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From Bibliometric Analysis to Experimental Validation: Bibliometric and Literature Review of Four Cementing Agents in Soil Stabilization with Experimental Focus on Xanthan Gum

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Abstract: This article focuses on the search for efficient solutions to enhance the mechanical strength of geomaterials, especially soils, with crucial applications in civil engineering. Four promising materials are explored as soil improvement agents: natural latex (rubber trees), lignosulfonate (paper industry byproduct), xanthan gum (bacterial fermentation), and eggshell lime. While other sustainable options exist, these four were chosen for their distinct characteristics and potential for further study. Natural latex, derived from rubber trees, demonstrates exceptional potential for strengthening the mechanical resistance of soils, offering a path to effective stabilization without compromising environmental sustainability. Lignosulfonate, a paper industry byproduct, emerges as an alternative that can significantly enhance the load-bearing capacity of soils, boosting its applicability in civil engineering projects. Xanthan gum, produced through bacterial fermentation, possesses unique properties that increase soil cohesion and strength, making it a valuable option for geotechnical applications. Finally, despite potential challenges, eggshell lime shows promising potential in enhancing the mechanical resistance of soils. This study highlights the importance of evaluating and comparing these agents in terms of their effectiveness in improving the mechanical strength of soils in civil engineering applications. In the literature review, the impact of stabilizer addition (%) was examined for the four cementing agents studied, along with its influence on key soil properties like optimum moisture content (OMC, %), maximum dry density (MDD, gm/cc), California bearing ratio (CBR, %), uniaxial compressive strength (UCS) at 28 days (MPa), and the change in UCS (ΔUCS, %) among other physicochemical parameters. Appropriate selection of these materials can lead to developing more robust and sustainable geomaterials, promoting significant advancements in geotechnical engineering and civil construction practices. To evaluate their effectiveness, the efficiency of one of them was assessed experimentally. Xanthan gum (XG) was selected to biopolymerize clay soil. Specimens were prepared for strength and stiffness tests, including unconfined compression, scanning electron microscopy (SEM), and ultrasonic wave analysis. The impact of stabilizer concentration was examined (e.g., 1%, 3%, 5% xanthan gum) to assess how dosage affects the soil–stabilizer mixture. The results showed that the rubber increases the unconfined compression and stiffness of the soil, controlled by the XG's porosity/volumetric quantity ratio. The research demonstrates the potential of XG, but a broader analysis of all four materials with the outlined testing methods paves the way for future advancements in geotechnical engineering.

Keywords: soil stabilization; cementing agents; eco-friendly; geotechnical engineering

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Citation: Baldovino, J.d.J.A.; Palma Calabokis, O.; Saba, M. From Bibliometric Analysis to Experimental Validation: Bibliometric and Literature Review of Four Cementing Agents in Soil Stabilization with Experimental Focus on Xanthan Gum. *Sustainability* **2024**, *16*, 5363. https://doi.org/10.3390/su16135363

Academic Editor: Clara Celauro

Received: 20 April 2024
Revised: 29 May 2024
Accepted: 18 June 2024
Published: 24 June 2024

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1. Introduction

Soil stabilization is a crucial technique in civil engineering employed to enhance the mechanical properties of soils for various applications. Stabilization aims to improve

characteristics like strength, bearing capacity, and resistance to erosion, ensuring the soil's suitability for construction projects. Soil stabilization transcends the realm of solely addressing problematic soils, such as those with low friction due to mica flakes (e.g., micaceous soils). Even high-quality soils may necessitate stabilization for various engineering applications. This is primarily driven by the need to enhance the soil's mechanical properties to meet specific project requirements. For instance, soil stabilization becomes crucial for supporting structures like buildings and roads, ensuring adequate strength to bear significant loads and prevent excessive settlement or collapse.

Furthermore, stabilization is vital in mitigating soil erosion caused by wind, rain, and flowing water. By binding soil particles together, this process minimizes the risk of erosion, a primary environmental and economic concern. In earthquake-prone regions, soil stabilization can be a critical measure to prevent liquefaction where susceptible soil types lose their strength and behave like a liquid during seismic events. Additionally, stabilization can address specific limitations of even good-quality soils. For example, inherently strong clay soils may exhibit significant shrinkage and swelling with fluctuating moisture content. Soil stabilization can improve these characteristics, making the soil more suitable for construction. Therefore, while problematic soils undoubtedly benefit from stabilization, the technique plays a broader role in civil engineering by enhancing the overall suitability of various soil types for diverse applications.

Conventional Portland cement, a widely used stabilizing agent, presents a significant environmental concern due to its high CO_2 emissions during clinker production. This has driven research toward alternative cementitious agents with a lower carbon footprint. This paper focuses on four promising bio-based and potentially more sustainable alternatives to conventional cement: natural rubber latex, lignosulfonate, xanthan gum, and eggshell lime. While a detailed literature review will be presented in dedicated chapters for each material, this introduction provides a general overview of their potential for soil stabilization. Each material offers unique properties that can improve the mechanical performance of soils.

According to Hoy et al. [1], natural rubber latex (NRL), derived from rubber trees, acts as a binding agent within the soil matrix. This adhesive property enhances soil cohesion and strength, potentially improving its deformation and shear stress resistance. NRL film additive increases the studied blends' unconfined compressive strength (UCS) during high-temperature wet–dry cycles by enhancing particle bonding and reducing porosity within the matrix. On the other hand, lignosulfonate, a byproduct of the paper industry, exerts its influence through a unique mechanism compared with other bio-stabilizers. Functioning as a dispersant facilitates a more homogenous distribution of clay particles within the soil matrix. This enhances packing density, potentially influenced by intermolecular interactions between lignosulfonate and clay particles, and translates to a potentially more robust structure with improved load-bearing capacity. Additionally, lignosulfonate's tunable hydrophobicity/ hydrophilicity plays a role in its effectiveness with different soil types [2].

The biopolymer xanthan gum, a product of bacterial fermentation, demonstrates the potential for soil stabilization, especially in loose or sandy soils [3]. However, its effectiveness exhibits a dynamic response to drying conditions. Initially, xanthan gum has a marginal impact on soil strength. The biopolymer network forms weak, readily disrupted cross-links, with its fluid-like properties overshadowing its adhesive capabilities. Intriguingly, the drying process acts as a catalyst: as water evaporates (particularly at elevated temperatures), xanthan gum's bonding strengthens, leading to a marked increase in soil cohesion and shear resistance. Notably, drying at lower temperatures presents a unique scenario. While the outer surface experiences biopolymer cementation, the inner portion remains moist and poorly cross-linked, resulting in initial strength similar to untreated sand. Ultimately, complete desiccation maximizes the strengthening effect, but the concomitant shrinkage and embrittlement of the biopolymer can introduce variations in the final soil strength.

Regarding the last geomaterial considered, eggshell-derived lime, a product of calcined eggshells, presents a compelling alternative to conventional limes for soil stabilization. This

eco-friendly approach bypasses the environmental burdens associated with quarrying and processing limestone, the traditional source material. Research indicates that eggshell lime significantly reduces impacts on aquatic and terrestrial ecosystems and land use compared with its mainstream counterpart. Specifically, eggshell-based quicklime and hydrated lime generated a remarkable decrease in overall ecosystem damage, exceeding 65% and 50%, respectively. Suitable physicochemical properties for soil stabilization applications complement these environmental advantages. Eggshell quicklime primarily comprises calcium oxide (nearly 97%) with a minor magnesium oxide component (around 2%).

Similarly, eggshell-hydrated lime consists mainly of calcium hydroxide (almost 90%), with some magnesium hydroxide (approximately 3%) and a trace amount of calcium carbonate (around 5%). Furthermore, the literature demonstrates [4] the efficacy of eggshell quicklime and hydrated lime in enhancing soil strength and stiffness. This improvement is attributed to their pozzolanic reaction with supplementary materials like ground glass, leading to novel cementitious binding agents within the soil matrix.

However, regarding CO_2 emissions during their production, it is essential to note that the environmental impact can vary depending on the specific production and processes involved in each of these materials.

The extraction of natural rubber latex involves the collection of latex from rubber trees, and although this process does not produce significant CO_2 emissions on its own, there may be emissions associated with the energy used in its processing and transportation [5]. The production of lignosulfonate typically involves the extraction and modification of lignin, a byproduct of the paper industry [6]. While the process may be more sustainable than cement production, there may still be some CO_2 emissions associated with the required energy. Additionally, bacteria produce xanthan gum through the fermentation of sugars [7]. This process is less CO_2-intensive than cement production, but emissions can vary depending on fermentation conditions and the source of sugars used. Finally, the production of lime from eggshells typically involves the calcination of shells to obtain calcium oxide (quicklime). If energy-intensive calcination methods are used, there could be associated CO_2 emissions [8]. Although these materials are considered more environmentally friendly compared with conventional cement, CO_2 emissions during their production can vary depending on the specific processes used in their manufacturing. Therefore, it is essential to consider energy efficiency and sustainable production methods when assessing their carbon footprint.

This paper delves into the world of soil stabilization using bio-based cementing agents. It employs a two-pronged approach: a bibliometric analysis and a dedicated literature review. The bibliometric analysis provides a comprehensive overview of existing research on four promising agents—natural rubber latex, lignosulfonate, xanthan gum, and eggshell lime. Following this, in-depth literature reviews for each agent shed light on their specific capabilities in soil stabilization. Finally, the paper culminates in a focused experimental investigation on xanthan gum, aiming to validate its effectiveness through laboratory testing.

2. Methodology

The methodology was divided into three main stages. The first stage involved conducting a bibliometric analysis on alternative cementing agents for problematic soils, specifically natural rubber latex, lignosulfonate, eggshell lime, and xanthan gum. This bibliometric analysis was carried out using the metadata from the Scopus database (in .RIS file format) and then imported into the VOSviewer software (version 1.6.20). Subsequently, the second stage consisted of a review of the existing literature published in high-level scientific journals, highlighting the following topics: material definition, source, use, physicochemical properties, influence on the strength of stabilized soils, durability, and microstructure. Finally, an experimental study of xanthan gum (XG) use in clay stabilization was proposed.

3. Bibliometric Analysis

A bibliometric study assessed the state of the art regarding studies and ongoing research conducted worldwide. This study is known for its ability to focus on and examine the production of articles in a specific area of knowledge specified by the user. It maps academic communities, identifies networks of researchers and their scientific publications, and creates indicators to filter the most cited institutions, authors, and academics in co-authorship networks. This process identifies various theoretical, empirical, and methodological contributions within the area of interest.

The existing literature is analyzed and observed through bibliometrics, a quantitative method involving statistical analysis using books, articles, and other publications. The survey was conducted by searching for papers indexed in the Scopus and Web of Science databases, considering national and international publications from the last ten years. In this stage, we used bibliometric laws as references, including Zipf's law, which pertains to the frequency of keywords in the text, and Lotka's law, which relates to author productivity while taking into consideration the impact factor of authors' scientific production within their respective field of knowledge. The keywords used for the search were lignosulphonate, natural rubber latex, eggshell lime, and xanthan gum combined with soil stabilization. A search string was constructed with the defined keywords, as presented in Table 1. To narrow the scope, topics unrelated to the study, such as energy, medicine, earth, arts and humanities, agriculture, neuroscience, and psychology, were excluded.

Table 1. Search results for several documents depending on a summarized search string (from 2013 to 2023).

Stabilizer	Scopus String	Results
Lignosulphonate	"soil stabilization" AND "Lignosulphonate"	12
Natural rubber latex	"soil stabilization" AND "natural rubber"	7
Eggshell lime	"soil stabilization" AND "eggshell"	27
Xanthan gum	"soil stabilization" AND "xanthan"	67

As presented in Table 1, the search results correspond to a summarized string obtained by combining only the keywords with 'soil stabilization'. There were 12, 7, 27, and 67 documents obtained for 'lignosulphonate', 'natural rubber latex', 'eggshell lime', and 'xanthan gum', respectively. In bibliographic or documentary research, the research base data are obtained from documentary sources such as photos, maps, and written or digital forms to uncover, collect, and analyze the main contributions of a specific fact, subject, or idea.

It can be asserted that bibliometric research is a type of bibliographic research that connects various researchers worldwide through systems like Scopus and Web of Science, among others, using co-citations to form information networks. These networks consolidate research results and confirm hypotheses through interactions among researchers on specific subjects, as illustrated in Figure 1.

Due to the limited number of documents found with the reduced string, it has been extended to other keywords shown in Table 2. Keywords such as 'soil improvement' and 'ground improvement', synonymous with 'soil stabilization', have been included. A total of 51, 100, 414, and 459 documents were obtained for 'lignosulphonate', 'natural rubber latex', 'eggshell lime', and 'xanthan gum', respectively. However, the majority of the documents are not from the soil stabilization field as the included words 'sand' and 'clay' can be associated with agriculture, food, and chemical engineering areas. Thus, choosing a combination of stabilization and improvement soils with each stabilizer is necessary, as presented in Table 3. Table 3 shows search results for several documents, depending on a selected search string (from 2013 to 2023). A total of 15, 15, 37, and 105 documents were obtained for 'lignosulphonate', 'natural rubber latex', 'eggshell lime', and 'xanthan gum', respectively. The selecting string for density visualization (Figure 2) was: *((*"soil

stabilization" OR "soil improvement" OR "ground improvement") AND ("Lignosulphonate")) OR (("soil stabilization" OR "soil improvement" OR "ground improvement") AND ("natural rubber latex" OR "natural latex")) OR (("soil stabilization" OR "soil improvement" OR "ground improvement") AND ("eggshell" OR "egg lime")) OR (("soil stabilization" OR "soil improvement" OR "ground improvement") AND "xanthan"), and 172 results were selected, as a sum of individual strings presented in Table 3. The bibliographic coupling reveals the documents that employ closely related bibliographic sources in their studies, establishing connections among them. In this work, coupling among authors was considered, using a minimum of 2 documents associated with an author, resulting in the selection of 134 authors for the network. This outcome can be visualized in Figure 2. The number of documents by year is presented in Figure 3.

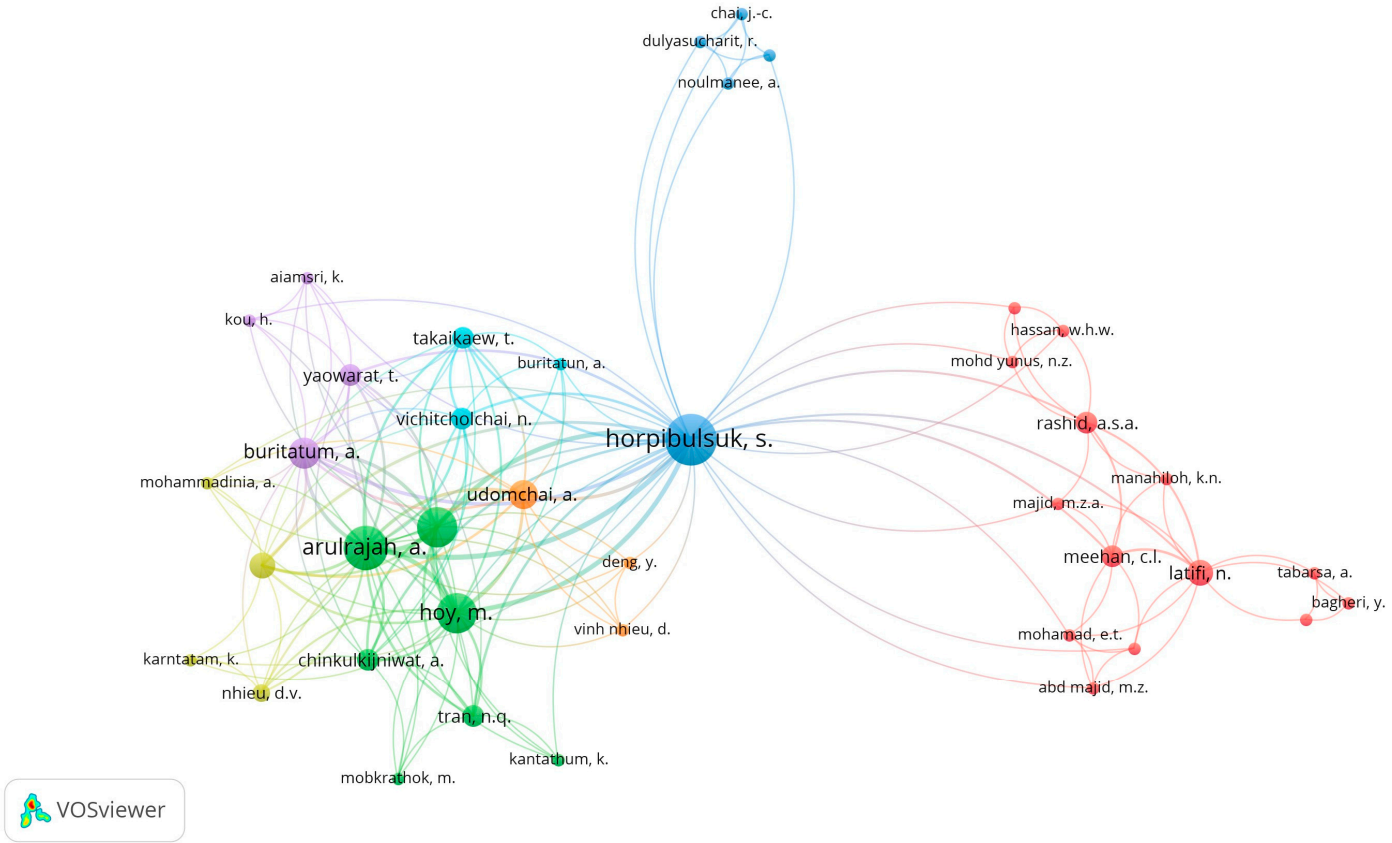


Figure 1. Co-authorship analysis using an entire counting method.

Table 2. Search results for several documents depending on an extended search string (from 2013 to 2023).

Stabilizer	Scopus String	Results
Lignosulphonate	"soil stabilization" OR "soil improvement" OR "ground improvement" OR "soil" OR "sand" OR "clay" OR "silt" AND "Lignosulphonate"	51
Natural rubber latex	"soil stabilization" OR "soil improvement" OR "ground improvement" OR "soil" OR "sand" OR "clay" OR "silt" AND "natural rubber latex" OR "natural latex"	100
Eggshell lime	"soil stabilization" OR "soil improvement" OR "ground improvement" OR "soil" OR "sand" OR "clay" OR "silt" AND "eggshell" OR "egg lime"	414
Xanthan gum	"soil stabilization" OR "soil improvement" OR "ground improvement" OR "soil" OR "sand" OR "clay" OR "silt" AND "xanthan"	459

Table 3. Search results for several documents depending on a selected search string (from 2013 to 2023).

Stabilizer	Scopus String	Results
Lignosulphonate	(“soil stabilization” OR “soil improvement” OR “ground improvement”) AND (“Lignosulphonate”)	15
Natural rubber latex	(“soil stabilization” OR “soil improvement” OR “ground improvement”) AND (“natural rubber latex” OR “natural latex”)	15
Eggshell lime	(“soil stabilization” OR “soil improvement” OR “ground improvement”) AND (“eggshell” OR “egg lime”)	37
Xanthan gum	(“soil stabilization” OR “soil improvement” OR “ground improvement”) AND “xanthan”)	105

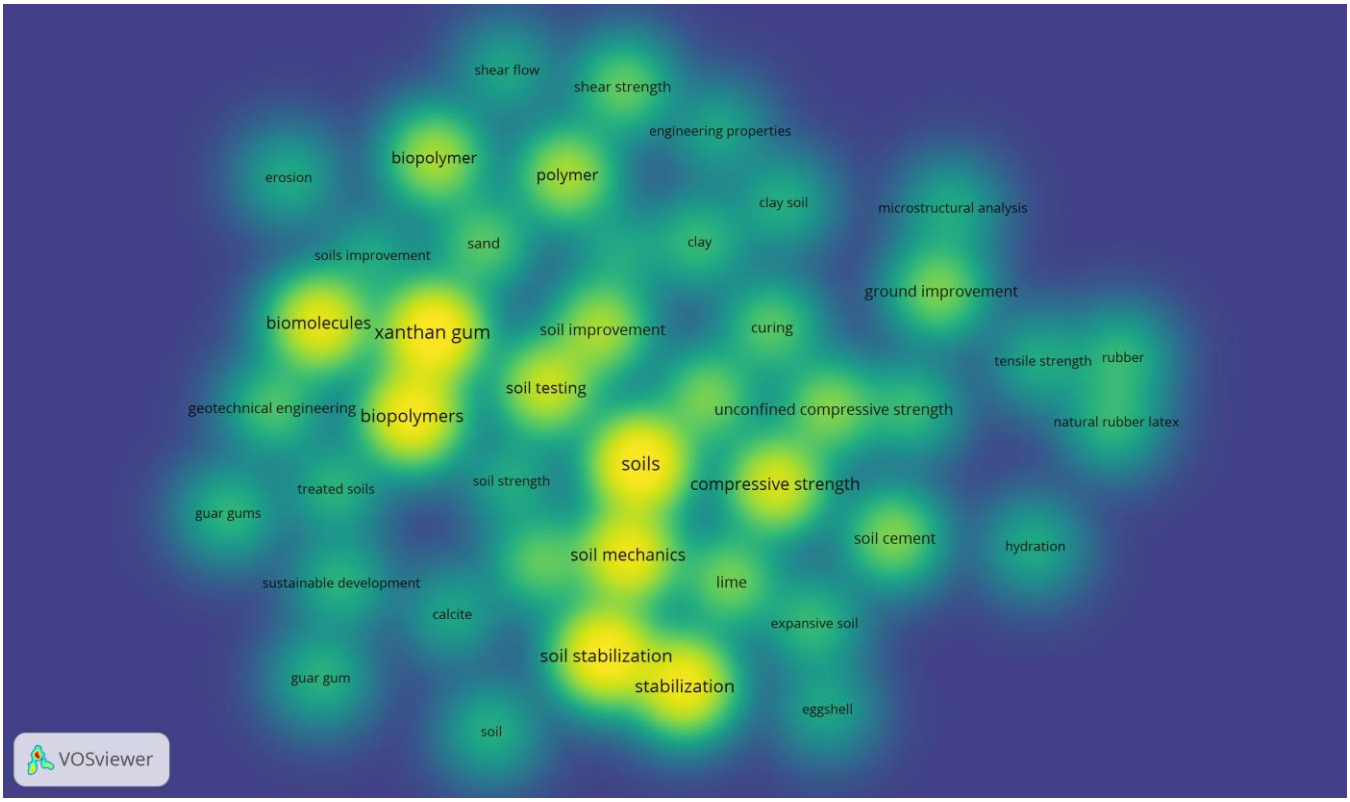


Figure 2. Density visualization.

It is evident in Figure 3 that the highest concentration of scientific production is found in ‘xanthan gum’, followed by ‘eggshell lime’. However, the use of these two alternative binders only began in 2015. In the case of ‘lignosulphonate’, studies have been conducted since 2013, but productivity has been low. This may be because the residue is not produced worldwide but in concentrated areas of Asia. The most recent utilization is ‘natural rubber latex’, which was first used for soil improvement as recently as 2020 and is on the rise. By 2023, 8 documents have already been published, significantly more than those related to ‘lignosulphonate’, despite its extended history of use.

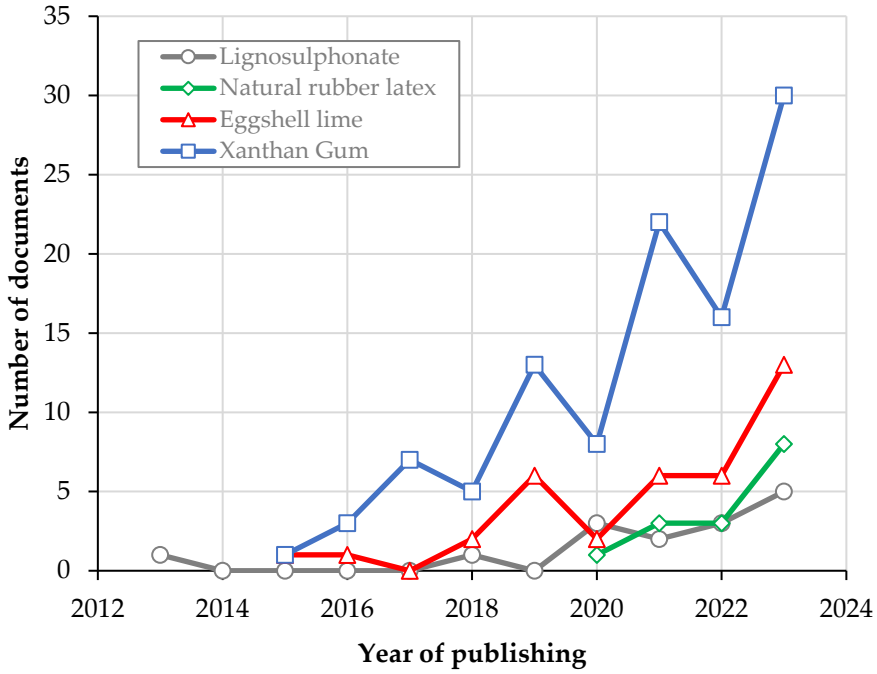


Figure 3. Number of documents by year.

4. Bibliographic Review

In civil engineering, the quest for practical solutions to enhance the mechanical strength of geomaterials, particularly soils, takes center stage. This article explores four promising materials as agents for soil improvement: natural latex, lignosulfonate, xanthan gum, and eggshell lime. From the exceptional potential of natural latex to the unique properties of xanthan gum, these materials offer promising avenues for bolstering soil mechanical resistance without compromising environmental sustainability. This study emphasizes the importance of evaluating and comparing these agents to advance the development of more robust and sustainable geomaterials, propelling significant progress in geotechnical engineering and civil construction practice. For the literature review and analysis of the use of different soil stabilizers in problematic soils, ten scientific articles have been selected for each to establish a background and, subsequently, study their primary applications, advantages, disadvantages, and effects on the physico-mechanical properties of soils.

In addition, with the thorough literature review articulated in the main body of this manuscript, Appendix A provides a meticulous scrutiny of 18 recent scholarly articles spanning the last half-decade. These works analyze over 120 soil amalgams, scrutinizing diverse pivotal parameters. Nonetheless, it warrants acknowledgment that while these investigations furnish valuable insights, a lacuna necessitates further exploration, notably in facets such as shear and petrography examinations. Elucidating the underlying mechanisms underpinning the fortification of soil capacity engendered by natural latex, lignosulfonate, xanthan gum, and eggshell lime necessitates deeper inquiry. Furthermore, conducting meticulous cost/benefit appraisals, durability assessments, and discerning potential environmental toxicity represent indispensable endeavors toward comprehensively delineating the utility of these materials in soil stabilization contexts. By addressing these imperative facets, forthcoming research endeavors are poised to elevate our comprehension and augment the efficacy and sustainability of soil enhancement methodologies within civil engineering.

4.1. The Process Involves Obtaining Lignosulphonate, Natural Rubber, Xanthan Gum, and Eggshell Lime

Lignosulfonate of sodium is a chemical additive derived from lignin, a natural component found in wood. It results from a sulfonation process of lignin, which involves introducing sulfonic groups into its molecular structure [9]. This process renders lignin soluble in water and imparts unique and valuable properties for various industrial applications. Sodium lignosulfonate is commonly available in powder or liquid form and is widely used across different industries due to its dispersing and viscosity-reducing properties. It is mainly known for its ability to disperse solid particles in liquids, preventing agglomeration and improving the homogeneity of mixtures [10]. Additionally, its ability to reduce viscosity facilitates the flow and handling of denser liquids. Currently, lignosulfonates are the most available and commercially traded source of lignin worldwide.

The sulfonate group binds to the alpha position of the benzene ring at pH levels below 5 (Figure 4). Lignosulfonates are extracted from pulping liquor by precipitation with lime to form calcium lignosulfonate [11]. A photo of LS in powder can be seen in Figure 5a. It can eventually be transformed into salts with other cations or the ammonium ion. Lignosulfonates are complex polymeric materials with a molecular weight ranging from 2000 to 100,000 g/mol (wide molecular weight distribution), with 0.4 to 0.7 sulfonate groups per unit of phenylpropane and twice the number of methoxyl groups [12]. The sulfonate groups contribute the most critical characteristic of lignin: its water solubility. In general, lignosulfonates possess adhesive, dispersing, and surface tension-modifying properties, from which their main applications derive. Lignosulfonates, in their solid powder form, are also highly hygroscopic.

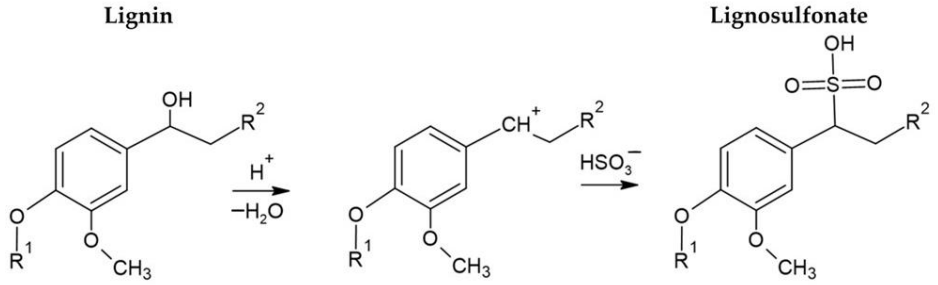


Figure 4. The Formation of lignosulfonate.

Natural latex rubber is obtained from rubber trees, mainly from the Hevea brasiliensis tree (Figure 5b). The rubber is produced through "tapping", where an incision is made in the tree's bark to allow latex to flow into a container [13]. The collected latex is coagulated and then processed to remove impurities and water, thus obtaining natural latex rubber in liquid or solid form [14].

Xanthan gum is produced through the fermentation of carbohydrates by the bacterium *Xanthomonas campestris* [15]. This bacterium synthesizes xanthan gum as a viscous substance to aid its survival and protection [16]. The production process involves cultivating the bacteria in a growth medium containing carbohydrates such as glucose or starch and then purifying the produced xanthan gum, as presented in Figure 5c. In addition, the xanthan gum production in a series of stirred tank fermenters is explained in Figure 6.



Figure 5. Photos of the raw materials. (**a**) LS [17], (**b**) natural rubber latex [18], (**c**) xanthan gum [19], and (**d**) eggshell lime https://doi.org/10.3390/jcs7070278 [20].

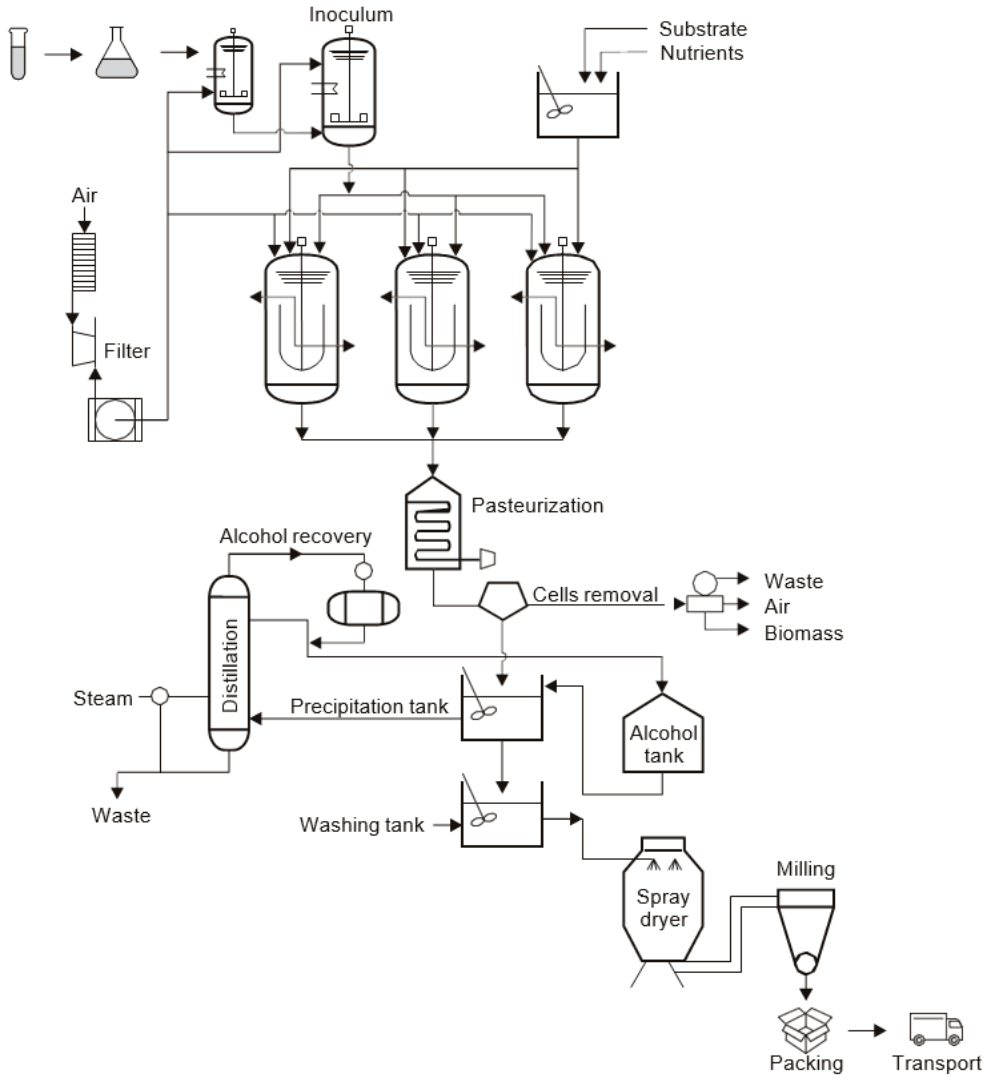


Figure 6. Flowchart of xanthan gum production in a series of stirred tank fermenters [21]. Used with permission. Copyright © 2015 National Agricultural and Food Centre, Slovakia.

To obtain eggshell lime (see Figure 5d), calcination is performed after collecting and washing the eggshells, which is basically heating the shells to high temperatures to remove

any organic residue and convert the calcium carbonate present in the shells into calcium oxide (CaO). The calcination process typically involves cleaning, drying, and heating them to a high temperature, usually around 800–900 °C, in a furnace or similar device [22]. During this process, calcium carbonate decomposes into calcium oxide and carbon dioxide. After calcination, the resulting calcium oxide is allowed to cool to room temperature. Once calcination is complete, the resulting calcium oxide is ground into a fine powder through grinding (see complete process in Figure 7). This ground and calcined eggshell powder can then be used as an additive for soil stabilization due to its calcium oxide content, which can react with silicates present in the soil to form compounds that enhance its mechanical properties [4]. Through calcination and grinding, eggshells are transformed into a more suitable and practical material for application in soil stabilization [23,24].

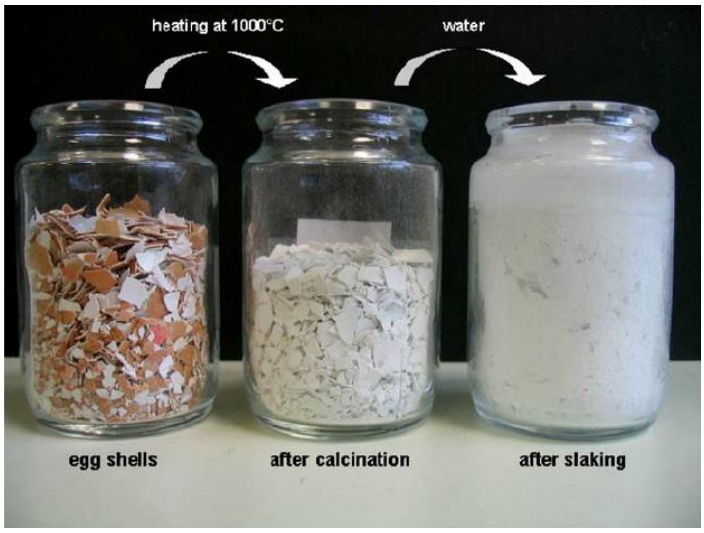


Figure 7. Process of obtaining eggshell limes [25].

Table 4 presents some examples of experimental studies about the use of XG, LS, NRL, and eggshell limes on the strength of stabilized soils. Each raw material affects treated soils' unconfined compressive strength, durability, and microstructure. Some raw materials (in concordance with references) can be mixed with other binders, such as cement, limes, or fly ashes [1,26–31].

Table 4. Overview of sustainable soil stabilizations studied in the literature.

Material	Use	Physicochemical Properties	Influence on Strength of Stabilized Soils	Durability	Microstructure	Ref.
Lignosulfonate	Soil stabilization	Residual byproduct of paper industry; hydrophilic and hydrophobic groups; nontoxic and noncorrosive; sulfonation process	Enhanced soil strength; improved shear strength, penetration resistance, and erosion resistance; effective in wet conditions	Not explicitly addressed	Three-dimensional polymer; aliphatic and aromatic portions	[32–36]

Table 4. *Cont.*

Material	Use	Physicochemical Properties	Influence on Strength of Stabilized Soils	Durability	Microstructure	Ref.
Natural rubber latex	Soil stabilization	Cis-1,4-polyisoprene; biodegradable; adhesive properties; nontoxic	Enhanced soil stability; improved shear strength and compaction characteristics; effective in various soil types	Biodegradable; nontoxic	Polymer chains of cis-1,4-polyisoprene	[1,14,37–39]
Eggshell lime	Soil amendment, stabilization	Calcium carbonate; alkaline pH; source of calcium; potential pozzolanic reactivity	Improved compressibility and strength; reduced plasticity; enhanced durability; pH modification	Enhances durability; pH modification	Calcium carbonate particles	[4,23,40,41]
Xanthan gum	Soil stabilization, erosion control	Polysaccharide; hydrocolloid; biodegradable; high viscosity; water retention	Improved shear strength and erosion resistance; effective in sandy soils; enhanced water retention	Biodegradable; high viscosity	Extended, helical structure of polysaccharide chains	[42–46]

4.2. Lignosulphonate Use in Soil Stabilization

Lignosulfonate (LS) is a residual byproduct of the paper manufacturing industry, with an estimated global annual production of 50 million tons [35]. This polymeric compound, based on lignin and containing various hydrophilic groups, including sulfonate, phenolic hydroxyl and alcoholic hydroxyl groups, along with hydrophobic groups that include the carbon chain, enhances soil strength and durability. Its advantageous environmental nonharmful properties, coupled with being a byproduct of other processes, render it relatively cost-effective and competitive in terms of costs compared with other stabilizers [47]. Therefore, unlike traditional agents, LS is nontoxic, and its use for soil stabilization does not alter the soil's pH or brittleness [48]. Previous research on soils stabilized with LS has revealed its effectiveness in improving soil strength properties. Most of these studies were conducted on silty clay, sandy silt, and low-plasticity clay (CL). In this regard, the potential of lignosulfonate as a soil stabilizer has been investigated, examining shear strength, penetration resistance, erosion resistance, compaction characteristics, and durability [49], demonstrating its effectiveness, particularly in wet conditions [50].

In line with the considerations mentioned earlier, it should be noted that the significant potential of lignosulfonate in soil treatment has garnered the attention of numerous researchers in this field. Previous research has demonstrated that applying lignosulfonate in soil stabilization can enhance samples' critical hydraulic shear stress, erosion coefficient, and strength characteristics [36]. Most of these research studies have been conducted on soils with low or negligible calcite content, and little attention has been given to calcareous soils, particularly under adverse environmental conditions such as freeze–thaw cycles.

Lignosulfonate is a nontoxic and noncorrosive waste material from the wood and paper processing industry. In the industrial process, lignin is separated from cellulose, and since lignin has limited solubility in water, it is converted into lignosulfonate through a chemical process known as sulfonation. This byproduct is available in both solid and liquid forms, containing carbon (C), oxygen (O), sulfur (S), and sodium (Na) [51]. After numerous investigations, some authors have determined through a series of microchemical analyses on soil treated with LS that the improved performance exhibited by the LS-stabilized soil can be attributed to the reduction in the thickness of the double layer due

to the neutralization of surface charges on soil particles and the subsequent facilitation of a constant grain conglomeration [47]. It is important to note that since trees vary as raw materials in paper mills, the composition of LS differs from one production group to another, depending on the resources and wood production process.

The chemical structure of lignosulfonate (LS) has been investigated by various authors using EDS (energy-dispersive X-ray spectroscopy) and FTIR (Fourier transform infrared) techniques, establishing that this compound is a highly cross-linked amorphous polymer consisting of aliphatic portions (i.e., hydrophilic sulfate groups, hydroxyl, methoxyl, carboxyl, phenolic groups) and aromatic portions (i.e., hydrophobic favorable aromatic structure), but its net charge is negative. Its basic chemical structure, which includes a benzene ring, can form complexes with cations such as Ca, Na, and Mg, allowing it to compete for adsorption sites on clays or form covalent coordinated bonds with multivalent metal ions. Furthermore, LS could be classified as calcium lignosulfonate if its chemical structure coordinates with a multivalent calcium cation (Ca^{2+}) [35].

Thus, lignosulfonate is a three-dimensional polymeric compound derived from wood extract. Although the structural characteristics of the lignin molecule are not fully known, it is generally accepted that it consists of three alcohol monomers with the main polymeric structure, including coniferyl alcohol, sinapyl alcohol, and p-coumaric alcohol. Figure 8 presents a schematic of the lignosulfonate structure.

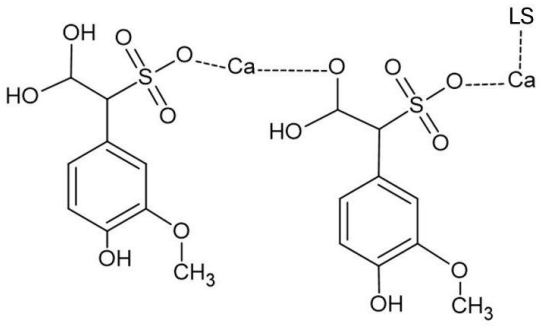


Figure 8. Molecular structure of lignosulfonate (LS).

4.3. Natural Rubber Latex (NRL) Properties and Its Use in Soil Stabilization

Natural rubber latex (NRL) has emerged as a sustainable and environmentally friendly alternative for soil stabilization, offering unique properties that make it an attractive choice compared with conventional cement-based stabilizers. NRL, derived from the *Hevea brasiliensis* rubber tree, is a colloidal dispersion of polymers in water, primarily consisting of cis-1,4-polyisoprene. The use of NRL in soil stabilization presents several advantages that contribute to its efficacy and eco-friendliness.

One of the critical characteristics of NRL is its inherent biodegradability. Unlike traditional stabilizers that may leave long-lasting environmental footprints, NRL decomposes naturally over time without causing harm to ecosystems. This aligns with the principles of sustainable development where materials with minimal environmental impact are sought after for various applications. The biodegradability of NRL ensures that its presence in the treated soil does not persist indefinitely, minimizing any potential adverse effects on the environment.

Moreover, NRL exhibits excellent adhesion properties, forming a robust bond with soil particles. This adhesion enhances the overall stability of the soil structure, improving shear strength and resistance to erosion. The ability of NRL to adhere to soil particles is attributed to the presence of hydrophilic groups in its chemical composition, allowing for effective interaction with the soil matrix. This makes NRL particularly effective in preventing soil erosion, a critical aspect of soil stabilization, especially in areas prone to heavy rainfall or water flow. Regarding cost-effectiveness, NRL holds an advantage similar to lignosulfonate (LS) as it is a byproduct of another industry—the rubber industry. This byproduct nature makes NRL a relatively cost-effective option for soil stabilization as its production is not the

primary purpose of the rubber industry. Using byproducts for soil stabilization aligns with sustainable practices by repurposing materials that would otherwise be considered waste.

NRL also exhibits nontoxic properties, ensuring its use does not harm the environment or human health. This is a crucial aspect of soil stabilizers as toxic substances can harm ecosystems and groundwater quality. The nontoxic nature of NRL makes it a safe and environmentally responsible choice for soil stabilization applications. Research on NRL's effectiveness in soil stabilization has shown promising results. Studies have explored its impact on various soil types, including clayey and sandy soils, demonstrating improvements in shear strength, compaction characteristics, and resistance to environmental factors. Additionally, the effectiveness of NRL in different climatic conditions, such as wet environments, has been investigated, further establishing its versatility as a soil stabilizer.

The chemical structure of NRL (Figure 9), similar to LS, has been analyzed using advanced techniques like Energy-Dispersive X-ray Spectroscopy (EDS) and Fourier Transform Infrared (FTIR). These analyses reveal a complex structure with hydrophilic and hydrophobic components, contributing to its adhesive properties. The chemical structure of NRL allows it to interact with soil particles, forming stable bonds that enhance soil stability.

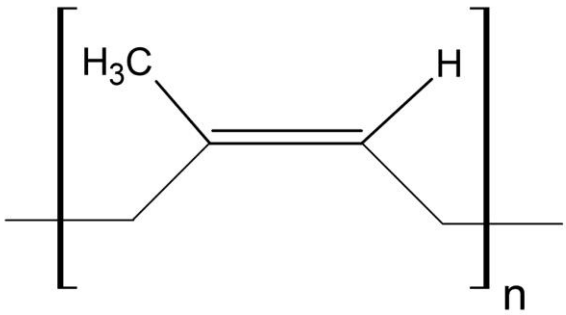


Figure 9. Molecular structure of natural rubber latex (NRL).

4.4. Xanthan Gum Properties and Its Impact on Soil Stabilization

This biopolymer was discovered in the 1950s by researchers at the NRRL (Northern Regional Research Laboratory), part of the United States Department of Agriculture, in Illinois, USA [52]. It is a natural polysaccharide obtained through fermentation using the bacterium *Xanthomonas campestris* [53]. Xanthan gum is a high molecular weight (around 2 million g/mol) biopolymer with excellent biodegradability (decomposing within two days). Notably, it shares a similar backbone structure with cellulose, as depicted in Figure 10. This linear polymer possesses a unique trisaccharide repeating unit within its main chain. Moving outward from the reducing end, this unit comprises a β-d-mannopyranosyl unit, a β-d-glucuronopyranosyl unit, and an α-d-mannopyranosyl unit with a 6-acetate substitution at the nonreducing terminus.

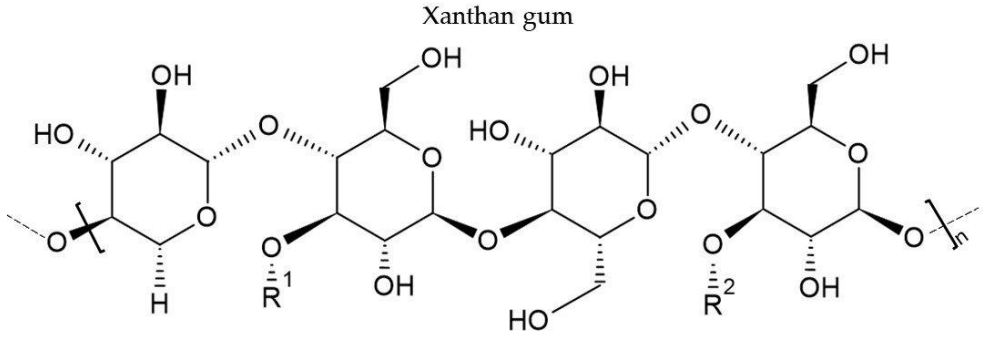


Figure 10. Molecular structure of xanthan gum.

Xanthan gum, a polysaccharide produced by the bacterium *Xanthomonas campestris*, has gained attention as an environmentally friendly alternative for sustainable soil stabilization.

This biopolymer exhibits unique properties that make it an attractive choice compared with conventional cement-based stabilizers, echoing the environmentally conscious approach observed with lignosulfonate (LS). Xanthan gum is derived through fermentation processes involving *Xanthomonas campestris* bacteria [54]. This sustainable production method aligns with eco-friendly practices [52].

Xanthan gum has shown promise in soil stabilization and erosion control. Its high viscosity and water retention properties improve soil structure and prevent erosion [53]. Much like lignosulfonate, which enhances soil strength and durability, xanthan gum contributes to soil stability, particularly in areas prone to erosion. Xanthan gum is a polysaccharide with repeating glucose, mannose, and glucuronic acid units. Its unique structure imparts high viscosity and water-holding capacity, making it an effective stabilizer [55]. These properties contribute to its environmentally friendly profile as it is biodegradable and poses minimal risk to ecosystems.

Research on xanthan gum's impact on soil stabilization indicates positive effects on shear strength and erosion resistance [56]. Xanthan gum's use in soil stabilization is associated with enhanced durability. Its ability to form a stable bond with soil particles contributes to long-lasting stabilization effects, reducing the need for frequent reapplication. This durability is crucial for sustainable soil management practices. Furthermore, the microstructure of xanthan gum involves extended, helical chains of polysaccharide molecules. This structure facilitates its ability to form stable bonds with soil particles, improving overall soil stability [30]. Research into xanthan gum's role in soil stabilization should continue, exploring its performance across various soil types and under different environmental conditions. Ongoing scientific investigations will provide valuable insights into the optimal applications and potential limitations of xanthan gum as a sustainable soil stabilizer.

4.5. The Use of Eggshell Lime in Soil Stabilization

Eggshell lime, derived from discarded eggshells in the food industry, represents a noteworthy environmentally sustainable option for soil stabilization. The material's production involves crushing and processing these eggshells, transforming them into a valuable resource for soil improvement. While calcium carbonate ($CaCO_3$) is the primary constituent of uncalcined eggshells, eggshell lime itself is a composite material dominated by calcium oxide (CaO) with some magnesium oxide (MgO) and potentially residual calcium carbonate ($CaCO_3$) depending on the calcination process [57]. This characteristic has significant physicochemical implications, influencing both soil structure and pH. Calcium carbonate creates a favorable environment for enhanced soil structure by elevating the soil's pH. Eggshell lime effectively stabilizes soil due to its high calcium carbonate content. Acting as a potent soil amendment, it imparts essential nutrients and positively influences the physical properties of the soil. The slow release of calcium from eggshell lime ensures sustained improvements over time, making it a valuable contributor to soil stability.

The literature has highlighted the material's impact on soil strength and compressibility [35]. Eggshell lime significantly improves soil compressibility and strength by interacting with soil particles, forming stable bonds, and reducing soil plasticity. This enhancement becomes particularly crucial in establishing stable foundations for construction projects. The utilization of eggshell lime in soil stabilization is associated with enhanced durability. Its slow-release properties contribute to sustained soil improvement, reducing the necessity for frequent reapplication. This aligns with observed long-lasting effects in soil stabilization projects, showcasing eggshell lime's potential for extended and robust soil management practices.

While lacking the complex polymeric structure in other stabilizers, such as lignosulfonate, eggshell lime's microstructure involves calcium carbonate particles. These particles engage with soil particles, forming aggregates crucial for improving overall soil stability. This microstructural aspect underscores the material's physical influence on the soil matrix. Beyond its practical utility, eggshell lime stands out for its eco-friendly attributes.

Sourced from food industry byproducts, its production aligns with sustainability goals by repurposing waste into a valuable resource. The slow-release properties and long-term effects of eggshell lime further contribute to sustainable soil management practices. Essentially, eggshell lime emerges as a scientifically grounded and environmentally conscious alternative for soil stabilization. Its unique physicochemical properties make it a valuable addition to soil stabilizers, contributing to enhanced soil structure, strength, and long-term durability. Ongoing research will continue to unveil the optimal applications and potential synergies of eggshell lime across diverse soil types and environmental conditions, reflecting an ongoing commitment to sustainable practices in the construction and agricultural industries.

5. Experimental Study of Xanthan Gum Use in Clay Stabilization

This section presents the results of an experimental study of soil stabilization with xanthan gum.

After the Industrial Revolution, Portland cement was invented and became one of the most used materials in the construction industry. It was also adopted in soil stabilization techniques [53]. Over the years, excessive use of this material has negatively affected the environment as cement production causes high carbon dioxide (CO_2) emissions into the atmosphere, contributing to one of today's biggest problems, global warming. Since the beginning of the 21st century, new stabilization techniques that use biological processes began to be studied due to their potential to improve soil properties and their advantage of reducing environmental impact, providing an alternative to conventional techniques. Currently, several soil stabilization techniques use biological processes, one of which is using biopolymers. Within the scope of the present study, the biostabilization of a laboratory-prepared soil classified as clay will be addressed with a xanthan gum biopolymer to analyze the influence of varying its dosage on the resistance and rigidity of the biostabilized soil.

5.1. Materials and Methods

In the experimental program, clay soil was improved with XG addition.

The soil used in this study was the same as that used in the recent study by Roman Martínez et al. [58] which was collected in the northern area of Cartagena de Indias (10°30′22.0″ N 75°28′26.5″ W). The soil is classified as a low-plasticity clay (CL) according to the Unified Soil Classification System (USCS) and ASTM D2487 [59]. The specific gravity was measured as 2.80 in accordance with ASTM standard D854 [60]. The particle size distribution of the silt was as follows: 10% clay, 78% silt, and 12% sand. The soil's coefficient of curvature and uniformity were calculated as 0.96 and 7.14, respectively. The diameters corresponding to the 10% and 50% finer fractions were 0.0021 mm and 0.011 mm, respectively. The liquid limit and plasticity index were determined in the laboratory as 42% and 26.05, respectively, resulting in a plasticity index of 15.95% following American ASTM standard 4318 [61]. The clay activity value was 1.60, which is considered moderate. Table 5 summarizes the results of soil characterization. The chemical and mineral composition of the soil was determined using X-ray fluorescence (XRF) and X-ray diffraction (XRD). The soil is composed of 66% SiO_2, 21.7% Al_2O_3, 5% SO_3, 3.1% K_2O, 3% CaO, 0.9% Fe_2O_3, and 0.3% TiO_2. Additionally, the soil mainly consists of kaolinite and feldspar minerals. Figure 11 presents the clay morphology recorded in the SEM analysis. The morphology of the soil sample can be seen in detail in Roman Martínez et al. [58], and it is constituted by kaolinite and feldspar particles.

Table 5. Physical properties of soil sample.

Properties	Soil	Standard
LL Limit liquid of soil, %	42.00	[61]
PL Plastic limit of soil, %	26.05	[61]
PI Plastic index of soil, %, (i.e., LL-PL)	15.95	[61]
Gravel particles (diameter—2 mm), %	0	[62]
Coarse sand particles size (0.6 mm—diameter—2 mm), %	0	[62]
Medium sand particles size (0.2 mm—diameter—0.6 mm), %	0	[62]
Fine sand particles size (0.06 mm—diameter–0.2 mm), %	12	[62]
Silt particles size (0.002 mm—diameter—0.06 mm), %	78	[62]
Clay particles size (diameter < 0.002 mm), %	10	[62]
Effective size of soil (D_{10}), mm	0.0021	[62]
Mean particle diameter of soil (D_{50}), mm	0.011	[62]
Uniformity coefficient of soil (C_u)	7.14	[62]
Coefficient of curvature of soil (C_c)	0.96	[62]
The specific gravity of the soil sample	2.80	[60]
Activity of clay, A [A = PI/(% < 0.002 mm)]	1.60	[63]
Color	Black	-
Classification of soil sample (USCS)	CL	[62]

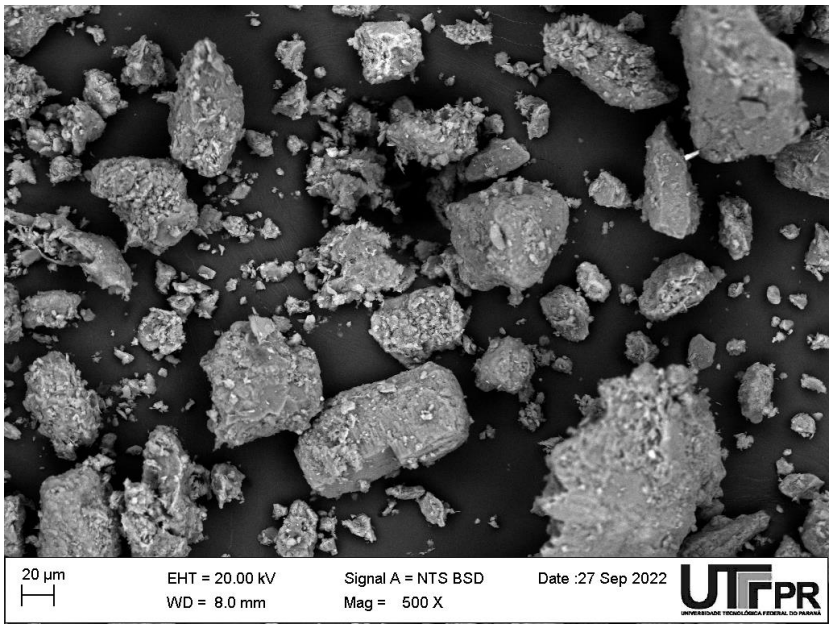
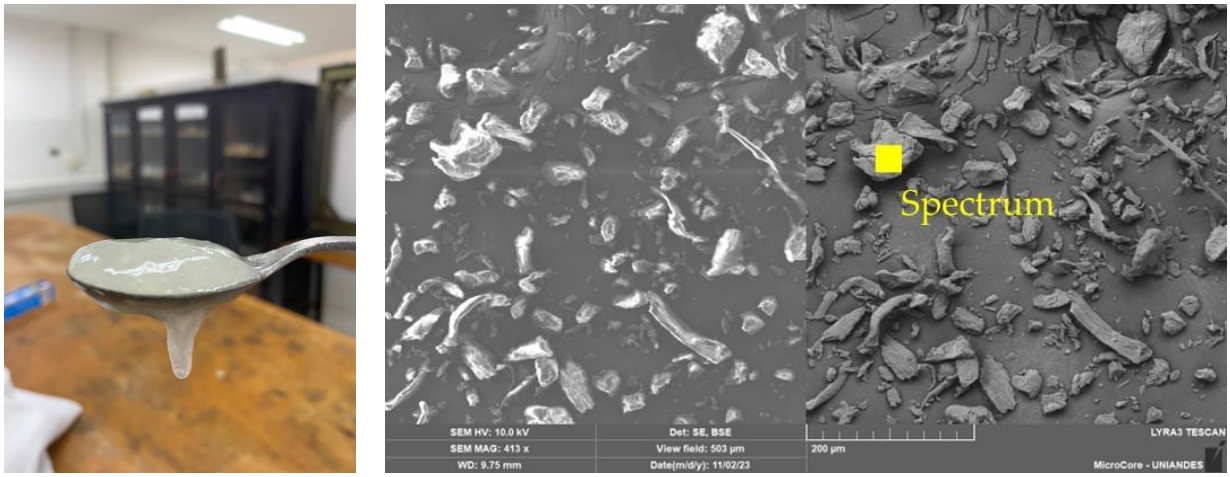


Figure 11. Clay morphology was recorded in the SEM analysis.

The xanthan gum used was acquired from a local distributor. A quantity of 1 kg was purchased to be sufficient to conduct all experiments. Xanthan gum (XG) used in this study is a polysaccharide secreted by the bacterium *Xanthomonas campestris*. It consists of pentasaccharide repeat units comprising glucose, mannose, and glucuronic acid in the molar ratio of 2:2:1. The density of XG was measured as 1.5 g/cm^3. The pH of XG was calculated as 6.34, and its viscosity was measured as 1200 MPa·s. XG is sparingly soluble in cold water and completely soluble in warm water; therefore, it was solubilized in warm water for this study. Figure 12a illustrates the appearance of XG solubilized in water at a 1% mass concentration, and Figure 12b shows the morphology of the undissolved powder particles. The energy-dispersive X-ray spectroscopy (EDX) analysis was also conducted to determine the chemical composition in the selected spectrum (see Figure 13). The following chemical elements were detected: 54.05% C, 43.47% O, 1.59% Na, and 0.89% Ca.



(**a**) (**b**)

Figure 12. (**a**) Xanthan gum in water after mixing; (**b**) xanthan gum morphology recorded in the SEM analysis.

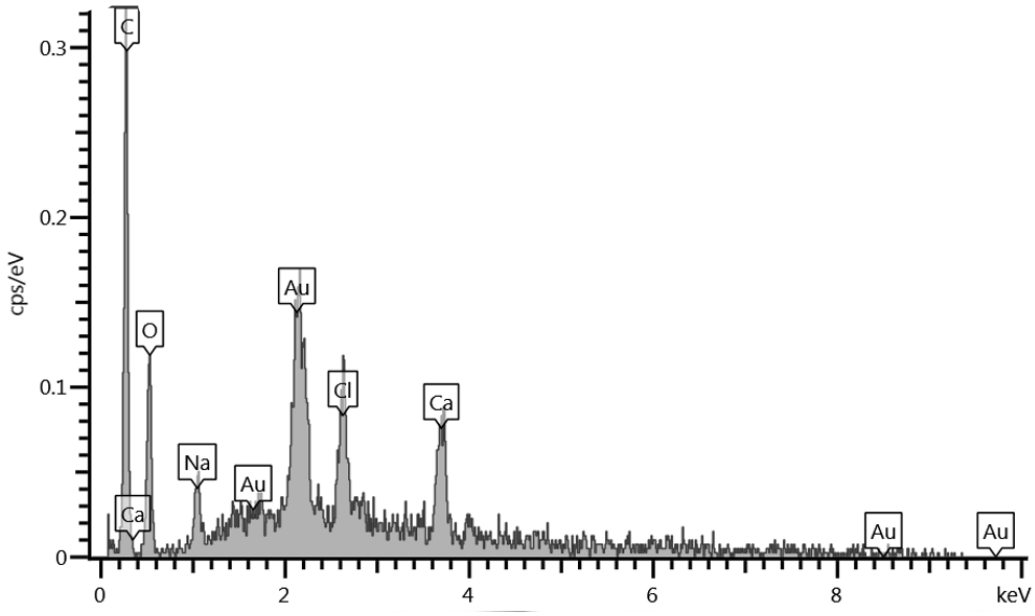


Figure 13. The spectrum recorded in the XG sample (Figure 12b).

To determine the effectiveness of XG addition in clay soil, an experimental program was designed to study the effects of the gum quantity on the mechanical strength, stiffness, and microstructure of the soil.

Specimens for strength and stiffness tests were prepared using a stainless steel mold with a height of 100 mm and a diameter of 50 mm by applying static compaction. The geometry of specimens was chosen in concordance with previously stabilized soil related to the literature, e.g., [64,65]. The silt soil was dried in an oven at 100 ± 5 °C and divided into uniformly dispersed portions to mix with different xanthan gum (XG) contents. Distilled water was used as the liquid in the molding process. The chosen amounts of XG were 1%, 3%, and 5% of the dry mass of the soil. Similar XG contents were used in recent studies [52,53,66].

During the molding of the test specimens, the dry powder quantity of XG was dissolved in water until a viscous mixture was obtained (Figure 12a). Subsequently, the dry soil was taken, and the XG was added in a viscous state until the mixture became homogeneous. Next, the mixture was statically compacted into three equal layers in a

metallic mold with a diameter of 5 ± 0.1 cm and a height of 10 ± 0.1 cm. For each mix and XG content, the samples were compacted in triplicate. The dry unit weights of 17 and 17.5 kN/m^3 were selected as molding densities, considering previous studies [58,67]. Additionally, specimens were cured for 28 days before the tests—unconfined compression tests, scanning electron microscopy, and ultrasonic wave analysis.

After demolding, the weight and dimensions of the specimens were measured. For moisture control, the remaining material was added to three capsules and placed in an oven at 100 °C for at least 24 h. The curing of the test specimens was carried out in a humid chamber with controlled temperature and humidity of 23 °C ± 2 and above 95%, respectively. The specimens were placed on flat glass plates slightly inclined to prevent water accumulation at the base. To prevent suction from becoming an uncontrolled variable in the test, the specimens were submerged in water for 24 h one day before reaching the curing time. After saturation, the nondestructive ultrasonic pulse velocity (Vs) test was recorded in each compacted specimen, and the mix (Go) stiffness was calculated, as explained in Figure 14. G_o tests followed the ASTM C597 standard [68] Finally, the strength of the mixtures was evaluated following the ASTM D2166 standard [69] where the specimens were axially loaded (Q) through controlled deformation in a hydraulic press at a speed of 1.14 mm/min until failure in concordance with Figure 14 setup.

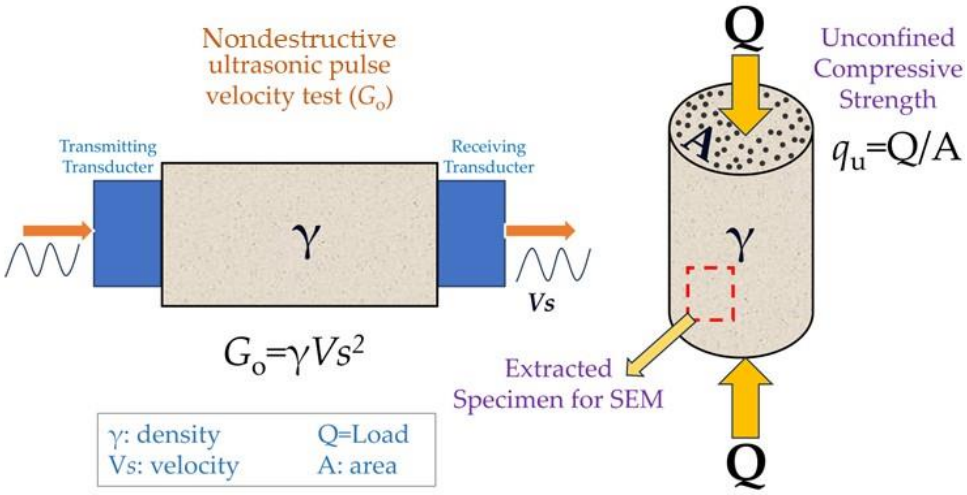


Figure 14. Testing setup for stiffness (G_o), unconfined compressive strength, and microstructural analysis samples.

5.2. Results and Discussions

Figure 15 presents the mechanical behavior of the soil–xanthan gum mixtures considering 1%, 3%, and 5% XG. The behavior of uniaxial compression for each percentage of gum (denoted as XG) was compared. When using 3% XG, the increase was 29% (compared with 1%), while for 5% XG, the increase was 44% compared with 1% gum. A 15% increase was calculated for xanthan gum between 3% and 5%. The increase in resistance was due to xanthan acting as a binding agent (or dry-state gum), forming bonds between soil particles. This enhances cohesion between the particles, resulting in more excellent resistance to simple compression or shear and improved soil-bearing capacity.

Additionally, xanthan has a high capacity for retaining water. Adding xanthan to the soil retains more water in soil pores, aiding in maintaining soil moisture and cohesion. This can prevent excessive soil shrinkage and expansion due to changes in moisture, thereby enhancing its stability and strength.

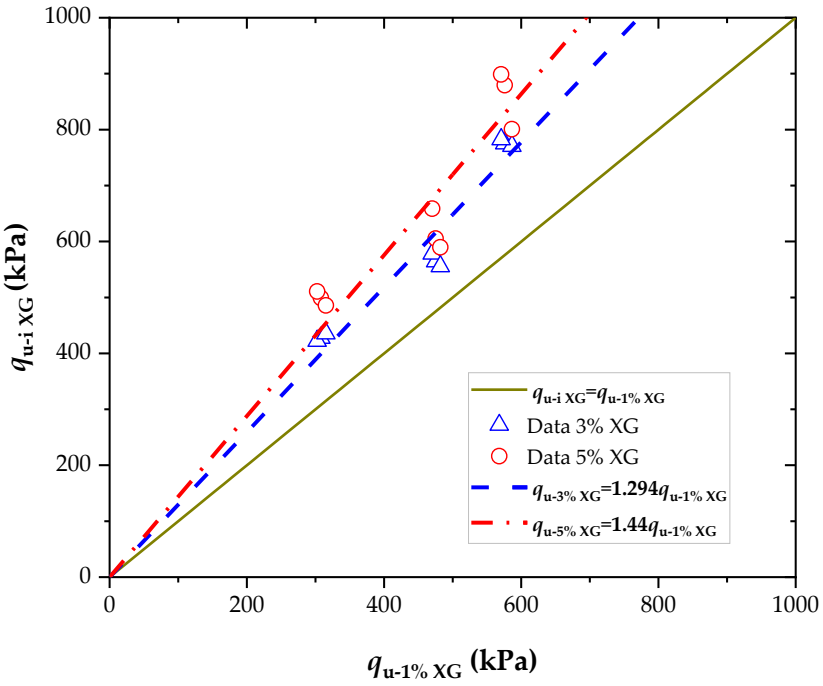


Figure 15. Comparing the influence of xanthan gum addition on unconfined compressive strength of compacted clay.

Figure 16 presents the initial stiffness behavior at small deformations of the soil–xanthan gum mixtures considering 1%, 3%, and 5% XG. The stiffness behavior for each percentage of gum (denoted as Go-i $_{XG}$) was compared. The increase in stiffness when using 3% XG was 36% (compared with 1%), while for 5% XG, the increase in G_o was 57% compared with 1% gum. Additionally, a 21% increase in G_o was calculated for xanthan gum between 3% and 5%. Comparing the results of the increase in G_o and q_u, it can be analyzed that the increase in stiffness is more significant than the increase in compressive strength. This is mainly due to soil densification from adding xanthan gum, which clogs the voids. Xanthan gum (XG) is a biopolymer known for its ability to increase the viscosity of solutions, demonstrating this property across wide temperature ranges (withstanding up to 383 °C) and within a pH range of 2 to 12 [70]. Of the total amount of xanthan produced globally, it is estimated that 65% is applied in the food industry where it is used as a stabilizing, emulsifying, and thickening agent in foods. Another 15% is used in the petroleum industry, with the remaining percentage used in various applications [54]. Recent studies suggest that xanthan can also be applied in geotechnical engineering where it can improve the mechanical properties of soils. Chang et al. [53] investigated two different mixing methods, the dry method (xanthan powder is directly mixed into the soil) and the wet method (xanthan is mixed in water, and the solution is subsequently added to the soil), on a soil referred to as red yellow to study compressive strength at 3, 7, 14, 21, and 28 days of curing for an XG concentration of 1%. This study suggests that the dry method is more efficient, resulting in higher compressive strength values for different curing times than the wet method.

The evolution of XG effects on the strength of compacted clay can be analyzed using the proposed porosity/cement index and change to voids/xanthan gum index (η/C_{iv}). The parameter voids/xanthan gum factor correlates the porosity of the compacted mixture (η) with the volumetric content of xanthan gum (C_{iv}) adjusted by the internal exponent x (as a cement–clay mix). Consequently, this correlation facilitates determining the power–type relationship, as Equation (1) indicates.

$$q_u = A_i \left[\frac{\eta}{(C_{iv})^x} \right]^{-B} \quad (1)$$

where q_u is the unconfined compressive strength, A_i is a constant in kPa, and B and x exponents depend on soil type and XG properties. For example, in soil–cement mixtures, the constant A_i in Equation (1) holds significant theoretical importance as it is contingent upon various factors that influence the strength behavior of the mixture. These factors encompass the soil's critical state strength ratio, the uniaxial compressive strength of the cement, the cement stress ratio, the porosity at a critical state, and the ratio between unconfined compression and extension strengths. The exponents B and x play a pivotal role in characterizing the relationship between soil and cement properties and the strength behavior of the mixture. Diambra et al. [71,72] investigated this relationship and noted that the values of x and B are primarily contingent upon soil characteristics, with x being approximately the inverse of B ($x \approx 1/B$). Furthermore, the scalar A_i is influenced by the properties of both the soil and the cementitious matrix. Also, the evolution of XG effects on the G_o of compacted clay can be analyzed using the proposal porosity/cement index as presented by Equation (2).

$$G_o = Ag\left[\frac{\eta}{(C_{iv})^x}\right]^{-B} \quad (2)$$

where Ag is a constant in MPa depending on soil XG properties; within each η/C_{iv} value, minor differences in the average small strain stiffness were discernible across the tested dosages.

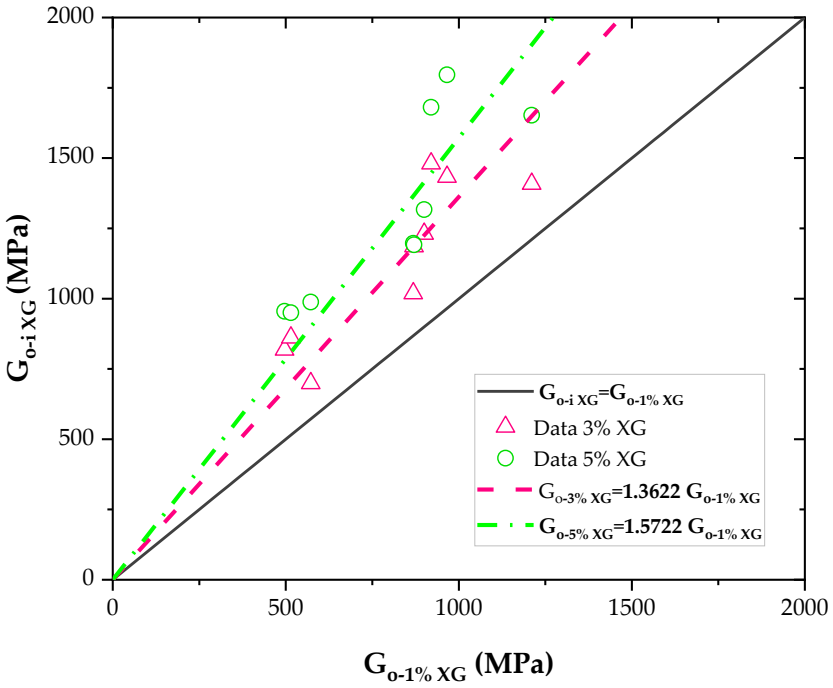


Figure 16. Comparing the influence of xanthan gum addition on stiffness (G_o) of compacted clay.

Figure 17 presents the evolution of the unconfined compressive strength of the soil–xanthan gum mixtures during 28 days of curing adjusted to the porosity/cement ratio (raised to an exponent of 0.04). Regarding cemented soils, the exponent value is typically 0.28 (Portland cement), but as observed in Figure 17, this adjusted value for xanthan gum is 0.04. This indicates that the porosity value exerts greater significance in developing the compression of the geomaterial. To compensate for this, a higher percentage of xanthan gum must be added to try to equalize the influence of the soil voids. Equation (3) describes the q_u values in kPa depending on η/C_{iv} index. The value of B = −5.29 and x = 0.04.

$$q_u = 119.35 \times 10^9 \left[\frac{\eta}{(C_{iv})^{0.04}}\right]^{-5.29} \left(R^2 = 0.96\right) \quad (3)$$

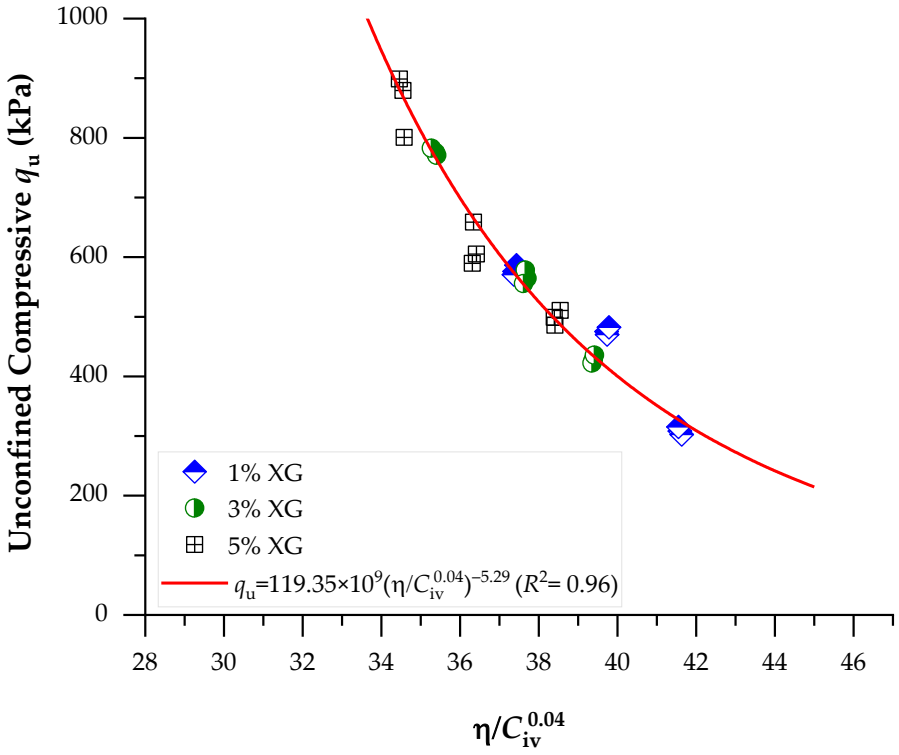


Figure 17. Impact of porosity-to-xanthan gum index on unconfined compressive strength of bio polymerized clay.

Figure 18 presents the variation of the initial stiffness of the soil–xanthan gum mixtures during 28 days of curing adjusted to the porosity/cement ratio (raised to an exponent of 0.04). Similarly to uniaxial compression, the calculated exponent for stiffness is 0.04. In physical-mechanical terms, porosity exerts a more significant influence on the development of the geomaterial's stiffness than xanthan gum. Equation (4) describes the G_o values in MPa depending on η/C_{iv} index. The value of B = −5.29 and x = 0.04.

$$G_o = 228.76 \times 10^9 \left[\frac{\eta}{(C_{iv})^{0.04}}\right]^{-5.29} \left(R^2 = 0.93\right) \quad (4)$$

If Equations (3) and (4) are divided (in the same magnitudes MPa), a scalar is computed in Equation (5). The calculated scalar is 1976.72, where G_o can be recorded with q_u assumptions.

$$\frac{G_o}{q_u} = 1916.72 \quad (5)$$

Figure 19 presents the direct (empirical) relationship between uniaxial compression and initial stiffness at small deformations of the soil–xanthan gum mixtures. Additionally, this result has been compared with the empirical relationship calculated by Roman et al. [58] for soil-crushed limestone–cement mixtures. Roman et al. used the same soil applied in this research. It is noted that the coefficient for the soil–xanthan gum mixtures is 1915.3 times the value of uniaxial compression. For the soil–cement mixtures, this value is 4828.8, which is expected as the material with cement is stiffer. However, the stiffness of xanthan gum increases with its content in the soil.

$$G_o = 1915.3 q_u \left(R^2 = 0.98\right) \quad (6)$$

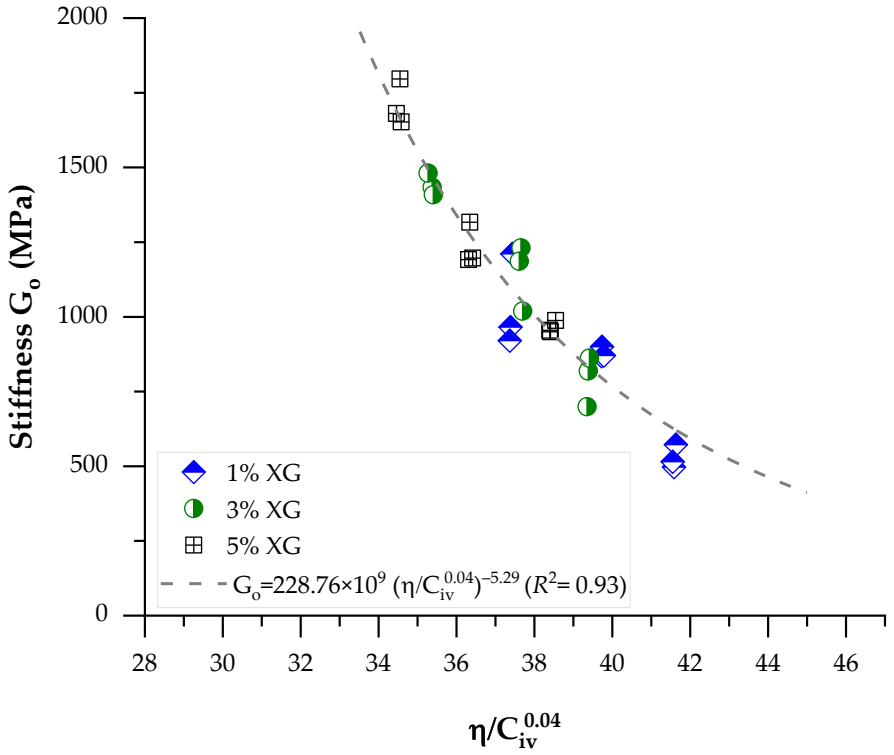


Figure 18. Impact of porosity-to-xanthan gum index on the initial stiffness of the soil–xanthan gum mixtures.

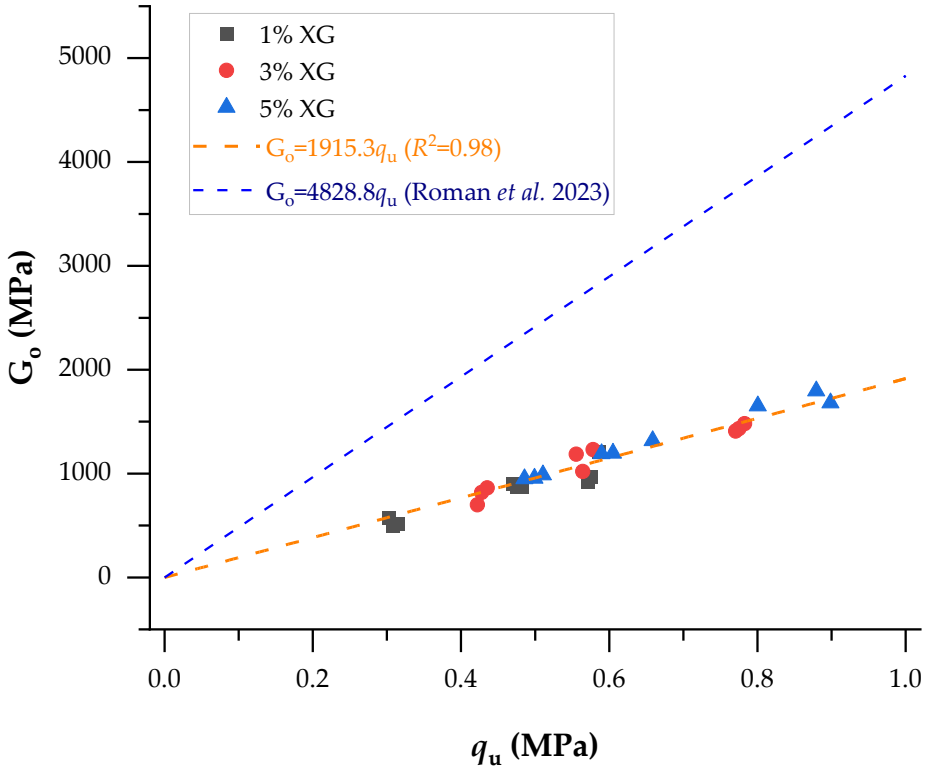


Figure 19. The direct relationship between unconfined compressive strength and G_o of compacted clay [58].

In Equation (5), the scalar calculated as a function of the porosity/cement index is 1916.72, which is very close to the one obtained directly from Figure 19. This means that

the relationship between both values (G_o and unconfined compressive strength) is not dependent on the quantity of xanthan gum or dry unit weight.

In order to identify the presence of xanthan in biostabilized soil and to compare the soil structure and chemical constituents between samples without stabilization and with stabilization, the SEM-EDX assay was conducted. For this purpose, samples containing 3% xanthan were subjected to analysis. Thus, Figure 20 shows a scanning electron microscope (SEM) image of an XG (xanthan gum)-biopolymerized clay sample with a 3% addition at an amplification of 20,000 times. The formation of Xanthomonas campestris bacteria, characteristic of XG, is observable in the image. The soil morphology appears to be covered by small, dissolved sheets of XG, which reduce porosity and enhance the mechanical resistance and rigidity of the clay. Figure 21 presents the chemical analysis of the spectrum of the SEM image (Figure 20). In addition to carbon and oxygen, sodium, calcium, and chlorine were found among the chemical elements, indicating an increase in the amount of carbon compared with the unstabilized sample. Also, observing the bonds formed between the biopolymer and the soil particles is possible.

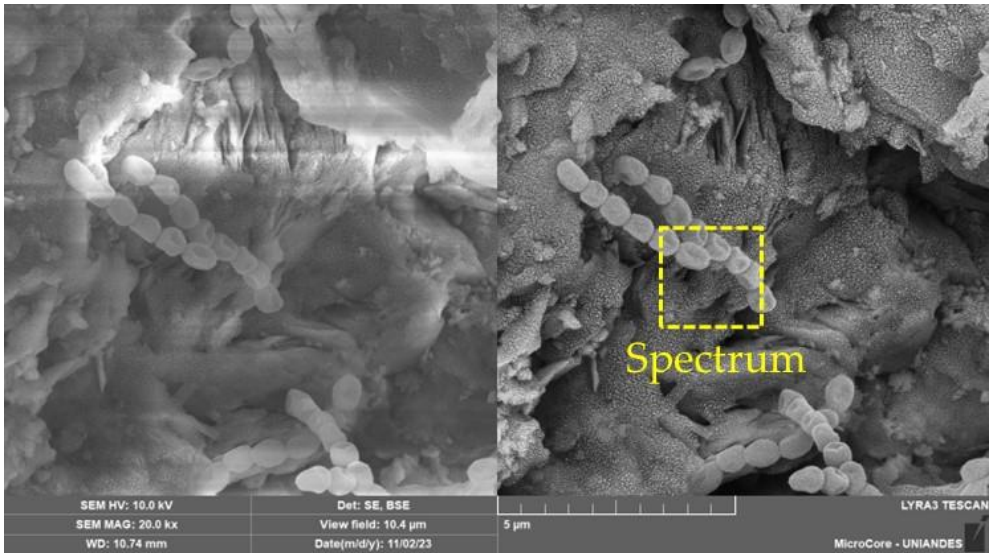


Figure 20. Clay–XG morphology was recorded in the SEM-EDX analysis.

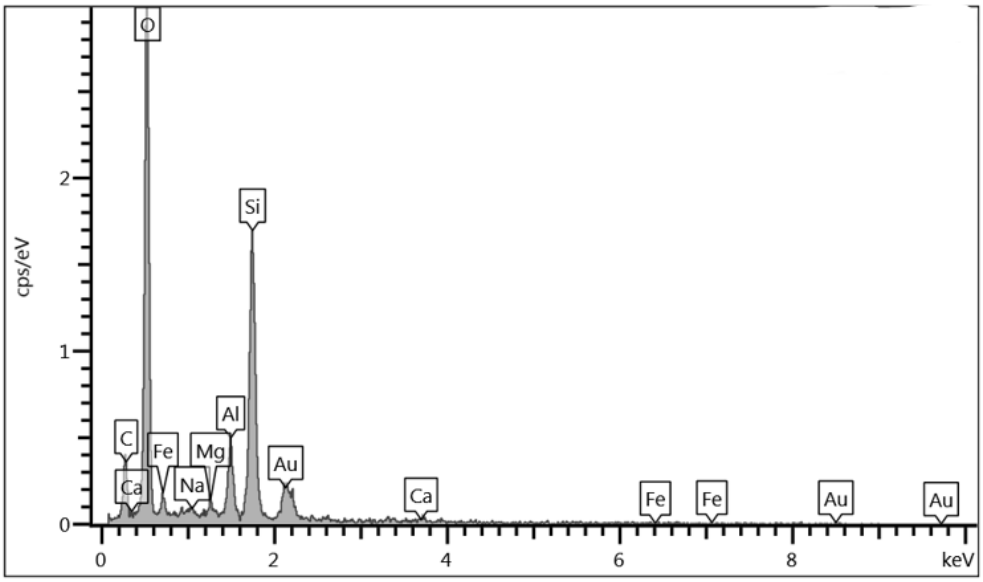


Figure 21. The spectrum recorded in the clay–XG mix is analyzed in Figure 19.

Figure 22 shows a scanning electron microscope (SEM) image of an XG (xanthan gum)-biopolymerized clay sample with a 1% addition at an amplification of 600 times, in smaller amplitude than Figure 20, to show the macrostructure of the mixture. Comparison between the untreated soil (Figure 11) and Figure 22 reveals significant particle agglomeration in 28-day-cured samples treated with 1.0% XG biopolymer. Moreover, a notable reduction in voids is observed compared with the untreated soil (more details of the microstructure of compacted untreated soil in [58,73]). These SEM images provide compelling evidence of the soil-strengthening mechanism facilitated by XG treatment. This mechanism is attributed to the direct interaction between clay particles and xanthan monomers through hydrogen bonding and electrostatic interactions. The electrically charged clay particles promote the interaction of XG monomers with flaky clay sheets via hydrogen bonding and cation bridging.

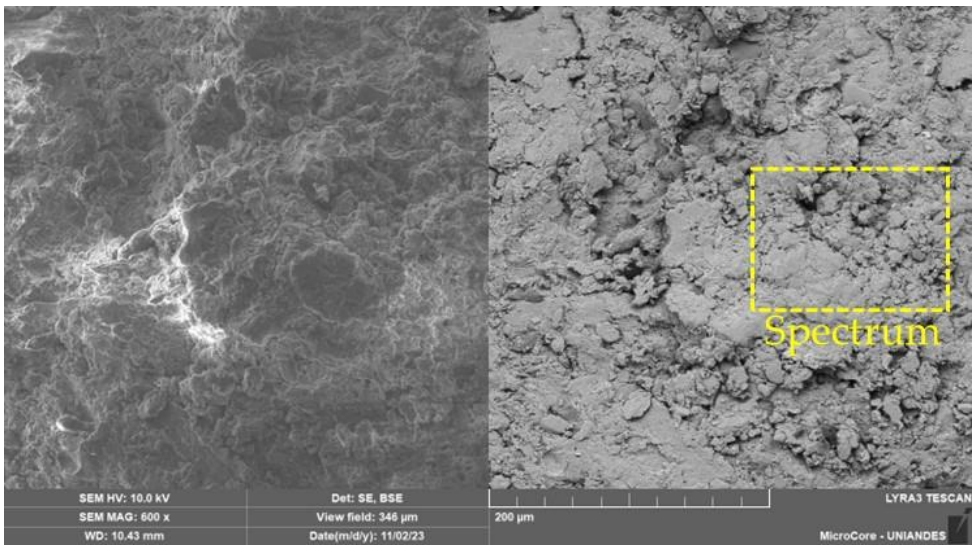


Figure 22. Superficial clay–XG morphology was recorded in the SEM-EDX analysis at the magnification of 600×.

Additionally, the xanthan monomers serve as bridges between distant particles, further enhancing soil cohesion [66]. Figure 23 presents the spectrum recorded in the clay–XG mix is analyzed in Figure 22. The EDX analysis detected silicon, magnesium, oxygen, and sodium. In sands, for example, Chang et al. [53] concluded that XG enlarges the contact surface area between soil particles and establishes bridging connections between spatially distant particles. This underscores the pivotal role of the strength of the xanthan gum fiber matrices—manifested in the form of threads or fabrics—present within the pore structure in determining the strength properties of xanthan-treated coarse-grained soils. In the present study, SEM analysis validates the aggregation of particles and the development of gel-like cementitious substances, resulting in a discernible enhancement of q_u and G_o.

Xanthan gum enhances the microstructure of clay by augmenting its cohesion, diminishing porosity, and ameliorating soil stability. Occupying the interstitial voids among clay particles engenders a cohesive matrix that elevates the soil's water resistance and structural stability, thereby mitigating erosion and enhancing water retention within the soil. Sulaman et al. [42] investigate the role of xanthan gum biopolymer in enhancing soil properties, primarily focusing on sustainable soil improvement practices. The findings reveal a direct correlation between the concentration of xanthan gum and the duration of curing, indicating notable enhancements in soil compressive strength and cohesion while reducing the internal friction angle. Despite the potential detrimental effects of wetting/drying cycles on soil strength, the soil treated with biopolymer consistently demonstrates superior strength compared with untreated soil samples. These findings offer valuable insights into practical engineering applications, highlighting the efficacy of biopolymer treatments in bolstering

soil stability and resilience. Oliveira et al. [74] explore the influence of organic matter (OM) on the effectiveness of soil stabilization using xanthan gum biopolymer. By examining five artificial soils containing OM levels ranging from 1.5% to 7.7%, the research conducts UCS (unconfined compressive strength) and oedometer tests to evaluate strength, stiffness, and compressibility parameters. The results, complemented by SEM (scanning electron microscopy) analysis, unveil that soil stabilization enhances strength and stiffness up to an OM content of 5.5%. However, beyond 7.7% OM, stabilization efficacy diminishes, likely attributable to increased hydration of hydrogels and subsequent heightened compressibility. Oedometer tests further illustrate a significant decrease in consolidation coefficient and an elongation of primary consolidation time with xanthan gum stabilization, underscoring the complex interplay between OM content, xanthan gum, and soil stabilization processes.

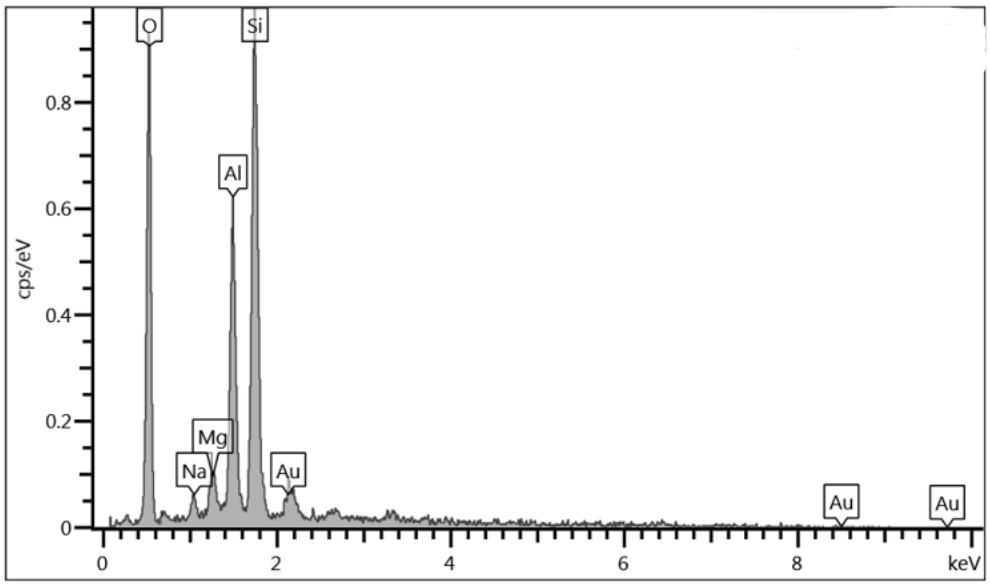


Figure 23. The spectrum recorded in the clay–XG mix is analyzed in Figure 22.

6. Future Implications

Future research should focus on exploring combinations of the evaluated stabilizing agents, such as natural latex, lignosulfonate, xanthan gum, and eggshell lime, to identify synergies that could further enhance the mechanical strength of soils. Some catalysts, such as sodium hydroxide or increasing the curing temperature to 40 degrees, as discussed in recent studies by Consoli et al. [75,76], may aid in this process. Additionally, further studies on optimal proportions and mixing conditions could reveal combinations that offer significant advantages in terms of durability and sustainability [16,77,78]. Simultaneously, conducting detailed studies on the energy efficiency and CO_2 emissions associated with producing these stabilizers is crucial. Research focusing on improving production processes to reduce emissions and energy consumption would be highly beneficial.

Moreover, future studies should include evaluations of the long-term durability of soils stabilized with these agents under various environmental and loading conditions. Recent studies have demonstrated the increasing durability of geomaterials, for example, in moisture–drying and freeze–thaw cycles in cold regions [31,76]. This would include tests in different climates and exposures to moisture–drying and freeze–thaw cycles. American standards ASTM D559 [79] and ASMT D560 [80] establish criteria for the durability of these new geomaterials. At the same time, conducting a comprehensive assessment of their environmental impact and potential toxicity is essential. Research focusing on the long-term effects of these materials on soil and groundwater is vital to ensure they do not present ecological risks.

Another promising research direction is the performance of these stabilizers in a broader range of soils, including expansive, clayey, and sandy soils. This will help better

understand the applicability and limitations of each stabilizer in different geotechnical contexts. Additionally, integrating advanced technologies such as numerical modeling and simulation can provide a deeper understanding of how these stabilizers affect soil properties at the microstructural level. Advanced characterization techniques such as micro-computed tomography (micro-CT) and Raman spectroscopy could reveal crucial details about the interaction between the stabilizers and soil particles.

From a practical perspective, the studied stabilizers can offer viable and sustainable solutions for infrastructure construction, such as roads, bridges, and buildings in areas with problematic soils. Their ability to improve soil strength and stability can reduce the need for traditional and costly construction materials, such as cement and steel, lowering construction costs and the carbon footprint of construction projects [81]. Furthermore, these materials have great potential in rehabilitating existing infrastructures. They can stabilize slopes, reinforce foundations, and repair damage in old structures, extending their useful life and improving safety.

Research on these stabilizers can also lead to the development of new advanced geomaterials that not only enhance the mechanical properties of the soil but are also self-sustaining and environmentally friendly. This can open up new opportunities in designing and constructing sustainable infrastructures. Likewise, implementing these stabilizing agents can optimize construction processes by allowing the use of local soils that would otherwise be unsuitable for construction. This reduces the need to transport large volumes of construction materials, which is costly and generates significant CO_2 emissions [4,22].

To fully leverage the advantages of these stabilizers, it will be necessary to develop training and education programs for engineers and construction workers. This will ensure that the new techniques and materials are used correctly and efficiently in the field. However, it is important to consider limitations and areas for further research. The inherent variability in the properties of natural materials, such as latex and xanthan gum, can affect the consistency and predictability of results [52]. Therefore, additional studies should focus on standardizing the properties of these materials and developing methods to mitigate variability.

While experimental results are promising, the scalability and economic viability of producing and applying these stabilizers in large-scale projects must be investigated. This includes detailed cost analyses and case studies in real projects. Moreover, the interaction between these stabilizers and other construction materials, such as chemical additives, geotextiles, and other soil stabilizers, must be studied to ensure compatibility and optimize stabilized soil performance [6,82]. Finally, the long-term effects of these materials on the environment and human health need to be evaluated to ensure they do not pose risks. Research including toxicological and long-term degradation studies is essential for widespread acceptance.

7. Conclusions

Based on the bibliometric analysis, literature review, and experimental case presented, the following conclusions can be drawn:

- The bibliometric analysis reveals a clear trend in scientific production, with XG emerging as the most extensively studied binder, followed by eggshell lime. Despite their relatively recent adoption since 2015, these alternatives have garnered substantial attention within the research community. Conversely, although studied since 2013, lignosulphonate has exhibited lower productivity, potentially due to its limited geographical production scope, primarily concentrated in Asia. A notable development is the recent utilization of NBL for soil improvement, with its first documented use in 2020 and a notable increase in research output by 2023, surpassing that of LS despite its more extended application history. This underscores a shifting focus toward novel materials in soil stabilization research, with NRL emerging as a promising candidate warranting further investigation.

- The experimental study presented on the influence of xanthan gum (XG) on the strength and stiffness of biostabilized clay demonstrates that with XG percentages ranging from 1 to 3%, a substantial increase in soil strength can be achieved, up to 44% and 55% for the parameters q_u and G_o, respectively. Moreover, given the limited global production of XG, small percentages close to or less than 1% are recommended in the literature. In the study, the increases in strength and stiffness can reach up to 20%. This aligns with existing literature where similar strengths to those found with the clay studied here have been reported.
- In the biostabilized soil, the SEM images depict the formation of bonds attributed to the presence of the biopolymer xanthan. These bonds play a crucial role in enhancing the cohesion and stability of the soil matrix. Additionally, the SEM-EDX results indicate a notable increase in the concentration of carbon and oxygen within the biostabilized soil compared with the non-stabilized soil. The elevated carbon and oxygen levels can be attributed to the incorporation of xanthan, which is rich in these elements, during the biostabilization process. This increase in carbon and oxygen content further corroborates the successful integration of xanthan into the soil matrix.
- In concordance with the bibliografic review, the novelty exploration of materials for soil improvement, such as natural latex, lignosulfonate, xanthan gum, and eggshell lime, underscores the ongoing pursuit within civil engineering to enhance the mechanical strength of geomaterials. The comprehensive literature review and analysis conducted in this study shed light on the potential of these materials yet also highlight areas for further exploration, particularly in understanding underlying mechanisms and conducting thorough cost-benefit and environmental impact assessments. By addressing these imperatives, future research endeavors are poised to enhance our understanding and elevate the efficacy and sustainability of soil enhancement methodologies within civil engineering.

Author Contributions: Conceptualization, J.d.J.A.B., O.P.C. and M.S.; methodology, J.d.J.A.B., O.P.C. and M.S.; validation, J.d.J.A.B. and M.S.; formal analysis, J.d.J.A.B.; investigation, J.d.J.A.B., O.P.C. and M.S.; resources, O.P.C.; writing—original draft preparation, J.d.J.A.B. and M.S.; writing—review and editing, J.d.J.A.B. and O.P.C.; visualization, M.S.; supervision, J.d.J.A.B.; funding acquisition, O.P.C. All authors have read and agreed to the published version of the manuscript.

Funding: The Fundación Universitaria Los Libertadores—Colombia (FULL) (Project No. ING-07-24) funded the APC.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Acknowledgments to the Materials Characterization Multiuser Laboratory—UTFPR (CMCM) for the SEM-EDS services.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Bibliographic Review of the Effects of LS, Xanthan Gum, Natural Rubber Latex, and Eggshell Limes in the Geotechnical Properties of Treated Soils

Material	Addition (%)	OMC (%)	MDD (gm/cc)	CBR (%)	UCS 28 Days MPa	ΔUCS (%)	Shear Tests	ΔTs	Microstructure	Petrography	Observations	Ref.
Lignosulphonate	0.0	19.0	1.7	2.3	0.3		–	–	SEM	–	The results showed that the untreated soil had a CBR of 2.27%, while the soil with 45% additives achieved a CBR of 5.05%. Introducing 50% additives resulted in performance levels of 30.21%, 17.42%, and 12.82% for (a) liquid limit, (b) plastic limit, and (c) plasticity index, respectively. Additionally, the inclusion of the stabilizers significantly enhanced the mechanical properties of the soil.	[82]
	5.0	18.0	1.7	3.7	0.3	10.7	–	–		–		
	5.0	17.7	1.8	3.9	0.4	32.1	–	–		–		
	10.0	17.0	1.8	4.4	0.4	35.7	–	–		–		
	20.0	16.4	1.8	4.9	0.4	35.7	–	–		–		
	30.0	15.3	1.9	5.2	0.4	42.9	–	–		–		
	40.0	14.2	2.0	5.1	0.4	42.9	–	–		–		
	45.0	12.5	2.0	5.1	0.4	46.4	–	–		–		
	50.0	10.8	2.1	6.7	0.4	46.4	–	–		–		
	0.0	22.2	1.6	–	0.2		–	–	SEM + XRD	–	Limitations of lignosulphonate as a stabilizer for expansive soil were identified. An extensive experimental investigation was conducted on a proposed composite binary admixture (CBA) with hydrated lime aimed at improving the geotechnical characteristics of expansive soil. The optimal binary admixture (OBA) was identified based on the plasticity index.	[12]
	0.4	22.2	1.6	–	0.2	7.8	–	–		–		
	0.9	22.2	1.6	–	0.2	10.4	–	–		–		
	2.0	22.2	1.6	–	0.2	14.3	–	–		–		
	0.8	22.5	1.6	4.5	N/A	N/A	–	–	SEM + XRD	–	The CBR values of both untreated and LS-treated soil samples decreased significantly by 86% and 75.6%, respectively, when soaked, compared with their unsoaked states. The LS treatment was determined to be chemically inert, with stabilization primarily reliant on intermolecular interactions. Analysis of pavement thickness revealed that both untreated and LS-treated soils were unsuitable for pavement construction and would necessitate the addition of an extra sand cushion layer.	[83]
	0.0	21.3	1.6	–	0.3	–	0.2	–	SEM	–	As compaction moisture content increased, strength parameters decreased for both treated and untreated soils. LS stabilization resulted in a decrease in both swell percentage and swell pressure of the expansive clay. Additionally, the stabilization led to a reduction in the soil's plasticity index, thereby changing the soil expansivity category from high to moderate. These enhancements in soil properties can be attributed to the electrostatic reaction between the LS–water mixture and soil particles, promoting soil aggregation.	[84]
	0.5	21.4	1.6	–	0.4	33.9	0.3	13.2		–		
	0.8	21.5	1.6	–	0.4	42.9	–	–		–		
	1.0	21.6	1.6	–	0.4	25.0	–	–		–		
	2.0	21.9	1.6	–	0.3	21.4	–	–		–		
	3.0	22.1	1.6	–	0.3	14.3	–	–		–		
	4.0	22.3	1.6	–	0.3	5.4	–	–		–		

Material	Addition (%)	OMC (%)	MDD (gm/cc)	CBR (%)	UCS 28 Days MPa	ΔUCS (%)	Shear Tests	ΔTs	Microstructure	Petrography	Observations	Ref.
Lignosulphonate	0.0	22.9	1.6	–	0.2	–	–	–	SEM + XRD	–	The treated soil demonstrates an average strength improvement of approximately two times when an optimal LS content of 1.5% is applied. Moreover, the treated soil exhibits a notable reduction in both swell potential and swell pressure compared with the untreated soil. This manuscript predominantly explores the behavior of expansive soil amended with LS concerning strength and swelling characteristics, as well as the method to enhance the interaction mechanism between LS and soil composites.	[9]
	0.5	22.9	1.6	–	0.5	104.5	–	–		–		
	1.5	22.9	1.6	–	0.5	122.7	–	–		–		
	3.0	22.9	1.6	–	0.4	86.4	–	–		–		
	6.0	22.9	1.6	–	0.4	93.2	–	–		–		
	0.0	18.0	1.4	–	0.2	–	–	–	SEM	–	The findings suggest that lignosulfonate has a notable impact on the strength characteristics of expansive soils. The optimal percentage of lignosulfonate is determined by the fine content in the soils. Treatment with lignosulfonate led to a decrease in the negative surface charge of the soils and the development of a polymer chain microstructure, along with a microstructure of flocculated or aggregated particles. These changes potentially contribute to the improved strength of the expansive soils.	[49]
	0.0	19.0	1.7	–	0.2	–	–	–		–		
	0.5	18.0	1.4	–	0.2	11.8	–	–		–		
	0.5	19.0	1.7	–	0.3	40.9	–	–		–		
	1.0	18.0	1.4	–	0.2	14.7	–	–		–		
	1.0	19.0	1.7	–	0.3	47.7	–	–		–		
	2.0	18.0	1.4	–	0.2	17.6	–	–		–		
	2.0	19.0	1.7	–	0.3	40.9	–	–		–		
	4.0	18.0	1.4	–	0.2	32.4	–	–		–		
	4.0	19.0	1.7	–	0.3	27.3	–	–		–		
Natural Rubber Latex	0.0	7.8	2.8	–	4.7	–	–	–	SEM+XRD	–	This study investigates the influence of Natural rubber latex (NRL) on the strength development of cement-stabilized lateritic soil (LS) blends with steel slag (SS) as a sustainable pavement base. Various SS replacement ratios and dry rubber to cement (r/c) ratios were examined. The r/c ratio significantly affected the compactability and unconfined compressive strength (UCS). Microstructural analysis revealed that increasing NRL content decreased the degree of cement hydration due to NRL film retardation; yet, at optimal r/c ratios, a balance between cement hydration and NRL films enhanced interparticle bond strength, leading to UCS development. Although optimal r/c ratios varied, NRL's percent improvement remained consistent. The r/c ratio emerged as a crucial factor influencing interparticle bond strength, facilitating the development of a cost-effective and time-saving relationship between UCS and ITS for geotechnical and pavement engineering design, showcasing the effective utilization of NRL and recycled materials in sustainable pavement applications.	[38]
	3.0	8.0	2.9	–	5.2	10.6	–	–		–		
	5.0	8.1	2.8	–	5.1	8.5	–	–		–		
	10.0	8.4	2.8	–	4.9	4.3	–	–		–		
	15.0	8.6	2.5	–	4.8	2.1	–	–		–		
	0.0	7.8	2.5	–	4.0	–	–	–		–		
	3.0	7.9	2.5	–	4.5	10.6	–	–		–		
	5.0	7.9	2.4	–	4.1	2.1	–	–		–		
	10.0	8.1	2.4	–	3.9	−2.1	–	–		–		
	15.0	8.2	2.4	–	3.8	-4.3	–	–		–		

Material	Addition (%)	OMC (%)	MDD (gm/cc)	CBR (%)	UCS 28 Days MPa	ΔUCS (%)	Shear Tests	ΔTs	Microstructure	Petrography	Observations	Ref.
Natural Rubber Latex	0.0	8.1	2.1	18.2	2.9	–	–	–	–	–	Exploring the integration of natural rubber latex (NRL) as an eco-friendly supplement in cement stabilization of base courses reveals enhanced short- and long-term performance. Cement–NRL combinations exhibit superior unconfined compressive strength (UCS) compared with cement alone across various cement contents and NRL replacement rates, attributed to synergistic effects between cement hydration and latex film formation, with peak UCS achieved at specific NRL replacement ratios.	[39]
	10.0	8.1	2.1	18.2	3.2	10.3	–	–		–		
	15.0	8.1	2.1	18.2	3.5	20.7	–	–		–		
	20.0	8.1	2.1	18.2	3.9	34.5	–	–		–		
	25.0	8.1	2.1	18.2	3.6	24.1	–	–		–		
	30.0	8.1	2.1	18.2	3.2	10.3	–	–		–		
	0.0	9.2	2.0	13.0	2.5	–	–	–		–		
	10.0	9.2	2.0	13.0	3.0	20.0	–	–		–		
	15.0	9.2	2.0	13.0	3.1	24.0	–	–		–		
	20.0	9.2	2.0	13.0	3.2	26.0	–	–		–		
	25.0	9.2	2.0	13.0	3.0	20.0	–	–		–		
	30.0	9.2	2.0	13.0	2.9	14.0	–	–		–		
	0.0	12.0	1.9	–	3.2	–	–	–	SEM + XRD	–	This study examines the impact of natural rubber latex (NRL) on the performance of cement-stabilized recycled concrete aggregate (RCA) for pavement bases. Factors such as various cement contents and dry rubber-to-cement (r/c) ratios were analyzed. NRL replacement improved the unconfined compressive strength (UCS) and indirect tensile strength (ITS) of cement-stabilized RCA, with peak values observed at optimal r/c ratios. Microstructural analysis revealed cement hydration products and NRL films, which enhanced adhesion and interparticle bonds. However, excessive NRL hindered cement hydration, resulting in lower UCS and ITS beyond optimal r/c ratios, though still meeting base material requirements.	[85]
	5.0	11.9	1.9	–	3.3	1.6	–	–		–		
	10.0	11.5	1.8	–	3.7	15.6	–	–		–		
	15.0	10.6	1.8	–	3.5	9.4	–	–		–		
	0.0	12.3	1.9	–	4.8	–	–	–		–		
	5.0	12.1	1.9	–	5.8	20.8	–	–		–		
	10.0	11.8	1.9	–	4.9	2.1	–	–		–		
	15.0	11.4	1.9	–	4.1	−15.6	–	–		–		
	0.0	12.5	1.9	–	6.8	–	–	–		–		
	5.0	12.4	1.9	–	6.9	1.5	–	–		–		
	10.0	11.5	1.9	–	6.8	0.0	–	–		–		
	15.0	11.2	1.9	–	6.2	−8.8	–	–		–		

Material	Addition (%)	OMC (%)	MDD (gm/cc)	CBR (%)	UCS 28 Days MPa	ΔUCS (%)	Shear Tests	ΔTs	Microstructure	Petrography	Observations	Ref.
Xanthan Gum	0.0	14.5	1.8	–	0.2	–	–	–	–	–	The main objective of this study is to investigate how the addition of minimal amounts of biopolymers, specifically xanthan gum and guar gum, influences the physical characteristics of residual soil (at concentrations of 1%, 2%, 4%, and 5%). Parameters such as Atterberg limits, optimal water content, maximum dry density, pH, and specific gravity are analyzed in this research. Additionally, the study experimentally explores the shear strengths of both treated and untreated soil at different curing durations through unconfined compressive strength testing.	[42]
	1.0	14.5	1.8	–	0.2	4.3	–	–		–		
	2.0	14.5	1.8	–	0.3	15.2	–	–		–		
	4.0	14.5	1.8	–	0.3	41.3	–	–		–		
	5.0	14.5	1.8	–	0.4	60.9	–	–		–		
	0.0	14.5	1.8	–	0.2	–	–	–		–		
	1.0	14.5	1.8	–	0.3	13.0	–	–		–		
	2.0	14.5	1.8	–	0.4	52.2	–	–		–		
	4.0	14.5	1.8	–	0.4	56.5	–	–		–		
	5.0	14.5	1.8	–	0.4	73.9	–	–		–		
	0.0	21.7	1.7	–	1.2	–	–	–	SEM + XRD	–	This research investigates how xanthan gum biopolymer enhances soil properties, aiming for sustainable soil improvement. Results indicate that increasing xanthan gum concentration and curing time enhances soil compressive strength and cohesion and reduces internal friction angle. Despite wetting/drying cycles reducing soil strength, biopolymer-treated soil maintains higher strength compared with untreated soil, offering insights for practical engineering applications.	[55]
	0.5	21.7	1.7	–	1.8	45.8	–	–		–		
	1.0	21.7	1.7	–	2.1	75.0	–	–		–		
	2.0	21.7	1.7	–	2.9	141.7	–	–		–		
	0.0	–	–	–	0.02		–	–	SEM	–	This paper examines how the presence of organic matter (OM) impacts the efficacy of soil stabilization using xanthan gum biopolymer. Five artificial soils with OM content ranging from 1.5% to 7.7% undergo UCS and oedometer tests to assess strength, stiffness, and compressibility. Results, supplemented by SEM analysis, reveal that stabilization enhances strength and stiffness up to 5.5% OM but deteriorates beyond 7.7%, likely due to increased hydrogel hydration and subsequent compressibility. Oedometer tests demonstrate a notable reduction in consolidation coefficient and an elongated primary consolidation time with xanthan gum stabilization.	[74]
	1.0	–	–	–	0.04	131.0	–	–		–		
	0.0	–	–	–	0.02		–	–		–		
	1.0	–	–	–	0.05	137.0	–	–		–		
	0.0	–	–	–	0.02		–	–		–		
	1.0	–	–	–	0.06	239.0	–	–		–		
	0.0	–	–	–	0.02		–	–		–		
	1.0	–	–	–	0.06	270.0	–	–		–		
	0.0	–	–	–	0.02		–	–		–		
	1.0	–	–	–	0.01	−54.0	–	–		–		

Material	Addition (%)	OMC (%)	MDD (gm/cc)	CBR (%)	UCS 28 Days MPa	ΔUCS (%)	Shear Tests	ΔTs	Microstructure	Petrography	Observations	Ref.
Xanthan Gum	0.0	–	–	–	–	–	9.0		SEM	–	Kaolinite clay infused with xanthan gum biopolymer exhibits altered consolidation and swelling tendencies. The formation of xanthan gum hydrogels impedes pore spaces, leading to delayed consolidation, heightened energy dissipation, and increased compressibility. Additionally, the interaction between kaolinite and xanthan gum bolsters the undrained shear strength, thereby shortening the consolidation duration needed for specific bearing capacities. This study showcases potential applications in regulating hydraulic conductivity, seismic stabilization, and swift surface reinforcement, albeit requiring supplementary drainage for in situ implementation.	[30]
	0.5	–	–	–	–	–	14.0	55.6		–		
	1.0	–	–	–	–	–	16.0	50.0		–		
	2.0	–	–	–	–	–	–	–		–		
	0.0	18.9	1.7	–	0.2	–	–	–	SEM	–	The study examines the impact of wetting–drying cycles on xanthan gum biopolymer-stabilized soil. Initially, soil mechanical properties decline over the first four cycles, then stabilize. Soil treated with 1.5% xanthan gum exhibits roughly twice the compressive strength compared with untreated soil after 12 cycles, with a wetting–drying-induced strength reduction approximately 20% less than untreated soil.	[29]
	0.5	18.9	1.7	–	0.3	16.7	–	–		–		
	1.5	18.9	1.7	–	0.3	33.3	–	–		–		
Eggshell Lime	0.0	–	–	–	0.3	–	–	–	SEM	–	This study explores the utilization of eggshell-derived calcium acetate in enhancing biocementation through soybean urease-mediated enzyme-induced carbonate precipitation (EICP). By assessing various EICP solution compositions, the research identifies optimal conditions yielding maximal precipitation efficiency and reinforcing effects on sandy soil. Results indicate that a 1:1 molar ratio of $Ca(CH_3COO)_2$ to urea, supplemented with 50 g/L soybean solution, achieves peak precipitation efficiency and yields the highest 7-day unconfined compressive strength (UCS) of 371 kPa, with a calcium carbonate content of 0.40%. Additionally, the eggshell-soybean EICP method exhibits an 8.5% increase in UCS compared with the CaCl2-soybean EICP, despite comparable calcium carbonate content.	[27]
	0.4	–	–	–	0.4	26.2	–	–		–		
	0.3	–	–	–	0.3	18.7	–	–		–		
	0.2	–	–	–	0.3	10.2	–	–		–		
	0.4	–	–	–	0.4	24.8	–	–		–		
	0.0	9.3	2.1	–	2.9	–	–	–	–	–	This experimental investigation assesses the characteristics of geopolymer-based stabilization of lateritic soil incorporating eggshell ash (ESA) and rice husk ash (RHA) for road construction. Findings indicate that increasing ESA content reduces soil plasticity index. While maximum dry density decreases slightly with ESA, RHA, and NaOH additions, unconfined compressive strength (UCS) exhibits a marginal decrease compared with cement stabilization. Among various mixes, combinations such as 3E1R1N and 2E2R1N demonstrate the most cost-effective strength outcomes with lower embodied energy and CO_2 emissions, suggesting geopolymer stabilization as a competitive alternative to cement for roadbase construction.	[28]
	1.0	9.3	2.1	–	3.0	3.4	–	–		–		
	2.0	9.3	2.1	–	3.8	29.3	–	–		–		
	3.0	9.3	2.1	–	4.0	37.9	–	–		–		
	4.0	9.3	2.1	–	2.9	0.0	–	–		–		
	0.0	15.0	1.8	5.0	0.1	–	–	–	SEM	–	The impact of incorporating crushed granulated blast furnace slag and calcined eggshell waste on the mechanical properties of compacted marl was examined. Results reveal a significant enhancement in marl's mechanical properties. Adding 15% of this composite binder increases the CBR index by 22 times. Moreover, notable improvements in cohesion and internal friction angle are noted, particularly over time. SEM analysis identifies the formation of new hydrates (C-S-H) post-treatment, suggesting the effectiveness of calcined eggshell-activated blast furnace slag as a stabilizer for clay soils.	[86]
	5.0	15.0	1.8	35.0	0.3	116.0	–	–		–		
	10.0	15.0	1.8	60.0	0.7	452.0	–	–		–		
	15.0	15.0	1.8	93.0	0.7	452.0	–	–		–		
	0.0	34.8	1.3	–	–	–	–	–	–	–	This study investigates the shear strength characteristics of clay soil treated with a blend of fly ash and eggshell powder geopolymer. The unconsolidated, undrained triaxial test was conducted to assess shear strength. Variations in NaOH molarity, curing time, and eggshell powder to fly ash ratio were examined. Findings suggest that 5% eggshell powder enhances shear strength. Higher NaOH molarity increases shear strength, indicating improved binding effects of the geopolymer. Prolonged curing impacts stabilized soil shear strength. This research underscores the efficacy of eggshell powder geopolymer as a clay soil stabilizer, advocating for its inclusion at a 5% ratio to augment soil shear strength.	[87]
	5.0	34.8	1.3	–	–	–	–	–		–		
	0.0	34.8	1.3	–	–	–	–	–		–		
	5.0	34.8	1.3	–	–	–	–	–		–		
	0.0	34.8	1.3	–	–	–	–	–		–		
	5.0	34.8	1.3	–	–	–	–	–		–		
	0.0	34.8	1.3	–	–	–	–	–		–		
	5.0	34.8	1.3	–	–	–	–	–		–		

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