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Enhancing Soil Quality: A Systematic Analysis of Solutions for Expansive Clays in Scopus Indexed Literature

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ABSTRACT

Significant economic losses and disasters have been recorded worldwide in constructions on soils with clayey minerals due to their low rigidity and resistance. Expansive clay soils in wet conditions have been problematic for civil engineering, especially in heavy structures, increasing improvement costs and time. This research endeavours to analyse the solutions applied to improve the quality of expansive clay soils through the systematisation of information published in the Scopus scientific database, co-occurrence map of keywords, methodological trends, and systematic review for the identification of current pinpoint lacunae and promising avenues for future study. The methodological approach revolves around employing thematic descriptors of expansive clays and soil improvement, applied to the Scopus scientific database, and the analysis statistically applying VOSviewer software, enabling the identification of the primary relationships between countries and researchers. This aim will also encompass the contribution of methodologies for adequately addressing this problem. Subsequently, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was applied, focusing on a systematic review of case studies. The analysis of scientific production revealed an increase in publications during the final period (2015-2023), which included methods implemented for soil improvement. Eco-friendly binders such as stabilisers with residual fibre mixtures, jet grouting, biopolymers, geopolymers, biotechnology, and organic and inorganic materials stand out. China and the United States lead the way in scientific publications due to the high content of clayey soils and the population growth in these countries. Within the systematic review, the use of the chemical method with a predominance of lime showed up in almost all the case studies, increasing the compressive and tensile strength of the material. This research establishes a comprehensive and specific analysis of conventional and current soil improvement methods while defining the growth in future study topics, such as implementing waste materials, recycled polymers, and alternative ecological binders aligned with infrastructure stability.

1. INTRODUCTION

Clay is one of the different types of predominant soil on the Earth's surface [1]. It has been used in engineering, cosmetology, and the pharmaceutical industry since prehistoric times [2]. Clay is composed of very fine (< 2 microns) and crystalline particles [3]. It is characterised as soft soil with a high plasticity index, low permeability, and low bearing capacity [4], making it prone to significant deformations. Due to its geotechnical characteristics, this type of soil generates problems in construction, especially when it meets water [5], causing significant disasters and economic losses. For instance, on August 28, 2017, in the village "Pusa" located in Guizhou, China, a landslide, which was approximately 8600m^3 of soil resulting from rainwater infiltration, killed 35 people [6].

A significant portion of the United States exhibits swelling and shrinking characteristics in soils, which inflicts expensive harm on various structures like foundations, residential buildings, roads, airfields, and embankments; in contrast, the destruction caused by natural events such as earthquakes, hurricanes, or tornadoes [7]. According to the Virginia Department of Mines, Minerals and Energy, in 2021, it was estimated that around 12.5% of households encountered damage to their infrastructure [8]. Expansive clays, containing hydrophilic minerals like montmorillonite and illite, are prone to changes in soil volume and are influenced by the number of smectite minerals present [9]. The triggering factor for this type of soil is climatic fluctuations, as wetting and drying cycles caused by climatic fluctuations cause swelling and contraction [10]. Soil shrinkage occurs when the soil's water content evaporates, causing desiccation. This desiccation decreases pore pressure, resulting in increased suction called capillary tension. This desiccation can cause lateral shrinkage, crack propagation, or a lower degree of saturation [11]. Swelling usually occurs due to rainwater infiltration into the soil surface, causing an increase in pore pressure and decreasing resistance and stability [12].

The high plasticity index (PI), low permeability, compressibility, differential settlements, and low shear strength [13] are the primary causes of damaged structures built on expansive clays. Soil improvement commonly refers to enhancing the engineering properties of soils through mechanical, chemical, thermal, and electrical methods [14]. Replacing soil with expansive clays influences costs and operation times due to earthwork, machinery, and personnel. Therefore, the continuous goal of geotechnical engineers is to improve rather than replace it [14], using different alternative binders [15], such as the use of recycled materials, as reflected in the increase in scientific research [16]. In Jombang, East Java, Indonesia, in 2021, a soil improvement study with expansive clays was carried out, using a mixture of oyster shell ash as a stabilising agent, reducing moisture, PI, and montmorillonite content [17]. In Curitiba, Brazil, rice husk fibre was used as a stabilising agent to analyse the mechanical behaviour of the soil [18]. Additionally, numerous studies have emphasised the effectiveness of the Deep Mixing Method (DMM) in improving soil resistance and settlement performance [19], as demonstrated at the East Port Said Port in Egypt. In this case, using lime and cement binders through the DMM reduced the PI, increased the liquid and plastic limits, and enhanced the clay's compaction properties [20]. Another improvement method used in this type of soil is that used by Ye et al. [21] in 2024, where the changes in the water content, suction, crack ratio and fractal dimension (D) of the clay improved with microconcrete particles in different quantities were studied. Applying this method allows the soil to be established with the mixture cracking slowly. This presents a higher water content, residual resistance, and suction, improving the clay's structural properties. Standard stabilisation methods include mixing soil with cement in dam and embankment slope projects, race pavement, and reservoir lining for foundation stabilisation. Additionally, lime stabilisation is used, reducing the potential for swelling, PI, shrinkage limit and strength. Among other additives, those that are calcium-based stand out, waterproofing the soil, improving durability, preserving the aggregate, and reducing construction and transportation costs [22].

The increasing urban population is forcing communities to occupy land not traditionally considered suitable for construction, such as expansive clays [23]. A study case of this problem is in the urban land southeast of Madrid, where the improvement technique was expansive clay and lime (6%) constructing of an embankment, which allowed for the area's urban development. Another case study is the research conducted by Yahgoubi et al. [23] in the western metropolitan area of Melbourne, Australia, where an improvement was made to the subgrade of a road on expansive clay soil using recycled glass. Over time, research on soil improvement techniques has existed; however, only some studies have performed bibliometric analysis [24, 25] and systematic review. The number of research papers published in databases such as Scopus allows for evaluating the latest advances and relevant information in practice on a specific topic [26]. The results of the application of this material showed a maximum dry density, reduction in moisture content, increase in the resilient moduli of the samples, reduction in compression and tension deformation, and increased useful life of the pavement. Bibliometric analysis collects many scientific articles in a comprehensive database such as Scopus or Web of Science (WoS), revealing research patterns such as influential publications, authors, important journals, and relevant information in a particular area [27, 28]. It also identifies research gaps in different disciplines [29, 30].

A systematic review, a cornerstone of academic research, is particularly significant in the context of soil improvement in expansive clays. It compiles data and analyses a specific topic, ensuring transparency and objectivity [31]. One method used in this context is the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), a tool that aids researchers in producing high-quality reports through its guidance, comprehensive updated checklist, and flowchart template [32].

Based on the preceding, the following research questions are formulated: What are the research trends in studies that link soil improvement with expansive clays? Which geographical areas are affected by instability in soils with expansive clays? And how have soil improvement techniques in expansive clays evolved? In response to these questions, the study seeks:

·To analyse the solutions applied to soil improvement in expansive clays.

·Systematisation of information published in scientific databases, co-occurrence maps of keywords (Study clusters) in VOSviewer and methodological trends in Bibliometrics.

·A systematic review of case studies related to soil improvement in urban areas, using PRISMA, for constructing a matrix that synthesises the primary factors and methodologies.

2. MATERIALS AND METHODS

This study employed a methodological approach that included statistical analysis of research trends in soil improvement with expansive clays. In geotechnical engineering, this problem is frequent, and there are several ways to approach solutions that improve the characteristics and quality of the soil. A literature review is essential to research, minimising biases and errors in selecting a field of knowledge [33]. This type of secondary research recognises possible gaps and highlights current lines of research with the application of solutions and research trends. Bibliometric studies use quantitative analysis to describe, evaluate, and monitor the scientific field of an area, identifying trends and growth of a topic [26, 34, 35]. For this research, a search was conducted in the Scopus database as a general analysis, focusing on case studies (Figure 1).

2.1 Phase I: Systematisation of information

The articles on soil improvement in expansive clays were reviewed through the Google Scholar database, which identified keywords and their synonyms. Subsequently, using Scopus database on January 8, 2024, Boolean operators were used to refine results, as shown in the following equation: ((TITLE-ABS-KEY ("expansive clay") OR TITLE-ABS-KEY ("expansive clay soil") OR TITLE-ABS-KEY ("clay soil*") OR TITLE-ABS-KEY ("expansive clay improvement*"))) AND ((TITLE-ABS-KEY ("soil improvement*") OR TITLE-ABS-KEY ("improve soil*") OR TITLE-ABS-KEY ("soil treatment*") OR TITLE-ABS-KEY ("soft soil improvement*"))). All languages and document types were considered for the search, and the year 2024 was excluded. The database was downloaded in .csv format and processed in Excel.

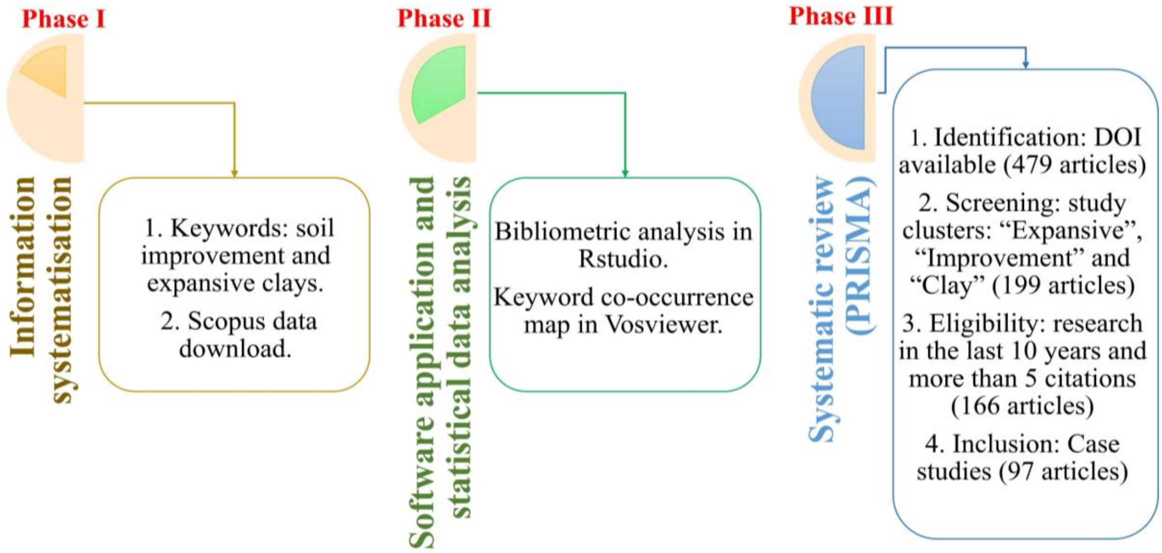

Figure 1. Methodological framework with a general and case study-focused approach

2.2 Phase II: Software application and statistical data analysis

The Scopus database cleaned and removed incomplete data (no authors, year, title, Digital Object Identifier (DOI), keywords, abstract or journal). The database was processed using RStudio, a programming language software. This software used the bibliometrix library to access the Biblioshiny platform. Its platform allows the generation of multiple maps and diagrams with statistical analysis for bibliometric analysis, such as international collaboration graphs and keyword trends. In Microsoft Excel, the growth analysis of scientific production was performed using pivot tables. The database was processed using VOSviewer software (version 1.6.17), developed by Van Eck and Waltman, to construct the geographical distribution map and the keyword co-occurrence map. This software allows the analysis of intellectual groups by considering authors, countries, keywords, references, and bibliographic data. The clusters generated with a frequency of five were analysed in Excel to identify the connection patterns between the themes and establish a name for each group [36]. The graph obtained lets you visualise the predominant groupings and topics within the research field.

2.3 Phase III: PRISMA systematic review

Based on the bibliometric analysis, the research focus of the PRISMA method consisted of four stages. The identification stage considered articles with DOIs for detailed review, for which Excel filters were used, determining that 61 documents do not comply with this restriction. In the screening stage, the analysis focused on articles that presented the clusters of soil improvement and expansive clays in their keywords; considering the main topics of this study's objective, 280 publications were excluded. In the eligibility stage, the database was limited to documents with more than five citations and published in the last ten years for their impact on the research area. In the inclusion criteria, the publications were limited to case studies to delve into the main results of soil improvement techniques. The systematic review generated a synthesis scheme based on the relationship between the method applied for the improvement and the improvement properties with the technical criteria, defining guidelines and lines for future research.

3. RESULTS

3.1 Scientific production, annual citations, and document types

As shown in Figure 2, it experienced a steady growth in publications from 1925 to 2023. This study divided the publications into three periods, considering the frequency of documents and citations (Table 1). Initial Period (1925-2000), Intermediate Period (2000-2015), and Final Period (2015-2023). Among the document types published within the thematic area, scientific articles stand out, followed by conference papers and book chapters. In 2021, a peak in production was observed, mainly with topics related to the mixture of silica and eggshell ash to stabilise and improve the engineering properties of soil (decrease in specific gravity, PI, and increase in moisture content and undrained shear strength) [37]; application of biochar [38] and improvement of expansive clay soils using recycled concrete cement [39].

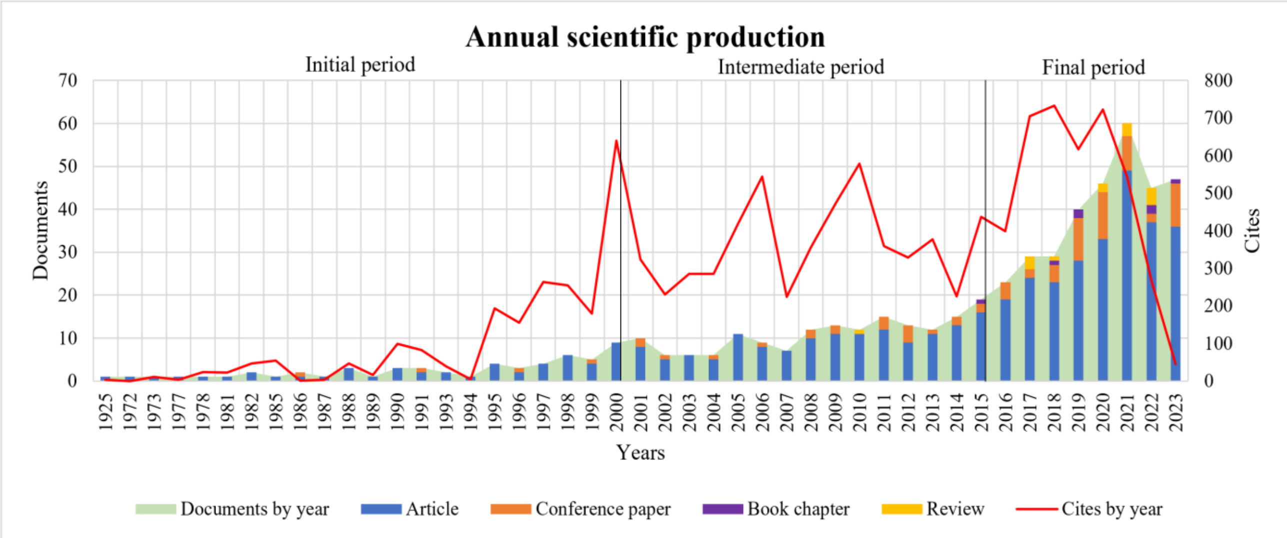

Figure 2. Annual scientific production, specifying document type and number of citations

Table 1. Division of study periods in bibliometric analysis

Study Periods Analysis	Main Content
Period 1925-2000 (start point)	Soil improvement in agriculture using mechanical methods with a milling machine [40], clayey soils with saline patches in crops [41], reinforcement using Jet Grouting to counteract softening of clayey soil, fissure and instability [42], the load-bearing capacity of improved soils using sand compaction piles in a series of centrifuge tests [43], binders such as fly ash, vertical drains to gain strength in soft clayey soils [44], rice husk ash decreases swelling behaviour, PI, California Bearing Ratio (CBR) value and shear strength [45].
Period 2000-2015 (middle point)	Utilisation of lime [46], comprehensive study of the behaviour of stabilised expansive clays for sulfate-rich soils using as stabilisers, class F fly ash, type V cement, granulated slag and lime mixed with polypropylene fibres [47], compaction grout test platforms to quantify changes in moisture content, density, compressive strength and collapse potential [48], lime piles with significant changes in Atterberg limits, compaction, linear shrinkage and strength of the treated soil [49].
Period 2015-2023 (final point)	Soil stabilisation with chitosan from shrimp shells showed an increase in soil particle interaction and improved mechanical properties [50], the combination of vacuum preloading and lime treatment to improve dredged fill increased the shear strength of all soil layers and consolidation rate [51], soil improvement in expansive clays with plant fibres (crushed) reduces swelling and increases cohesion [52], voltage optimization in expansive soils with saline solutions at different voltages, and improvement of expansive clayey soil with non-traditional binders such as biomass ash and silica-based nanotechnological stabiliser [4].

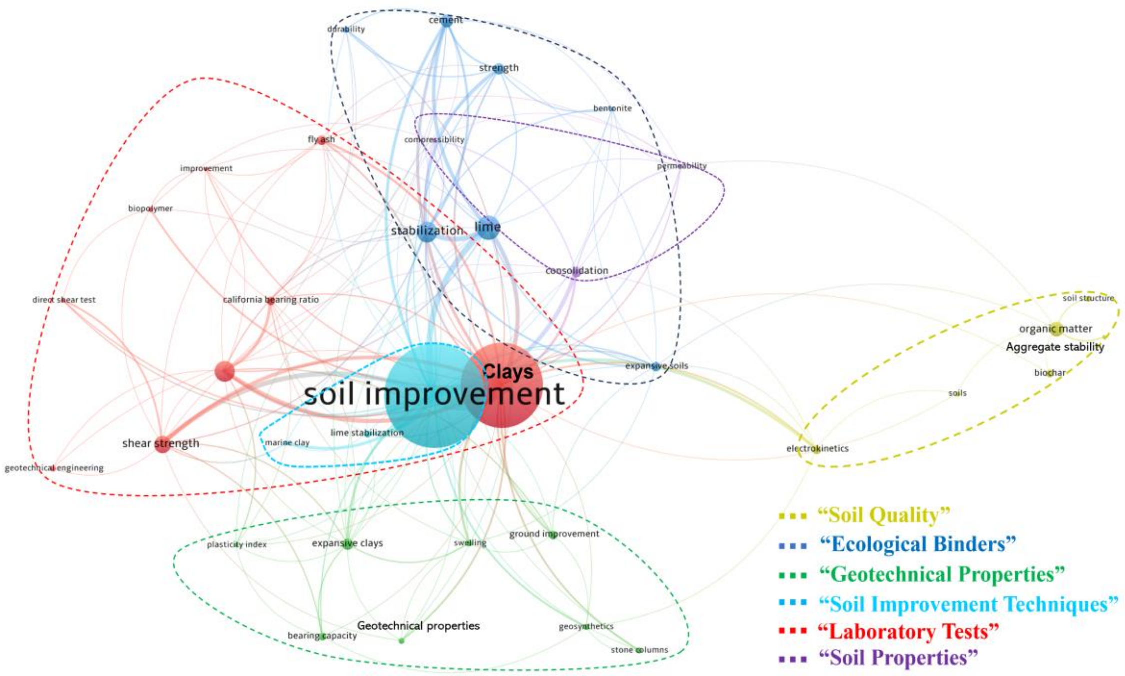

Figure 3. Study clusters with an occurrence frequency of five, generated using VOSviewer software

3.2 Study clusters based on keywords

Figure 3 allows for identifying of research topics and methodological trends in soil improvement based on the density distribution of the co-occurrence network of the authors' keywords. In this analysis, a frequency of five was considered in each term, defining six clusters of interest.

The "Laboratory Tests" cluster, denoted by red, is a vast and fertile study area boasting nine nodes and 30 links. It is a hub of research activity, with each node representing a unique aspect of soil improvement. This cluster is linked to a diverse range of tests, from determining the geotechnical properties of clay with silica nanoparticles [53] to studying the influence of rice husk ash and lime on the properties of the clayey subgrade [45] and exploring the effects of geosynthetic reinforcement on the bearing capacity of continuous footings [54]. It also encompasses research on soil improvement with sand, lime, and polypropylene fibres [55].

The green cluster, "Geotechnical Properties" has eight nodes with topics related to the improvement of the geotechnical properties of expansive clayey soils through the swelling-shrinkage behaviour improved by applying nanosilica, calcium carbide leftovers and geopolymer [56, 57], and the use of coconut fibres, granular piles with and without geomembrane lining, and electrokinetic treatment to improve the bearing capacity and strength of expansive clay [58, 59]. The blue cluster, known as "Ecological Binders", is essential in this research. It encompasses seven nodes, each delving into topics related to the most common types of binders and their derivatives that are used for the improvement of clayey soils, such as eggshell lime, rice husk ash [45, 60], characterization of strength, durability and microstructures of clayey soils enhanced with sustainable geopolymers [61]. Additionally, it explores the geotechnical properties of clayey soils improved with marble and granulated slag [62, 63].

The yellow cluster, aptly named "Soil Quality", reveals the practical implications of this research. This analysis found that urban waste, sewage sludge, and sawdust in semi-arid areas can enhance the physical properties of the soil, including hydraulic conductivity, water retention capacity, density, porosity, soil strength, and aggregate stability [64]. Furthermore, this study demonstrates that organic matter can significantly improve soil structure, quality, and productivity [65]. These findings directly impact the management of soil sustainability in semi-arid regions.

The purple cluster, "Soil Properties", mentions the combination of vacuum preloading and lime treatment to improve the technical properties of fill, such as shear strength and permeability [66], and the use of nano-bentonite to improve the technical properties of the soil (increase in the consolidation coefficient and permeability, reduction in the compressibility of clayey soil and facilitation of soil particle cementation) [67].

The light blue cluster, "Soil Improvement Techniques", highlights microbially induced calcite precipitation (MICP) for biological soil improvement (reduction of liquid limit and PI) [68], the use of biogrouting and the electrokinetic method to stabilise marine soil (improvement in soil shear strength and reduction in compressibility and electrical conductivity) [69].

3.3 Geographical distribution of scientific publications

In the cluster analysis based on the geographical distribution of publications (Table 2), 29 countries were identified with significant growth in topics related to soil improvement in expansive clays. Cluster 1 studies topics on mechanisms for removing contaminated soils and sediments with hydrophobic organic compounds [70] and improving soil aggregate stability with biochar through slow pyrolysis, hydrothermal carbonization, or torrefaction [71]. Cluster 2 relates to topics on settlement control using DMM in clayey soils [72], where polymers were used [50, 73] and the use of carbon dioxide to improve clay behaviour [74]. In Cluster 3, China was the most influential country, with 70 articles published, with topics regarding the application of the DMM to reduce the impact on nearby structures [75] and the improvement of clayey soils with MICP.

Table 2. Cluster of the relationship and distribution of countries based on their scientific publications

Cluster	Country	Number of Documents	Number of Citations
1	France	11	501
	Sweden	10	177
	Italy	9	214
	Algeria	8	72
	Netherlands	8	229
	Jordan	6	44
	Saudi Arabia	5	28
2	Iran	50	1069
	Brazil	26	717
	Egypt	14	333
	Japan	11	299
	Romania	5	9
	Russian federation	6	10
3	China	70	1354
	United Kingdom	23	751
	Germany	10	252
	Pakistan	6	132
	Poland	5	256
4	United States	69	2328
	Australia	38	982
	India	36	316
	South Korea	8	380
	Nigeria	7	71
5	Turkey	33	510
	Malaysia	28	350
	Indonesia	20	133
	Iraq	13	193
6	Canada	22	923
	Singapore	5	165

In Cluster 4, the United States stands out, with topics related to the stabilisation of clayey soils with a high organic matter content [76, 77] and the behaviour of stabilisers such as recycled glass, coconut fibres, and aqueous polymer [23, 78]. Cluster 5 presents research on applying binders such as hydrated lime in treating marine clays, coconut fibres modified with calcium hydroxide and magnesium nanoparticles, and steel waste dust [79-81]. Cluster 6 highlights Canada and Singapore with topics such as the mechanical behaviour and prediction of the vertical yield stress of clayey soil, using lime or cement as a stabilising agent [46], and low-concentration alkali cement based on fly ash [82].

3.4 Topic trends using author keywords

Figure 4 allows us to identify the evolution of keywords in soil improvement based on the frequency with which they are cited over a period. The database was processed in the Bibliometrix software, where the predominance of the words "soil," "clay soils," and "consolidation" as the most representative and long-lasting themes are evident.

Between 2000-2020, a burst of keywords emerged related to the application of sludge and fertilizers to improve soil properties and hydraulic conductivity [83], organic waste to improve soil structure [65, 84] electrokinetic bioremediation with phenanthrene in clayey soils [85], vertical drains [86], lime treatment in clayey soils [77], carbon sequestration to improve soil quality [87], granular fill layers [88], electrokinetic consolidation with electroosmosis principles used in the treatment of fine-grained soils such as silts and clays [89], industrial waste [90], vibro displacement gravel columns [91], and MICP nanomaterials as a promising technology for biological soil improvement [68].

In recent years, methodological approaches have focused on biogrouting through physical, biological, and chemical treatments to the soil [69], biochar improves hydraulic properties [92], recycled concrete aggregates, tyre polymer fibres, and glass improve strength properties [73], fibres that increase ductility, the tensile strength of improved soils, and delay the rupture process [93], biocementation through the addition of eggshell [94], cementitious jet grout method (CJG) for the reinforcement of building foundation soils, reducing the potential for settlement, permeability, and liquefaction [95], fly ash-based geopolymers as an eco-friendly alternative binder [96], recycled polymers [97], and glass fibres with nanoclays that increase shear strength parameters [98].

3.5 Systematic review

Based on the four criteria established in the systematic review, 97 publications were identified for the exhaustive synthesis of information, considering methodologies, geographical location, and soil improvement properties. Considering the case studies, five groups could be divided based on the methodologies applied (Figure 5). The chemical method, with 31 publications, stands out in Italy, Brazil, Turkey, Japan, Indonesia, Pakistan, China, Malaysia, Algeria, Australia, Iran, and India; the mechanical method with eight publications, in Algeria, Malaysia, Iran, India, and China; the thermal method with two articles in Syria and Brazil; the physicochemical method with one article in Iran; and finally, the analytical method with one article in Morocco.

3.5.1 Chemical method

Among the main themes based on the number of citations, which encompass the application of the chemical method, is the introduction of potassium chloride (KCl) solutions through perforations, such as the case of Italy, where an increase in the angle of friction and shear strength was observed due to the propagation of ions (increase in ionic concentration). In Brazil, the publications focused on studying the effect of geotechnical properties by adding lime, improving compressive and tensile strength. Among the methodologies, the injection of clay nanoparticles in improving collapsible soils also stands out, as in Iran, where the collapse index was reduced by up to 96%, and the mechanical behaviour of low-permeability soils was improved, becoming an economic and ecological technique. In the African continent, Algeria stands out with the study of the stabilisation of clayey soil with gypsum content, using lime as a stabilising agent, increasing compressive strength, improving soil stiffness, fragility to deformations and modulus of elasticity.

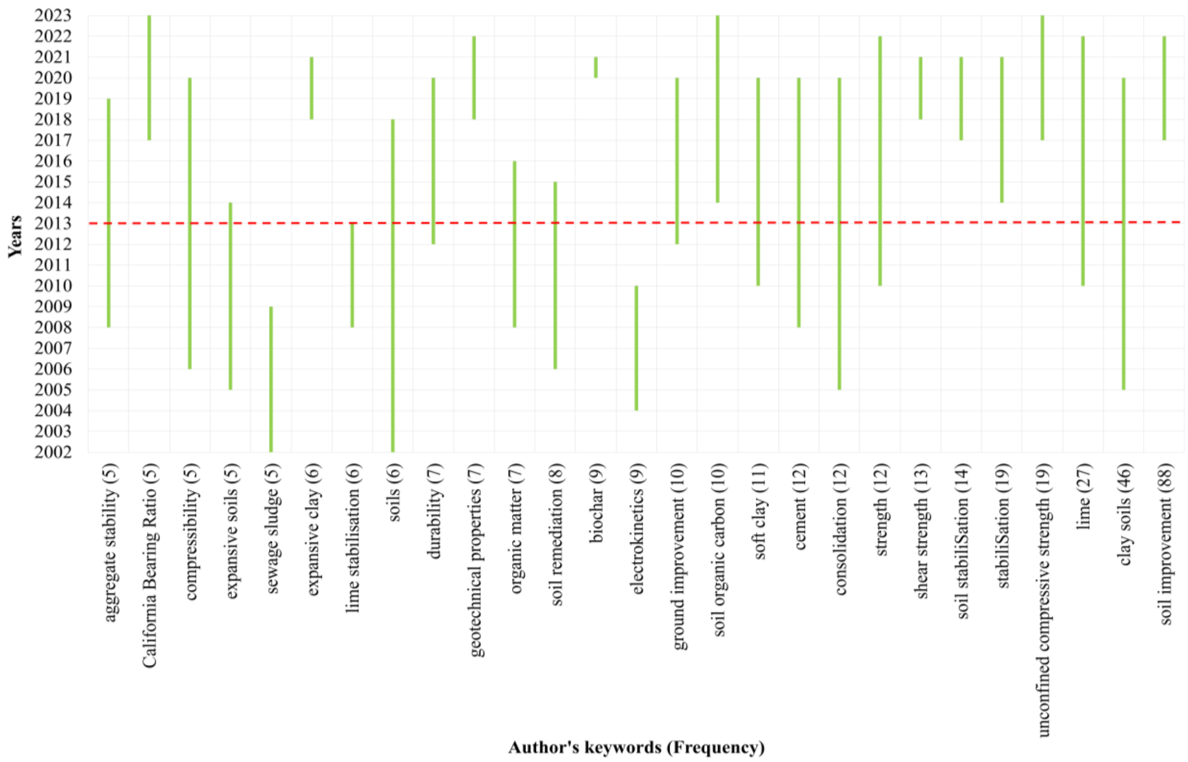

Figure 4. Thematic trends from 2002 to 2023, considering a frequency of 5 in author keywords

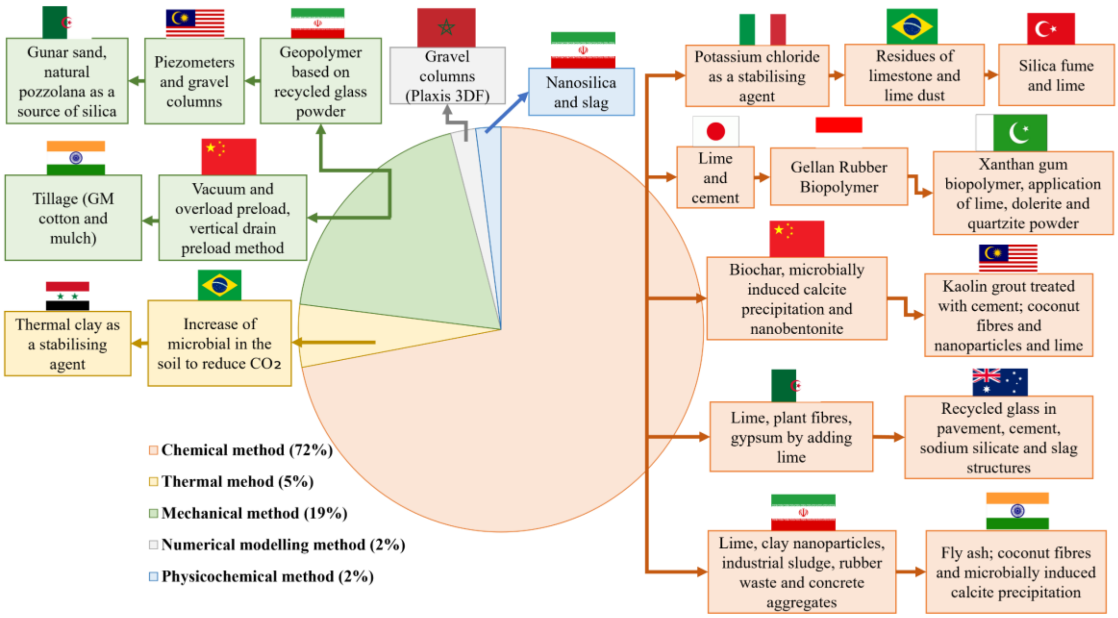

Figure 5. Summary of a systematic review based on case studies, defining five soil improvement methods

3.5.2 Mechanical method

The Asian continent, particularly China, stands out for its use of the mechanical method. The vacuum preloading and surcharge method was studied there to improve soft marine clay, reduce deep lateral displacement, water content, and compression coefficient, and increase compression modulus, cohesion, and friction angle. Additionally, research has been conducted on using the vacuum preloading method without sand combined with short and long prefabricated vertical drains (PVDs), achieving a more uniform shear strength profile, indicating that this proposed method is more effective than the conventional one. In Algeria, the geotechnical and mineralogical properties of clayey soil treated with dune sand were studied through laboratory tests, swelling oedometric tests, and X-ray diffraction (DRX), improving geotechnical characteristics.

3.5.3 Thermal method

A case study is presented in Syria, where the use of thermally treated clay as a stabilising agent decreased the PI by increasing the percentage of thermally treated clay, the natural soil swelling pressure, and linear shrinkage deformations, and the creation of cementing phases improved the technical properties of the soil. In Brazil, the temperature sensitivity of soil organic matter decomposition was analysed by adding different biochar rates, observing a decrease in CO_2 emission.

3.5.4 Physicochemical method

In Iran, the effects of wetting and drying cycles on the swelling-shrinkage behaviour of expansive soils improved by nanosilica and industrial waste were studied. The results demonstrated that the improved samples have fewer swelling and shrinkage variations under the influence of water content changes.

3.5.5 Numerical modeling method

Some studies in the Bouregreg Valley, Morocco, focused on ground improvement using numerical simulations and analytical methods with gravel columns. The study focused on comparing the behaviour of an isolated central gravel column with a group of gravel columns to gain insights into the interactions between the columns under various parameters related to the granular material and the surrounding soil. Constitutive models (Mohr-Coulomb) and finite element models (FEM) were employed using PLAXIS 3DF software, along with the Priebe method and the equilibrium method.

4. DISCUSSION

Publications in the field of soil improvement have evolved. It began 99 years ago with topics related to agricultural soil improvement [40, 99]. The second period (2000-2015) focused on topics like the effects of compost made from urban waste and sewage sludge on the physical properties of clay soils [64], removing metal contaminants [100], and controlling the strength of lime-stabilised soils [101]. In the final period (2015-2023), publications have grown exponentially, averaging 42 yearly documents (Figure 2). Topics include the use of polymers and different types of fibres like glass [73], natural fibres, polypropylene, and coconut [59, 102]. Scientific production peaked in 2021 (Figure 2) with 60 published articles. China published the most articles (18) on using stabilising agents like biochar [103-105] and inorganic materials: geopolymers [106], polymers [107], and inorganic amendments [105].

The cluster analysis of study topics shows the "soil properties" cluster within the "Ecological Binders" cluster, like the combined use of fly ash-stabilised clay columns [108] and kaolin grout [109] to improve compressive strength. The "Laboratory Tests" cluster directly relates to the "Improvement Techniques" cluster, highlighting the importance of characterizing soil type for improvement, as in the study of strength and swelling characteristics of expansive soils treated with calcium carbide waste [110].

Studies on this research topic have grown, with 125 authors (who published at least twice) in 27 countries. China and the United States have the highest number of publications. Developing countries with large populations [111] experience increased industrialization, urbanization, fertilizer use, and intensive soil consumption, leading to more significant environmental pollution [112]. China has red soils like latosols with a clayey structure and high water retention capacity [113]. Therefore, one of the places with the most publications is Nanjing and Jiangsu, located along the Yangtze River axis. This area has clay, silt, sandy soil, clay minerals, high moisture content, and density [114], with research on fibre-reinforced and geopolymer-stabilised soils [106]. In the southwestern United States, there are Alfisols, Mollisols, and Entisols soils [115, 116]. Studies were conducted on biochar's effect and particle size in water for plants in sandy, silt loam, and clay soils [92].

The graph of trending topics (Figure 4) shows that "CBR", "Soil Organic Carbon" and "Unconfined Compressive Strength (UCS)" were the dominant keywords in 2023. This analysis reflects the current focus on finding sustainable, eco-friendly soil improvement techniques using renewable organic materials. Researchers measure UCS and bearing capacity to determine if these organic stabilising agents positively impact soil.

"Clay Soil", "Consolidation", and "Soils" have consistently remained relevant topics throughout the period (2002-2023) due to urban sprawl in various countries, which leads to construction on problematic soils like expansive clays. Urban planning projects often involve fine-grained soils like clay, which are difficult to consolidate [117] and have low bearing capacity and high compressibility [118]. This problem has driven geotechnical engineers to constantly research and develop methods for improving these properties.

According to this secondary research involving a bibliometric analysis and systematic review, mechanical soil improvement methods require extensive, specialised machinery, resulting in significant financial costs. However, the literature shows a growing emphasis, particularly in the final period (2015-2023), on studies of ecological stabilising agents. These agents improve soil properties (stability, grain size, plasticity index, swelling-contraction potential, and cementation), reduce improvement costs, and offer more environmentally friendly approaches.

This review provides a baseline understanding of the studies and methodologies applied to soil improvement under various conditions and challenges. It highlights the diverse countries that have conducted research and implemented solutions to ensure the stability of structures, demonstrating that clay soils can be adapted and mitigated for use worldwide. Stabilising expansive clay soil by using phosphogypsum as a stabilising agent in Tamil Nadu, India, allowed optimal results to be obtained as the percentage of use of phosphogypsum and the curing time increased [116]. Chen et al. [67] mention the use of nano-bentonite in the Qixia District, Nanjing, China, improving the technical properties of the soil (increase in the coefficient of consolidation and permeability, reduction in the understandability of clay soil and facilitating the cementation of soil particles).

All geotechnical projects could be considered political implications as identified in this study; they denote construction regulations for the inclusion of guidelines on specialized geotechnical studies and the implementation of mitigation measures and urban planning to avoid building on expansive soils and guarantee the durability of the structures [119]. Furthermore, in the construction stage, humidity control in the clays is required with the construction of a drainage system, waterproofing in critical areas and the implementation of materials flexible to soil movement through chemical treatments such as lime that improve the properties of the clay soil. This study specifically analysed publications in the Scopus database. It's important to note that while this research downloaded all soil improvement studies, if did not consider articles indexed in databases like WoS, Dimensions, or Google Scholar. The focus was on identifying articles with various applications and study types, including those focused on soil improvement for agriculture or experimental cases that were analysed generally.

5. CONCLUSIONS

The review of publications about soil improvement in expansive clays identified 543 documents from 1925 to 2023 with exponential growth, highlighting 2021 with publications from China on using biochar as a stabilising agent. Cluster analysis and trend topics showed an increase in using stabilising agents (mainly fly ash, slag, polymers, lime, and cement) with residual fibres (glass, coconut, and rubber) in soil improvement methods in recent years. These agents improve properties like bearing capacity, plasticity index, tensile strength, and swelling-shrinkage behaviour, which are crucial for expansive clay soils.

XRD is highlighted for identifying clay minerals and complementing geotechnical characterization. The main tests used to demonstrate soil improvement are UCS, Atterberg limits, CBR, consolidation, and oedometer tests. China and the United States lead in the geographical distribution of publications, focusing on biochar and organic soils due to their high content of expansive clay soils, a major challenge in construction.

The systematic review focused on case studies of soil improvement, with the chemical method prevailing as a more economical option than the mechanical method. The chemical method primarily uses lime mixed with ecological binders. The mechanical method combines vacuum preloading with vertical drains and jet grouting. The thermal method applies voltage to the soil, the analytical method utilizes software like PLAXIS for FEM generation, and the physicochemical method studies the effect of wetting and drying. The chosen method depends on various factors like construction time, budget, material availability, project scope, and type of structure.

Future research directions in this analysis include using biochar, polymers, biopolymers, geopolymers, biotechnology, organic and inorganic materials, and nanoclays for expansive clay soil improvement. New methodologies aim to minimise natural resource use by implementing waste materials like eggshell powder or rice husk powder. Advanced modeling techniques are being developed using updated technology and software, including numerical models (FEM or finite difference method (FDM)) and constitutive models (Mohr-Coulomb or Linear Elasticity). This research identified current soil improvement methods for expansive clays, evaluated their effectiveness, and explored emerging techniques. This analysis is crucial as population growth necessitates construction on problematic soils like expansive clays, and environmentally friendly improvement options are essential. Among the methods and future lines, using nanomaterials such as colloidal silica, carbon nanotube, and bentonite stands out to improve the mechanical properties of the soil, reducing the environmental impact, energy consumption and costs compared to traditional methods (cement).

This research identified current soil improvement methods for expansive clays, evaluated their effectiveness, and explored emerging techniques. This analysis is crucial as population growth necessitates construction on problematic soils like expansive clays, and environmentally friendly improvement options are essential.

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