramics), and biological mechanisms (such as wool and banana fiber, molasses, and vinasse residues).

A comparative analysis of sustainable materials used to improve expansive soils on the Ecuadorian coast concludes the following:

- The mineralogy of Ecuador's highly plastic clay, dominated by kaolinite and with a low montmorillonite content, indicates moderate expansive behavior compared to soils such as those of Saudi Arabia, which are highly rich in montmorillonite. This difference suggests that less intensive improvement techniques could be employed in Ecuador, prioritizing sustainable and local strategies over aggressive chemical stabilization.
- The low content of reactive oxides such as CaO and Fe_2O_3 in Ecuadorian soils limits the effectiveness of conventional stabilizers such as lime or cement, which technically justifies the use of alternative additives with high pozzolanic reactivity, such as rice husk ash or local silica-rich byproducts, aligning with the study's sustainability focus.
- Mineralogical analysis reveals a marked difference between the expansive soils of Ecuador (30% kaolinite) and Saudi Arabia (34.7% montmorillonite), which explains their lower expansion potential. Regarding chemical composition, the low CaO content of the Ecuadorian clay (1.73%) compared to 9.31% in the Saudi soil significantly reduces the effectiveness of lime stabilization, highlighting the need for alternative additives.
- The evaluation of agricultural byproducts such as rice husk ash (SiO_2 = 97.69%) and sugarcane bagasse showed high pozzolanic potential, while using natural fibers such as jute (85% cellulose) increased tensile strength. Through the comparison index (Ic), it was shown that alternative materials significantly improve the UCS (up to 2.3 times) and the CBR (up to 1.9 times), positioning themselves as viable, sustainable solutions for lime-poor soils such as those of the Ecuadorian coast.
- Natural fibers in other countries, such as jute and coconut, have a high proportion of cellulose, improving the soil's mechanical properties. That reinforces the potential use of Ecuadorian plant fibers (such as plantain and abaca) as sustainable reinforcement materials, the experimental exploration of which is still pending at the national level.
- Agroindustrial byproducts available in Ecuador, such as rice husk ash and sugarcane bagasse, have chemical concentrations comparable to those used internationally in soil stabilization. That validates their application as sustainable alternatives to conventional additives, with the added value of promoting the circular economy and reducing environmental impacts.
- Treating Ecuadorian soil with recycled byproducts such as rice ash and ceramics has demonstrated significant bearing capacity (BBC) improvements, comparable with international studies. However, the lack of complementary data, such as UCS or MDD, highlights the need for additional trials to technically support the widespread adoption of these techniques in road and urban infrastructure projects. Ashes from agricultural and industrial sources significantly improve expansivity in the UCS value of the soils (and the CBR). Furthermore, combinations with alkaline activators or natural fibers maximize these effects. The results support using local waste in Ecuador as a viable, economical, and sustainable technical solution for soil stabilization in road infrastructure.

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Abbreviations

The following abbreviations are used in this manuscript:

AABs	alkali-activated binders
Al_2O_3	aluminum oxide
BA	bottom ash
BaO	barium oxide
$CaCl_2$	calcium chloride
$CaCO_3$	calcium carbonate
CaO	calcium oxide
CBR	California bearing ratio
CH	calcium hydroxide
CKD	cement kiln dust
CO_2	carbon dioxide
CSA	calcium sulfoaluminate
C-S-H	calcium silicate hydrate
CSMs	calcium-based stabilizer materials
CWD	construction and demolition waste
EICP	enzyme-induced carbonate precipitation
EPS	expanded polystyrene
FA	fly ash
Fe_2O_3	iron (III) oxide
FeO	ferrous oxide or iron (II) oxide
FeO_3	ferric oxide
FMs	crushed face masks
GGBS	ground granulated blast furnace slag
Ic	comparison index
K_2O	potassium oxide
KCl	potassium chloride
KOH	potassium hydroxide
LL	liquid limit
LP	plastic limit
IP	Plasticity Index
LOI	loss on ignition
MDD	maximum dry density
MgO	magnesium oxide
MICP	Microorganism–Induced Calcium Carbonate Precipitation
Mn_2O_3	manganese (III) oxide
MnO	manganese (II) oxide
MSWI	municipal solid waste incineration
Na_2O	sodium oxide
OMC	optimum moisture content
P_2O_3	phosphorus (III) oxide, diphosphorus trioxide, or phosphorus anhydride
P_2O_5	phosphorus oxide

PA	pond ash
POFA	palm oil ash
PP	polypropylene fiber
PWS	recycled crushed plastic waste strips
RHA	rice husk ash
SDGs	Sustainable Development Goals
SF	micro silica or silica fume
SiO_2	silicon (IV) oxide
SO_3	silicate anion
TiO_2	titanium (IV) oxide
UCS	uniaxial compressive strength
USCS	Unified Soil Classification System
UK	United Kingdom
US	United States
WOS	Web of Science

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