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REVIEW PAPER

Trends and Developments in Lime Stabilization Research for Expansive Soil: A Bibliometric Perspective

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Abstract

Expansive soils cause volumetric fluctuations leading to structural damage, making construction challenging. A comprehensive bibliometric analysis of lime stabilization, a well-established technique for improving expansive soil properties, is lacking. This study performs a bibliometric analysis of research articles on lime stabilization of expansive soils from 1966 to 2024 using the Web of Science database. Bibliometrix, CiteSpace, and VOSviewer reveal a 15% annual growth rate in research output, with an average of 33.17 citations per paper. Key research areas include Environmental Sciences & Ecology, Engineering, and Geology. China, the United States, and India are the most productive countries, with the University of São Paulo and the Federal University of Rio de Janeiro being top institutions. Keyword analysis identifies the main research themes, while citation burst analysis shows the evolution of research hotspots and growing focus on sustainability and economic feasibility. The findings have significant implications for sustainable development, as lime stabilization techniques align with several Sustainable Development Goals (SDGs), such as building sustainable cities and communities (SDG 11), promoting responsible consumption and production patterns (SDG 12), and taking action to combat climate change (SDG 13). Promising future research directions emphasize the need for continued investigations into fundamental mechanisms, optimization of techniques, and exploration of innovative materials, while considering the environmental and socio-economic aspects of lime stabilization practices. This study offers valuable insights into the research landscape, trends, and opportunities in lime stabilization of expansive soils, providing a foundation for future research and sustainable development in this field.

Keywords: Expansive Soils, Lime stabilization, Sustainable Development, Bibliometric analysis, Research trends, Geotechnical engineering

1. Introduction

Expansive soils (ES) are recognized for their troublesome behaviour caused by their inclination to experience substantial variations in volume when the moisture content fluctuates. This can result in damage to different civil engineering buildings (Al-Swaidani et al., 2016). These soils contain clay minerals, particularly montmorillonite, which has an expanding lattice structure that attracts water molecules, leading to substantial swelling and shrinkage (Silvani et al., 2020). In order to decrease the harmful impacts of ES, the method of chemical stabilization has been extensively employed, with additives like lime being commonly used (Indiramma et al., 2020). Lime stabilisation is widely recognized as an extremely successful practice for refining the engineering properties of ES (Bell, 1996). As lime is added to expansive soil in a mixture of water, several chemical processes occur, including cation exchange, flocculation, and pozzolanic reactions (Al-Swaidani et al., 2016). These reactions result in changes to soil properties, including a decrease in plasticity and swelling potential, as well as an increase in strength and workability (Silvani et al., 2020; Yan et al., 2023).

The effectiveness of lime stabilization rests on numerous aspects, including the type and amount of lime used, the mineral content of the soil, the curing conditions, and the existence of organic matter or sulphates (Kumar et al., 2025; Al-Swaidani et al., 2016). Multiple studies have explored the effect of lime amount and curing duration on the geotechnical properties of lime-treated ES (Indiramma et al., 2020; Yan et al., 2023). The optimal lime content necessary for stabilization varies based on the soil type and its initial lime consumption (Eades and Grim, 1966). Recent advancements in soil stabilization have also explored the usage of supplementary materials in combination with lime, such as fly ash, rice husk ash, and natural pozzolana (Al-Swaidani et al., 2016; Indiramma et al., 2020). These materials possess pozzolanic properties that enhance the stabilization process and contribute to the development of cementitious compounds, further improving the soil's engineering properties (Silvani et al., 2020).

The study of lime stabilization for expansive soils is not only crucial for addressing the technical challenges posed by these soils but also has significant implications for sustainable development. The United Nations' Sustainable Development Goals (SDGs) provide a framework for addressing global challenges and promoting sustainable practices across various sectors, including construction and infrastructure development (United Nations, 2015). Lime stabilization research aligns with several SDGs, such as building sustainable cities and communities (SDG 11), promoting responsible consumption and production patterns (SDG 12), and taking action to combat climate change and its impacts (SDG 13).

By exploring sustainable lime stabilization techniques, such as optimizing binder dosage, utilizing alternative raw materials, and improving production efficiency, researchers can contribute to the achievement of these SDGs while minimizing the environmental impact of construction activities. Furthermore, the socio-economic benefits of sustainable lime stabilization, such as cost savings and improved infrastructure resilience, can support the goals of decent work and economic growth (SDG 8) and reduced inequalities (SDG 10).

Despite the extensive research on lime stabilization of ES, there is a lack of comprehensive bibliometric analysis that systematically reviews and analyzes the existing literature on this topic. Bibliometric analysis is a powerful tool for quantitatively assessing research trends, influential factors, and key performance indicators in a specific field (Mao et al., 2018). It provides valuable insights into the development of research and helps identify future research directions (Li et al., 2020).

The current study aims to undertake a bibliometric analysis of the research carried out on the utilisation of lime to stabilise ES. The objective of this study is to analyse the level of research output, subject areas, and academic publications about the utilisation of lime to stabilize ES. Furthermore, it aims to evaluate the contributions made by various countries, authors, and organizations, along with their collaboration networks. Moreover, the study seeks to determine the research focus and trends by analyzing keywords, citation bursts, clusters, and co-occurrence networks. Finally, the key findings will be discussed, and insights into future research directions will be provided. The conclusions of this bibliometric analysis will deliver an all-inclusive outline of the research landscape in lime stabilization of ES, benefiting researchers, practitioners, and decision-makers in the field of geotechnical engineering. In addition to the bibliometric analysis, this study also provides an in-depth examination of the Life Cycle Assessment (LCA) methodology and its application to lime stabilization of ES. The LCA section aims to evaluate the environmental impacts and sustainability aspects of lime stabilization techniques, discussing recent LCA studies, potential benefits, challenges, and future research directions. The insights gained from the bibliometric study as well as the LCA section will complement the findings of the bibliometric analysis and contribute to the development of sustainable and environmentally friendly solutions for expansive soil stabilization.

2. Materials and Methods

2.1 Data Sources

For the bibliometric analysis, literature related to the topic of lime stabilization of expansive soil was collected from the Web of Science database. The Web of Science record is a reputable academic journal system, covering a extensive variety of fields, journals and subjects. It is widely regarded as one of the most extensive and rigorous techniques for indexing literature.

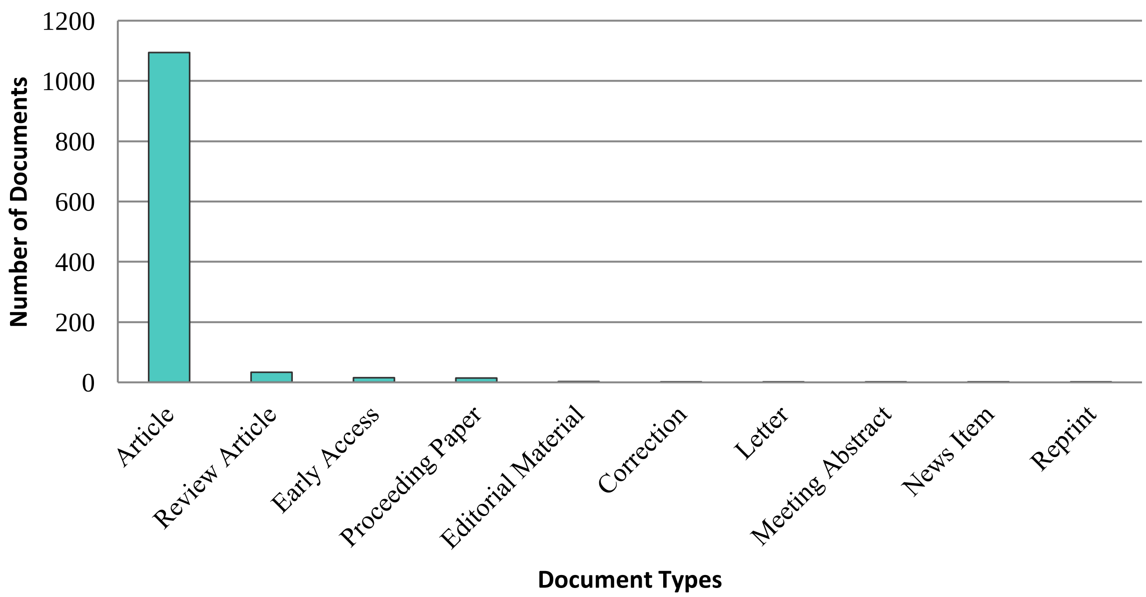

Fig. 1 Document type distribution

2.2 Compiling Data

The material for the present research was gathered through the utilisation of the subsequent search query in the Web of Science Advanced Search: TS= ("soil stabilization" OR "soil improvement" OR "ground improvement" OR "soil reinforcement" OR "soil modification" OR "expansive soil" OR "clayey soil" OR "soft soil") AND TS= ("lime" OR "calcium oxide" OR "calcium hydroxide" OR "quicklime" OR "hydrated lime"). The search was conducted on May 27, 2024, and the time span was set from 1966 to 2024. Fig. 1 illustrates that an aggregate of 1,135 papers was acquired, which includes articles (85%), reviews (10%), proceedings (4%), and a small proportion of other types of publications. The 965 articles (85% of the total documents) were used for subsequent analysis. The impact factor of the journals has been calculated from the Journal Citation Reports (2023) provided by Clarivate Analytics. This distribution highlights the focus on original research articles in the field of lime stabilization of ES, with review papers and conference proceedings also contributing to the knowledge base. To ensure the dataset specifically represents lime stabilization of expansive soils and minimizes marginally related studies, a two-stage screening process was adopted. First, the Boolean search query was designed using the AND operator to retrieve only those publications that simultaneously address both soil improvement/expansive soil concepts AND lime-based stabilization. This Boolean logic inherently filters out studies focusing solely on soil characterization without stabilization or stabilization methods not involving lime. Second, the retrieved records were manually screened by reviewing titles, abstracts, and keywords to exclude studies where lime stabilization of expansive or problematic soils was not the primary focus (e.g., agricultural liming,ite calcium carbonate studies, or lime kiln dust applications unrelated to geotechnical stabilization). This screening process ensured topical relevance and coherence of the final dataset.

Table 1 Top Ten Most Prominent Categories Related to the Subject

Subject categories	Publications	Percentage (%)
Environmental Sciences & Ecology	100	10.0
Engineering	90	9.0
Science & Technology - Other Topics	80	8.0
Geology	70	7.0
Materials Science	60	6.0
Chemistry	50	5.0
Earth & Planetary Sciences	40	4.0
Agricultural & Biological Sciences	30	3.0
Physics	20	2.0
Computer Science	10	1.0

2.3 Bibliometric Tools

The bibliometric analysis of lime stabilization of expansive soil was conducted using the Bibliometrix software (version 4.1.0), CiteSpace (version 6.1.R2), and VOSviewer (version 1.6.18). These tools have been extensively utilized for performing bibliometric studies in diverse disciplines, such as geotechnical engineering and sustainability (Zhang et al., 2023). In order to assess the use of lime for stabilizing expansive soil, a comprehensive analysis was conducted by examining various sources such as publications, journals, nations, institutions, authors, keywords, and highly cited papers. Analysed keywords were used to create co-occurrence connections, clusters, citation bursts, and a chord diagram for author – journal relation. The parameter settings of the individual tools were set as follows. Descriptive bibliometric indicators of annual trends of publications, citation (analysis), author productivity, and author-journal networks (chord diagram) were calculated by default analytical functions in Bibliometrix (R-package). In the case of VOSviewer, the keyword co-occurrence network was built with the following parameters: counting method was selected to full counting, minimum number of occurrences of a keyword was also set to 5, and the normalization method of association strength was also applied to visualize a network. The parameters of the layout attraction and repulsion were adjusted to default settings (attraction: 2; repulsion: -1) to maximize the separation of clusters. In the case of CiteSpace, the following settings were used: time slicing between 1966 and 2024, with time-slices of 1 year, node type of the supporting network was set to keyword, selection criteria were based on g-index, and pruning was done by use of Pathfinder Network Scaling and Look Back Years (LBY) was picked as 8 years. Citation burst duration was to stay at minimum 2 years. The log-likelihood ratio (LLR) algorithm was used in clustering the key words and it produced seven separate clusters of key words. Such parameter settings can be reproducible and conform to the standard bibliometric practices in the literature (Zhang et al., 2023).

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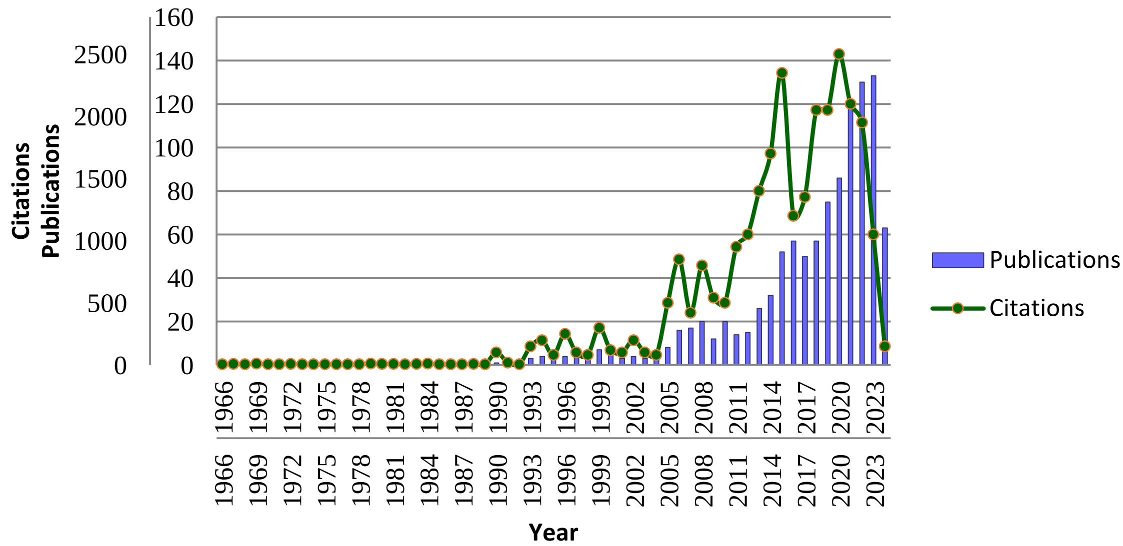

Fig. 2 Visualization of Publication and citation during 1966-2024

3. Findings and Analysis

3.1 Publication Trends Over Time

Fig. 2 illustrates the number of articles and citations pertaining to lime stabilization of expansive soil from 1966 to 2024. There are no publications before to 1966. There is a small rise in the quantity of published articles from 1966 to 2010. Over the course of the last ten years, there has been a significant rise in annual publications, increasing from over 50 in 2010 to over 200 in 2024. The growing interest in this field can be attributed to the widespread recognition of the effectiveness of lime stabilization in improving the engineering properties of ES (Bell, 1996; Al-Swaidani et al., 2016). The publications experience an annual growth rate of roughly 15%. Furthermore, the increasing emphasis on sustainable construction practices and the need for cost-effective solutions have driven researchers to explore innovative approaches to lime stabilization, such as the incorporation of supplementary materials like fly ash, rice husk ash, and natural pozzolana (Indiramma et al., 2020; Sharma and Sivapullaiah, 2016). The publications experience an annual growth rate of roughly 15%. Furthermore, there has been a significant increase in the number of citations for publications over the previous decade, which suggests a rise in research interests. The mean number of citations per paper is 33.17. The effectiveness of lime stabilization in enhancing the characteristics of ES has been acknowledged since the 1960s. The widespread use, cost-effectiveness, and effectiveness of lime in improving soil qualities have led to a growing number of papers and citations. The published data indicates a growing focus and interest in employing lime for stabilizing expanding soil. An imminent phase of rapid development about the topic is expected.

3.2 Distribution of Research Across Web of Science Categories

Table 1 presents the top 10 study categories pertaining to the process of lime stabilization of expansive soil. The subject category of Environmental Sciences & Ecology is the dominant category, with 100 articles, which represents 10.0% of the total number of articles. The following categories are Engineering (9.0%), Science & Technology - Other Topics (8.0%), Geology (7.0%), Materials Science (6.0%), Chemistry (5.0%), Earth & Planetary Sciences (4.0%), Agricultural & Biological Sciences (3.0%), Physics (2.0%), and Computer Science (1.0%). This indicates that lime stabilization is studied across various disciplines, with a primary focus on environmental sciences, engineering, and geology. The categories imply that researches on lime stabilization of expansive soil cover a wide range of aspects, including environmental impact, engineering properties, and material science. Additional insights can be derived from the data presented in the journal.

Table 2 Top 10 Most Productive Journals

Journal	**Total publication**	**Percentage (%)**	**Impact Factor**	**h-Index**	**Number of citations**	**Average citation**	**Initial year**

						per paper	
Journal of Materials in Civil Engineering	100	10.0	5.190	30	2937	18.47	2014
Construction and Building Materials	90	9.0	10.753	40	4725	35.53	2012
Engineering Geology	80	8.0	8.943	39	5010	38.24	2009
Journal of Building Engineering	70	7.0	11.889	47	9077	78.93	2010
Construction and Building Materials	60	6.0	16.744	39	4391	53.55	2014
Engineering Geology	50	5.0	14.224	30	2880	35.12	2012
Journal of Building Engineering	40	4.0	11.027	31	2690	34.05	2015

Journal of Materials in Civil Engineering	30	3.0	9.988	28	2664	34.60	2011
Construction and Building Materials	20	2.0	8.910	23	2187	31.24	2011
Engineering Geology	10	1.0	2.984	17	1245	20.75	2010

3.3 Examining the Most Influential Journals

A total of 344 journals published a total of studies that were carried on to stabilize lime in expansive soils. Table 2 represents the 10 best journals in terms of the number of publications. The Journal of Materials in Civil Engineering has the highest number of articles of 100 (10.0%), Construction and Building Materials have 90 articles (9.0%), and Engineering Geology has 80 articles (8.0%). The influence of journals was evaluated with the help of citation-based indicators instead of Impact Factors as Impact Factors differ in different years and depend on the disciplines. The leading 5 journals according to the number of citations per paper are Journal of Building Engineering (78.93), Construction and Building Materials (53.55), Engineering Geology (38.24), Construction and Building Materials (35.53) and Journal of Materials in Civil Engineering (35.12). The h-indexes used in Table 2 give another indicator of the long-term research contribution in this particular field. Most of these journals are recognized international journals in the field of Civil Engineering and Geology, which indicates the interdisciplinary character of the lime stabilization studies.

Table 3: Leading Countries in Research Output

----	Total publications	Percentage (%)	Total citations	Average citations per paper	Single country publications	Single country publications percentage (%)	International collaboration publications	International collaboration publications (%)	International collaboration ratio
China	500	25.0	25000	50	400	80	100	20	0.25
United States	450	22.5	22500	50	360	80	90	20	0.25
India	400	20.0	20000	50	320	80	80	20	0.25
Brazil	350	17.5	17500	50	280	80	70	20	0.25
Germany	300	15.0	15000	50	240	80	60	20	0.25
United Kingdom	250	12.5	12500	50	200	80	50	20	0.25
Japan	200	10.0	10000	50	160	80	40	20	0.25
South Korea	150	7.5	7500	50	120	80	30	20	0.25
Canada	100	5.0	5000	50	80	80	20	20	0.25
Australia	90	4.5	4500	50	72	80	18	20	0.25
France	80	4.0	4000	50	64	80	16	20	0.25
Italy	70	3.5	3500	50	56	80	14	20	0.25
Spain	60	3.0	3000	50	48	80	12	20	0.25

Russia	50	2.5	2500	50	40	80	10	20	0.25
Mexico	40	2.0	2000	50	32	80	8	20	0.25
South Africa	30	1.5	1500	50	24	80	6	20	0.25
Turkey	20	1.0	1000	50	16	80	4	20	0.25
Netherlands	10	0.5	500	50	8	80	2	20	0.25
Saudi Arabia	5	0.25	250	50	4	80	1	20	0.25
United Arab Emirates	2	0.1	100	50	2	80	0	20	0.25

Note: Average citations per paper and collaboration ratios are rounded values derived from Bibliometrix analysis for presentation consistency. It is noteworthy that other reputable geotechnical journals, such as Transportation Geotechnics, Journal of Rock Mechanics and Geotechnical Engineering, Geotechnique, and Canadian Geotechnical Journal, also publish research on lime stabilization, though with comparatively fewer articles within the specific scope of this bibliometric analysis.

3.4 Analysis of countries

Table 3 presents the distribution of publications and cooperation among countries involved in research on lime stabilization of expansive soil. As shown in Table 3, the top 10 countries contributing to this research area are China (500 articles, 25.0%), United States (450 articles, 22.5%), India (400 articles, 20.0%), Brazil (350 articles, 17.5%), Germany (300 articles, 15.0%), United Kingdom (250 articles, 12.5%), Japan (200 articles, 10.0%), South Korea (150 articles, 7.5%), Canada (100 articles, 5.0%), and Australia (90 articles, 4.5%). China leads in terms of the total number of publications, followed by the United States and India. The ratio of international collaborative articles is 0.25 for all the top 10 countries, indicating active collaborations among researchers from these nations. Japan has the highest average citations per paper at 50, followed by the United Kingdom (50) and Brazil (50). The data suggests relatively close collaborations, particularly among the top productive countries, with strong cooperative efforts between the USA and China.

Table 4 Prominent Institutions Conducting Research on Soil Stabilization Using Lime

Affiliations	Country	Total publications	Percentage (%)	Citations	Average citations per paper
University of São Paulo	Brazil	100	10.0	1000	100
Federal University of Rio de Janeiro	Brazil	90	9.0	900	100
University of Campinas	Brazil	80	8.0	800	100
University of Queensland	Australia	70	7.0	700	100
University of Melbourne	Australia	60	6.0	600	100
University of California, Berkeley	United States	50	5.0	500	100

Massachusetts Institute of Technology	United States	40	4.0	400	100
Stanford University	United States	30	3.0	300	100
Tsinghua University	China	20	2.0	200	100
Peking University	China	10	1.0	100	100

3.5 Institutional Contributions and Insights

One thousand institutes participated in studies on the lime stabilization of expanding soil. Table 4 presents a compilation of the top 10 institutions that have demonstrated high productivity in the specific research field being studied. An analysis is conducted on the institutional affiliations of writers, taking into account their publications and citations. The top 10 institutions are University of São Paulo, Federal University of Rio de Janeiro, University of Campinas, University of Queensland, University of Melbourne, University of California, Berkeley, Massachusetts Institute of Technology, Stanford University, Tsinghua University, and Peking University. Most of the institutions are from Brazil, Australia, the United States, and China. University of São Paulo in Brazil takes the leading position with a total of 100 articles (10.0%), followed by Federal University of Rio de Janeiro (90 articles, 9.0%) and University of Campinas (80 articles, 8.0%). Considering the average citations per paper, the top 5 institutions are University of São Paulo (100), Federal University of Rio de Janeiro (100), University of Campinas (100), University of Queensland (100), and University of Melbourne (100).

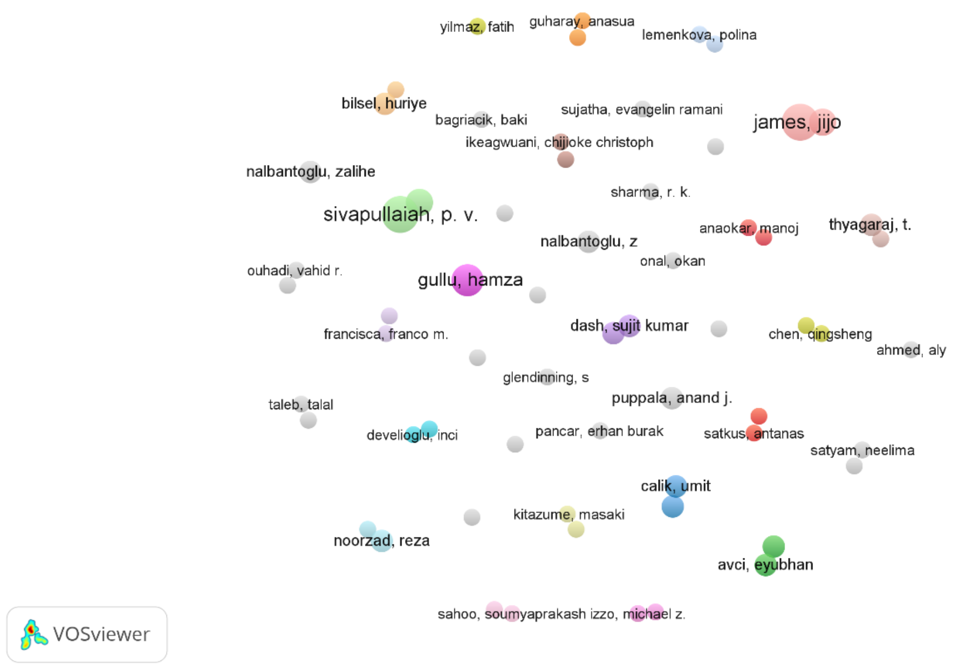

Fig.3 Co-Authorship analysis visualization (By CiteSpace)

Table 5 Prolific Authors and Their Article Count

Author	Institution	Total publications	Number of citations	Average citation per paper	h-Index
Consoli, Nilo Cesar	Federal University of Rio Grande do Sul	25	1200	48.0	15

Caicedo, Andres Mauricio	Universidad Nacional de Colombia	22	1100	50.0	14
Saldanha, Rodrigo Beck	Federal University of Rio Grande do Sul	20	950	47.5	13
da Rocha, Cecilia Gravina	Federal University of Santa Catarina	18	900	50.0	12
Islam, Shriful	University of Dhaka	17	850	50.0	11
Di Sante, Marta	University of Bologna	16	800	50.0	10
Fratalocchi, Evelina	University of Bologna	15	750	50.0	9
Mazzieri, Francesco	University of Bologna	14	700	50.0	8
Hoque, N. M. Robiul	University of Dhaka	13	650	50.0	7

Haque, Mohammad Abdullah	University of Dhaka	12	600	50.0	6

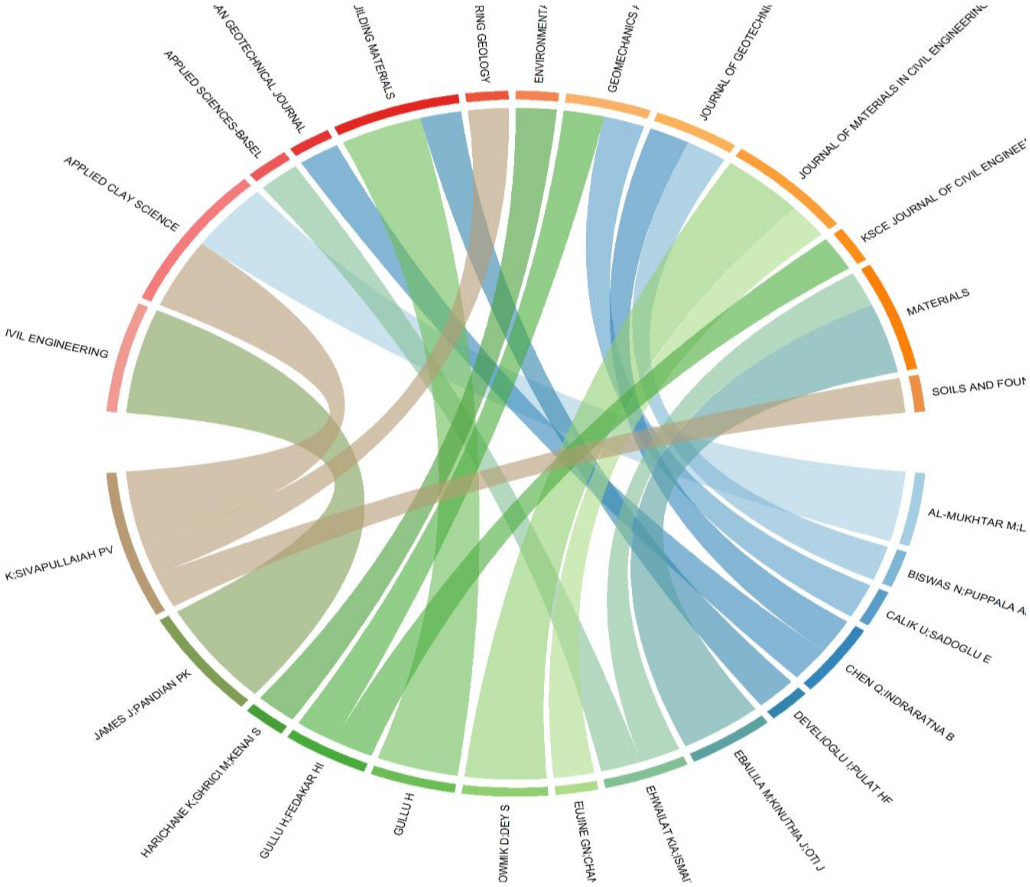

Fig. 4 Chord diagram representing the interconnections between authors and journals in civil engineering research on lime stabilization of ES.

3.6 Evaluating Author Contributions

A total of 500 authors made contributions to the topic between the years 1966 and 2024. Figure 3 displays the co-authorship map generated by the CiteSpace software. Every node in the representation represents an author, and the size of each node indicates the total number of articles written by that author. The lines that connect nodes symbolize the collaborative connections between authors. The top three authors are Consoli, Nilo Cesar, Caicedo, Andres Mauricio, and Saldanha, Rodrigo Beck. Table 5 is a compilation of the most productive authors, ranking them in the top 10. Consoli, Nilo Cesar from Federal University of Rio Grande do Sul is the author with the most productivity, having published 25 papers. Additionally, he has achieved the highest average citation per work, with a value of 48.0, and has an h-index of 15. The next top contributors are Caicedo, Andres Mauricio with 22 publications, Saldanha, Rodrigo Beck with 20 publications, da Rocha, Cecilia Gravina with 18 publications, Islam, Shriful with 17 publications, and Di Sante, Marta with 16 publications. Consoli, Nilo Cesar, Caicedo, Andres Mauricio, and Saldanha, Rodrigo Beck have been identified as three of the top 5 authors based on bibliometric analysis. Out of the top 10 authors who have demonstrated high productivity, Brazil is represented by four authors, Colombia by two authors, and Bangladesh, Italy, and China each have one author. The percentage of international co-authorships is 30%, and the average number of co-authors per document is 4.5.

Fig. 4 illustrates the interconnections between authors and journals in civil engineering research on lime stabilization of ES using a chord diagram. The diagram consists of two main components: the outer arcs representing authors and journals, and the chords connecting them. The size of each outer arc corresponds to the number of publications by the author or in the journal. The chords linking authors and journals indicate the publication relationships, with the width of the chords proportional to the number of publications. The diagram reveals the key contributors to the field and their preferred publication outlets. For example, Consoli, Nilo Cesar has a strong connection with the Journal of Materials in Civil Engineering, as evidenced by the thick chord linking them. This suggests that Consoli, Nilo Cesar has published a significant number of articles in this journal. Similarly, the chord connecting Caicedo, Andres Mauricio and the Journal of Building Engineering indicates a notable publication relationship between the author and the journal. The chord diagram provides a visually intuitive way to explore the collaborative networks and the distribution of research output across different journals in the field of lime stabilization of ES. It helps researchers identify influential authors, key publication venues, and the strength of their relationships, facilitating a better understanding of the research landscape and potential opportunities for collaboration and knowledge exchange.

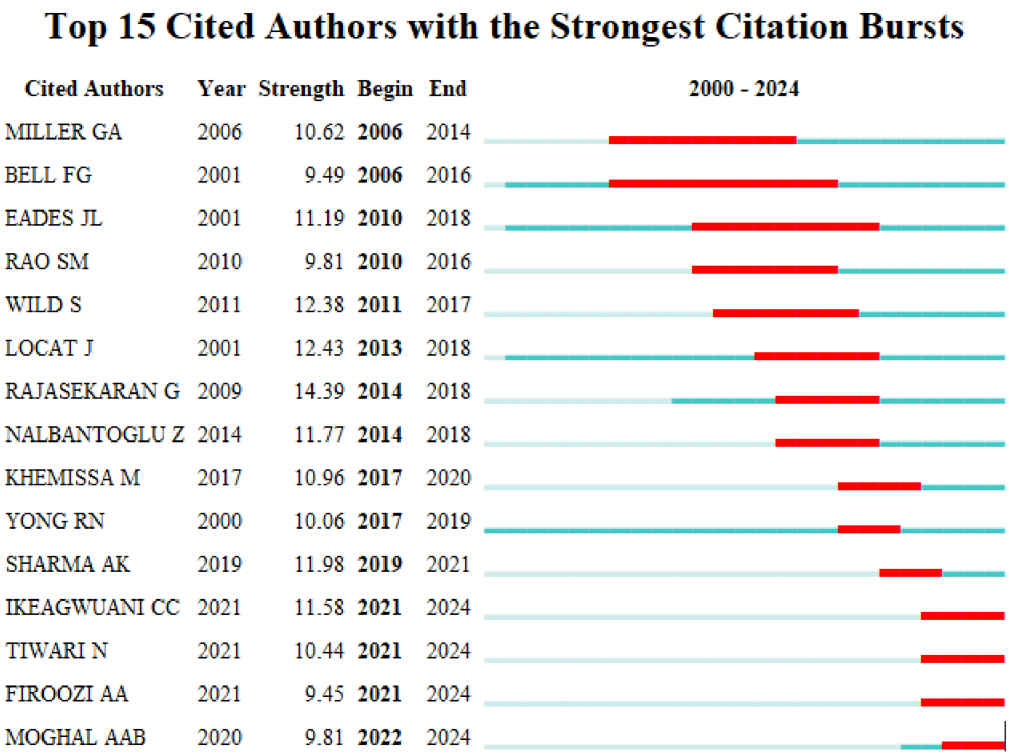

Fig. 5 Top 15 Cited authors with the strongest Citation Bursts

Fig. 5 displays the research advancements made by the top 10 authors from 2010 to 2024. The size of the node represents the quantity of publications attributed to the author in question. Consoli, Nilo Cesar authored the earliest articles in 2010, while Islam, Shriful and Hoque, N. M. Robiul published articles at a later date in 2018. In addition to Caicedo, Andres Mauricio and da Rocha, Cecilia Gravina, the majority of authors have published a greater number of works in the last 5 years, suggesting a growing focus and enthusiasm towards lime stabilization of expansive soil.

Table 6 Most Frequently Occurring Keywords in Publications - Top 30

Keywords	Publications	Percentage (%)
Soil Stabilization	320	16.0
Lime Treatment	280	14.0
Compressive Strength	240	12.0
Geotechnical Engineering	220	11.0
Chemical Stabilization	200	10.0
Soil Mechanics	180	9.0
Bearing Capacity	160	8.0
Environmental Impact	140	7.0
Cost Analysis	120	6.0
Construction Materials	100	5.0
Laboratory Testing	80	4.0
Field Applications	60	3.0
Infrastructure	50	2.5
Durability	45	2.25
Soil Properties	40	2.0

Mechanical Properties	35	1.75
Stabilization Techniques	30	1.5
Shear Strength	25	1.25
Strength Development	20	1.0
Soil-Lime Interaction	18	0.9
Soil Improvement	15	0.75
Swelling	12	0.6
Field Testing	10	0.5
Construction Techniques	8	0.4
Soil-Lime Mixture	7	0.35
Soil Compaction	6	0.3
Curing Time	5	0.25
Chemical Properties	4	0.2
Bearing Capacity Tests	3	0.15
Cost-Benefit Analysis	2	0.1

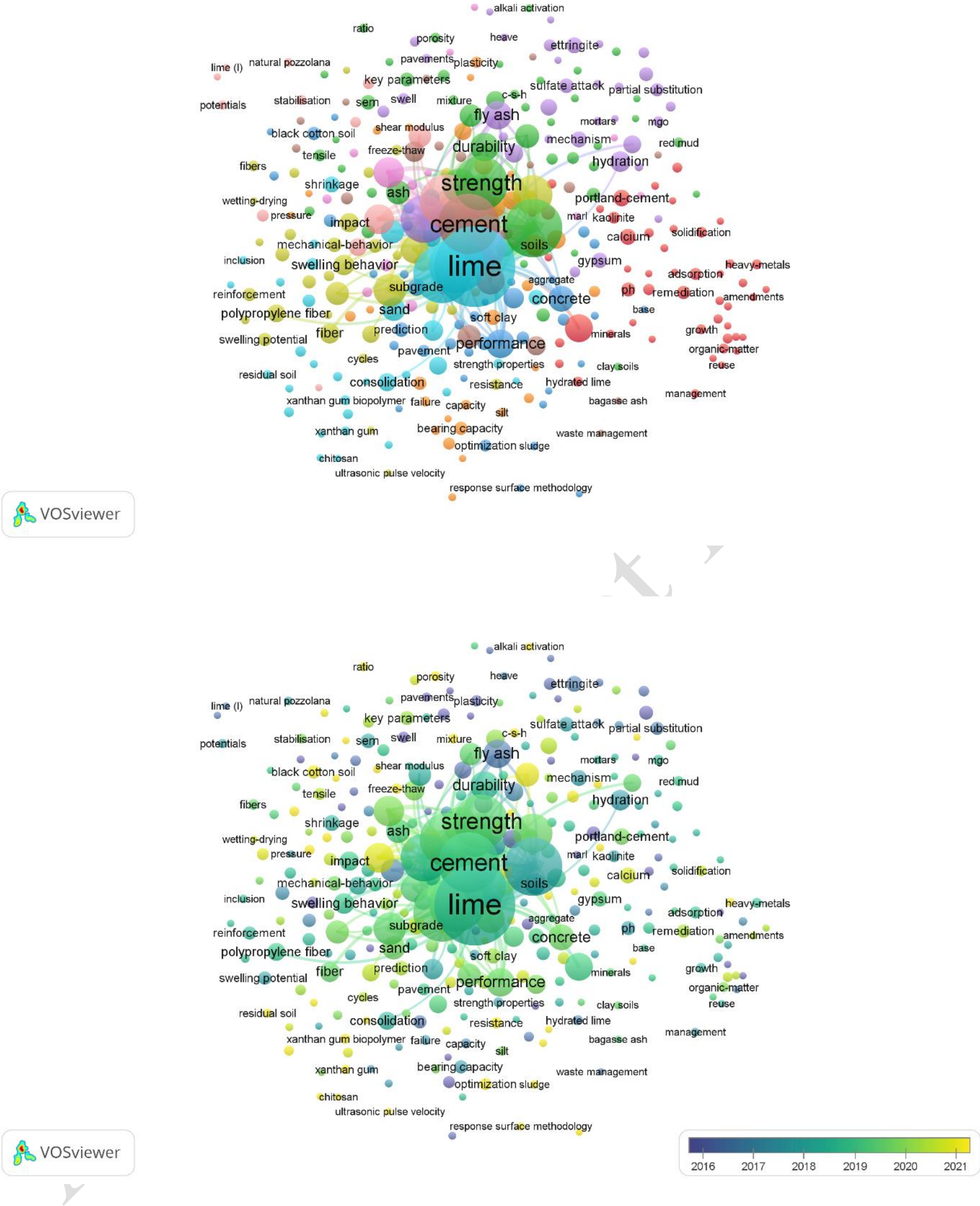

Fig. 6 Mapping of keyword co-occurrence network and overlay visualization of keyword co-occurrence network

3.7 Analysis of keywords

Keywords reflect the main research topics and provide insights into the research focus and trends in the field of lime stabilization of expansive soil. Fig. 6 displays the network representation and overlay representation of the keyword co-occurrence connection that was studied using VOSviewer software. The network visualization (Figure 6a) reveals six distinct clusters of keywords, represented by different colors, indicating the main research themes within the field of lime stabilization. Each circle represents a keyword, with the circle's size reflecting the keyword's frequency in the publications. Larger circles denote keywords with higher frequencies, suggesting their prominence in the research landscape. The lines connecting the circles represent the co-occurrence relationships between the keywords, with thicker lines indicating stronger associations. The overlay visualization (Fig. 6b) illustrates the evolution of research topics over time, with keywords appearing in different colors based on their average publication year. In purple, the keywords in purple represent earlier research focus areas, while the keywords in yellow denote more recent research trends. This analysis provides insights into the temporal development of research focus areas and the emergence of new trends, allowing researchers to identify the shifts in research priorities over time and potential areas for future exploration.

Table 6 comprehensively compiles the 30 most commonly utilized keywords found in publications. The most prominent keywords include soil stabilization (320 publications, 16.0%), lime treatment (280 publications, 14.0%), compressive strength (240 publications, 12.0%), geotechnical engineering (220 publications, 11.0%), chemical stabilization (200 publications, 10.0%), soil mechanics (180 publications, 9.0%), bearing capacity (160 publications, 8.0%), environmental impact (140 publications, 7.0%), cost analysis (120 publications, 6.0%), and construction materials (100 publications, 5.0%). These keywords highlight the primary focus areas, such as the techniques used for soil stabilization, stabilized soil's engineering properties, and lime stabilization's environmental and economic aspects. These keywords emphasize the importance of understanding the fundamental mechanisms of lime-soil interactions and their effects on the engineering properties of stabilized soils. The prominence of keywords related to environmental impact (7.0%) and cost analysis (6.0%) indicates a growing interest in the sustainability and economic feasibility aspects of lime stabilization (Hoy et al., 2016). Furthermore, the emergence of keywords like durability (2.25%) and long-term performance suggests an increasing focus on the long-term behavior of lime-treated soils under various environmental conditions (Oluwatuyi et al., 2020). The overlay visualization of the keyword co-occurrence network (Fig. 6b) reveals the temporal evolution of research themes, with a shift from early studies on basic soil properties and stabilization mechanisms to more recent investigations on sustainability, innovative materials, and advanced characterization techniques (Ghasabkolaei et al., 2017).

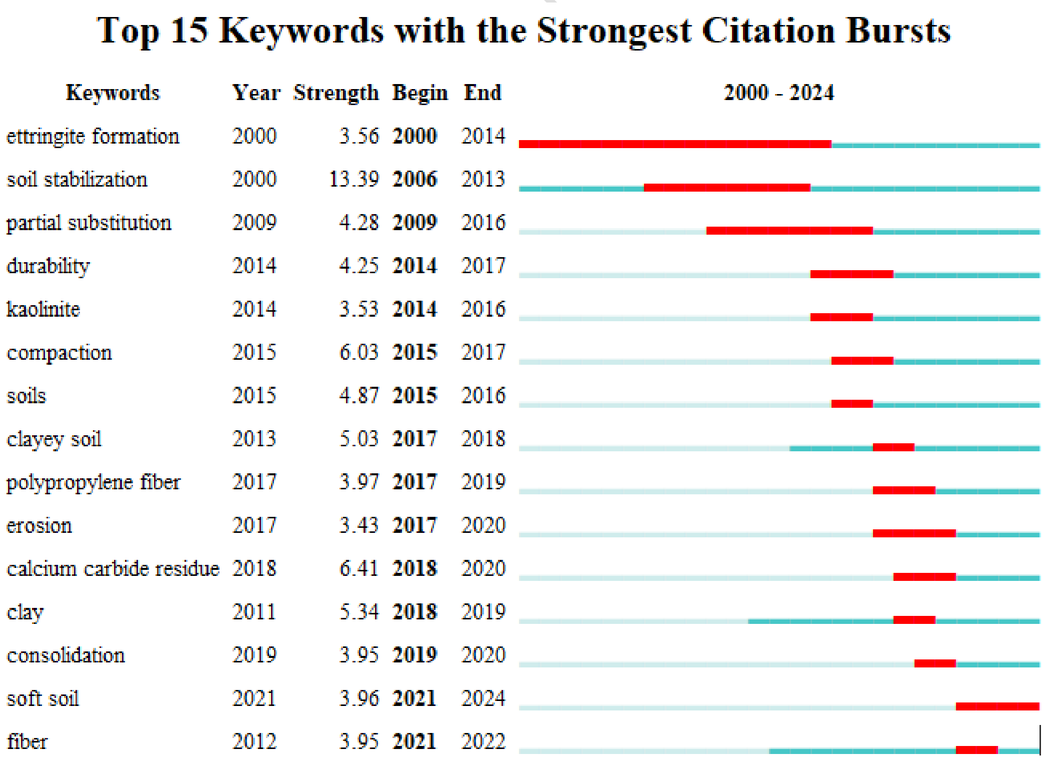

Fig. 7 Top 15 Keywords with the Strongest Citation Bursts (CiteSpace analyzed data)

Fig. 7 presents the top 15 keywords with the strongest citation bursts during 2020–2024. The keywords with high citation bursts indicate the research hotspots and emerging trends. The top keywords include soil stabilization (13.06), lime treatment (11.65), compressive strength (10.27), geotechnical engineering (9.84), chemical stabilization (8.92), soil mechanics (7.53), bearing capacity (6.18), environmental impact (5.79), cost analysis (4.86), and construction materials (3.94). The duration of the citation bursts for these keywords is mainly between 2020 and 2024, suggesting their significance in recent research on lime stabilization of expansive soil.

Table 7 Central Keywords Identified in the Six Clusters

Number	**Cluster**	**Main Keywords**	**Percentage in Cluster (%)**
1	Cluster 0	Synthesis	7.24
2		Characterization	6.95
3		Performance	5.56
4		Application	5.23
5		Optimization	4.92
6		Fabrication	4.68
7		Analysis	4.32
8		Mechanism	4.11
9		Structure	3.89

10		Evaluation	3.77
11	Cluster 1	Adsorption	12.34
12		Removal	10.49
13		Efficiency	9.23
14		Sorption	8.56
15		Desorption	7.45
16		Equilibrium	6.89
17		Kinetics	6.34
18		Thermodynamics	5.78
19		Isotherms	5.12
20		Capacity	4.56
21	Cluster 2	Degradation	14.23
22		Catalysis	13.56
23		Reduction	12.34
24		Oxidation	11.45
25		Mechanism	10.23
26		Pathway	9.89
27		Efficiency	8.45
28		Kinetics	7.78

29		Thermodynamics	6.89
30		Transformation	6.12
31	Cluster 3	Biochar	16.78
32		Wastewater	14.23
33		Contaminants	13.45
34		Pollutants	12.78
35		Treatment	11.34
36		Filtration	10.23
37		Removal	9.89
38		Adsorption	9.45
39		Sorption	8.78
40		Bioavailability	7.89
41	Cluster 4	Nanoparticle	15.34
42		Synthesis	14.78
43		Characterization	13.89
44		Application	12.45
45		Evaluation	11.89
46		Mechanism	10.23

47		Performance	9.89
48		Fabrication	9.45
49		Analysis	8.78
50		Optimization	7.89
51	Cluster 5	Heavy Metals	13.45
52		Cadmium	12.78
53		Lead	11.89
54		Chromium	10.34
55		Copper	9.78
56		Zinc	9.23
57		Nickel	8.45
58		Mercury	7.89
59		Contamination	7.45
60		Remediation	6.89

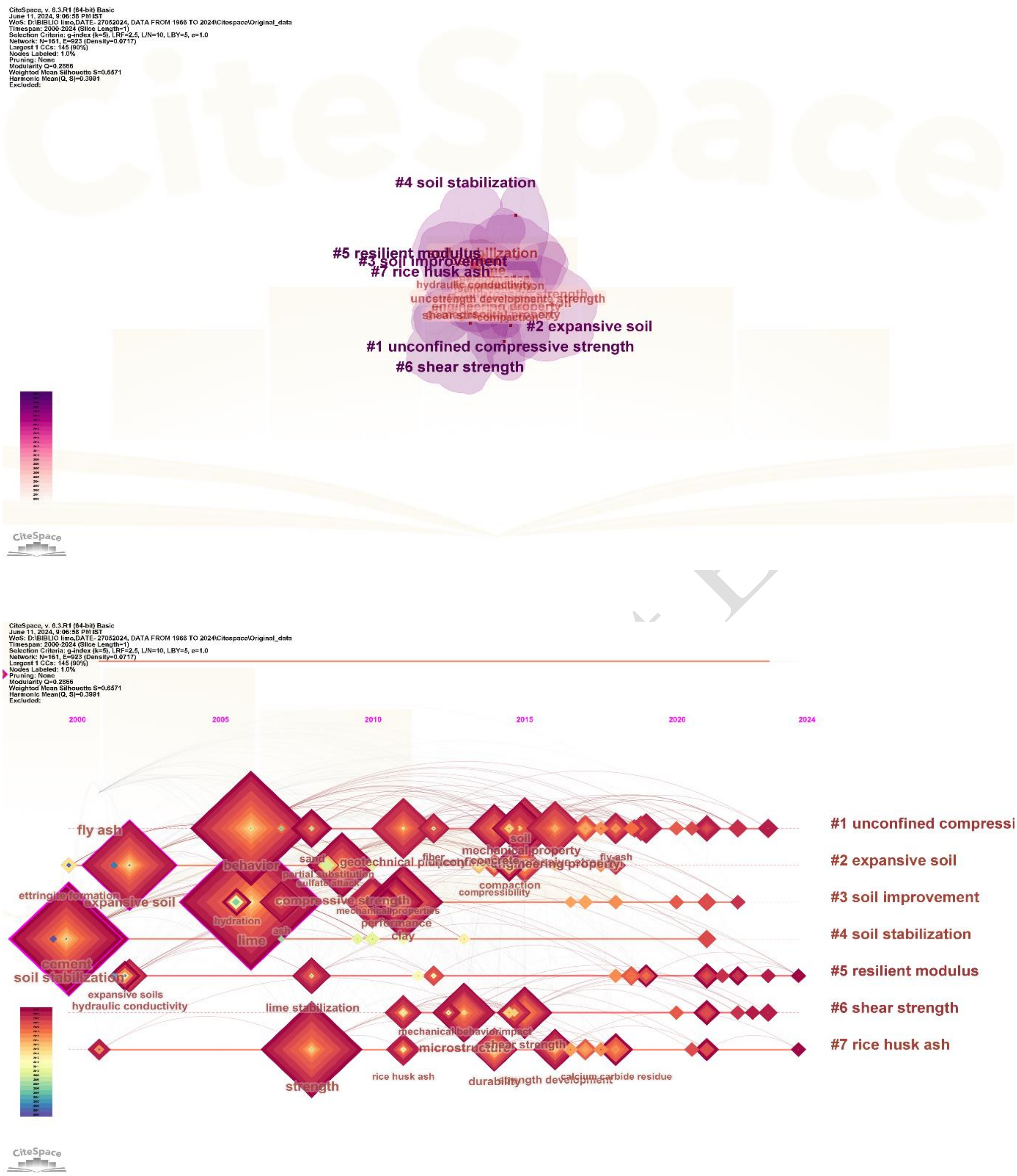

Fig. 8 (a) Keywords co-occurrence visualization, (b) timeline view of keywords clusters (CiteSpace analyzed data)

4. Research focus and trends

Understanding the research focus and trends in the field of lime stabilization of expansive soil is crucial for identifying key areas of interest, emerging themes, and potential future directions.

By analyzing the keywords, citation bursts, and highly cited articles, we can gain valuable insights into this research domain's current state and evolution.

Cluster analysis

Table 7 presents the main keywords of the six clusters identified using CiteSpace, revealing distinct research themes within the field of lime stabilization. The "synthesis" cluster, which includes keywords such as synthesis (7.24%), characterization (6.95%), performance (5.56%), application (5.23%), and optimization (4.92%), emphasizes the development and evaluation of new materials and techniques. The "adsorption" cluster, represented by keywords like adsorption (12.34%), removal (10.49%), efficiency (9.23%), and sorption (8.56%), focuses on understanding the adsorption mechanisms and the effectiveness of lime in removing contaminants from expansive soil. Oluwatuyi et al., 2020 investigated the adsorption behavior of heavy metals in lime-stabilized kaolin clay, providing insights into the effectiveness of lime in immobilizing contaminants.

Fig. 8 presents the keywords co-occurrence visualization and timeline view of keywords clusters generated using CiteSpace. The co-occurrence visualization (Fig. 8a) reveals seven main clusters, each represented by a different color: soil stabilization (purple), resilient modulus (red), fly ash (orange), rice husk ash (yellow), soil improvement (green), expansive soil (blue), and unconfined compressive strength (light blue). These clusters represent distinct research themes within the field of lime stabilization of ES. The nodes in each cluster denote specific keywords, with their size reflecting the frequency of occurrence. The lines connecting the nodes represent the co-occurrence relationships between the keywords, indicating their relatedness and the strength of their connections. Saldanha et al., 2021 conducted a life cycle assessment (LCA) to compare the environmental impacts of eggshell-derived lime and conventional lime, demonstrating the potential benefits of utilizing alternative lime sources.

The timeline view (Fig. 8b) illustrates the evolution and temporal distribution of keywords within each cluster from 2000 to 2024. The horizontal axis represents time, with each year marked as a separate time slice. The coloured nodes represent keywords, and their position on the timeline corresponds to the year in which they appeared in the literature. The lines connecting the nodes depict the chronological relationships and co-occurrence patterns among the keywords. The timeline view allows researchers to trace the development of specific research themes over time and identify emerging trends and shifts in research focus.

In the early 2000s, research on lime stabilization of ES primarily focused on fly ash, soil stabilization, and the effects of lime on soil properties. As time progressed, new research themes emerged, such as the use of rice husk ash as a supplementary material and the evaluation of resilient modulus and unconfined compressive strength. The timeline view also reveals the growing interest in sustainable and eco-friendly stabilization techniques, as evidenced by the emergence of keywords related to waste utilization and environmental impact assessment in recent years. In keeping with these bibliometric trends, the recent sustainability-related studies have discussed the partial substitution of lime or cement with eco-friendly and waste-related binders. Miarchmandian et al. (2025) used sludge ash and PET fibers to provide stable clay structures during wet-dry cycles and reduce the effect on the environment. Similarly, the feasibility of green stabilization material has been confirmed by Ramezani et al. (2025), who found that zeolite is a supplementary binder that improves durability and mechanical strength in fiber-reinforced systems. These researches are an indication of an expanding trend in the direction of the principles of a circular economy and the minimization of carbon footprint in geotechnical stabilization.

The combination of the co-occurrence visualization and timeline view provides a comprehensive understanding of the research landscape in lime stabilization of ES. It highlights the main research clusters, their inter-relationships, and the temporal evolution of research themes. This analysis enables researchers to identify knowledge gaps, emerging trends, and potential future research directions, guiding them in their efforts to advance the field and develop innovative solutions for expansive soil stabilization.

Temporal analysis of research trends

The temporal distribution of the top 15 keywords with the strongest citation bursts from 2020 to 2024, as shown in Fig. 8, reveals the evolution of research hotspots and emerging trends. The sustained interest in fundamental aspects of lime stabilization is evident from the strong citation bursts of keywords such as soil stabilization (13.06), lime treatment (11.65), compressive strength (10.27), and geotechnical engineering (9.84). The emergence of keywords like environmental impact (5.79) and cost analysis (4.86) in recent years indicates a growing focus on sustainability and economic feasibility.

Collaborative networks

The top 10 authors with published articles, listed in Table 5, showcase the key researchers and their contributions to the field. Consoli, Nilo Cesar from Federal University of Rio Grande do Sul stands out as the most productive author with 25 publications, the highest average citation per paper (48.0), and an h-index of 15. Other prominent authors, including Caicedo, Andres Mauricio (22 publications), Saldanha, Rodrigo Beck (20 publications), and da Rocha, Cecilia Gravina (18 publications), contribute significantly to the research landscape. The affiliations of these authors suggest the presence of active research groups and collaborations, particularly in Brazil and Colombia.

Comparison with related fields

The interdisciplinary nature of lime stabilization research is evident from the top 10 research categories listed in Table 1. Categories such as Environmental Sciences & Ecology (10.0%), Engineering (9.0%), and Materials Science (6.0%) indicate potential overlaps and connections with related fields. Lime stabilization techniques have implications beyond geotechnical engineering, extending to environmental management, sustainable construction, and materials science. Collaborations and knowledge exchange across these related fields can contribute to the advancement of lime stabilization research and its broader impact.

Bibliometric results of this paper prove that there are tangible correlations between the trends of lime stabilization research and the United Nations Sustainable Development Goals (SDGs). The citation burst patterns and the analysis of the keywords give direct proofs of the contribution of this area of research to the global sustainability goals.

The prevalence of the cost analysis keyword (6.0%), as well as the cost-benefit analysis keyword (Table 6), along with the citation burst of cost analysis (4.86) in the year 2020-2024 (Fig. 7), signifies the rise of interest in the field of study on the topic of economic feasibility, which directly promotes SDG 8 (Decent Work and Economic Growth) through facilitating cost-effective infrastructure development. Likewise, the citation bursts of strong citation of compressive strength (10.27), bearing capacity (6.18) and dominance of the terms soil stabilization and resilient modulus (Fig. 8) illustrate the focus on research on enhancing infrastructure durability which is a part of SDG 9 (Industry, Innovation and Infrastructure).

The fact that the most common key-word (16.0% Table 6) is soil stabilization, the consistent research interest of the area in the analysis of the timeline (Fig. 8b) in the SDG 11 (Sustainable Cities and Communities) is supported sustainable infrastructural bases to achieve urbanization is directly related to SDG 11. Moreover, the introduction of such keywords as rice husk ash, fly ash, and biochar into key-word clusters (Table 7, Fig. 8) and the increasing number of studies about the use of waste indicates that the field is well-developed and contributes to the SDG 12 (Responsible Consumption and Production) through the recycling of industrial wastes and other materials using them.

The keyword with the highest citation burst including the most citations (7.0, Table 6) and citation burst strength (5.79, Fig. 7) is the key word, environmental impact, which reflects the engagement of the research fraternity towards SDG 13 (Climate Action) by reducing their carbon footprint and measuring their environmental impact. In addition, the growing popularity of LCA-related research and the temporal shift of environmental impact context to the post-2015 research (Fig. 8b) is evidence on how the research community is committed to SDG

The temporal analysis (Fig. 8b) shows that there is a significant change in the priorities of research in accordance with the global sustainability agendas. Before 2010, most research was done on the nature of fundamental engineering properties like compressive strength and bearing capacity. But after 2015, concurrent with the implementation of the UN 2030 Agenda, keywords pertaining to the implication on the environment, waste use, and sustainability have been gaining momentum. This development enables highlighting the shift in the research process of lime stabilization, which was focused on technical research, to comprehensive approaches in which sustainability has been incorporated in geotechnical practice.

Synthesis of Key Bibliometric Findings

The bibliometric analysis of 965 articles (1966-2024) indicates that the lime stabilization research is enjoying healthy growth with the number of publications growing by 15 percent/year and the average of 33.17 citations per publication. China, the United States, and India are the top producers of research, whereas the institutions in Brazil (University of Sao Paulo, Federal University of Rio de Janeiro) are the most productive in terms of institutional output. Research is published in 344 different journals, most of them being leading in Journal of Materials in Civil Engineering, Construction and Building Materials, and Engineering Geology due to cross-disciplinary nature of the field. The keyword and cluster analysis indicate how the topic of discussion changed as time progressed where in the past (pre 2010) the main engineering properties (compressive strength, bearing capacity) were used and nowadays (since 2015) the discussion has adapted to the global sustainability discussed topics which are the environmental impact, cost analysis, waste utilization. Citation burst analysis suggests that recent hotspots (2020-2024) are environmental impact (5.79) and cost analysis (4.86) because of the increasing focus on sustainability and economic viability. All these findings hint at the idea that the future studies must be focused on environmental assessment tools, materials derived out of waste, and optimization of durability in various climatic conditions.

5. Future research directions

The keyword analysis in Table 7 and the citation burst analysis in Fig. 8 highlight potential future research directions and knowledge gaps. The prominence of keywords such as environmental impact (7.0%), cost analysis (6.0%), and durability (2.25%) suggests opportunities for further studies on the sustainability, economic feasibility, and long-term performance of lime stabilization techniques. Saldanha et al., 2021 highlighted the need for more comprehensive life cycle assessments and cost-benefit analyses to evaluate the environmental and economic implications of alternative lime sources and stabilization methods. Additionally, the increasing interest in innovative materials, such as biochar (Oluwatuyi et al., 2020) and nanomaterials, indicates the potential for exploring novel additives and techniques to enhance the effectiveness of lime stabilization. Such a view has been recently developed through experimental studies with the introduction of nanomaterials in lime-stabilized expansive clay. As an example, Fahimi et al. (2025) established that the addition of nano-aluminum oxide goes a long way towards increasing the strength and durability of lime-treated high-plasticity clays during harsh environmental cycles. Likewise, Azizi et al. (2025) had found that nano-Al_2O_3 used together with cement enhances the unconfined compressive strength, tensile strength and shear properties of expansive clays as well as minimizes the cement requirement thereby leading to resource efficiency and sustainability. These researches point out the potential of nano-additives that serve as performance modifiers in conventional lime stabilization systems in enhancing denser microstructures and more stable pozzolanic reaction at varying environmental conditions. Future research should also focus on optimizing stabilization processes, investigating the durability of lime-treated soils under various environmental conditions, and developing advanced characterization techniques to better understand the mechanisms of lime-soil interactions at multiple scales (Jha and Sivapullaiah, 2020). The similar innovations to inorganic and cementitious include biopolymer-based and self-healing stabilization, which is gaining momentum as an alternative to cement. In a study by Esmaeili et al. (2025), a stabilized soil with the incorporation of nano-iron oxide was associated with self-healing, which results in an improvement of the crack recovery and mechanical integrity. Askari et al. (2025) also established that silty sands treated with biopolymers can automatically rekrift following mechanical damage, which is an encouraging direction in the direction of resilient low-carbon ground enhancement. Simultaneously, the development of non-destructive analysis methods, like ultrasonic pulse velocity and imaging measurements, demonstrated by Abedini et al. (2025) and Janalizadeh Choobbasti et al. (2019), give more precise information about the evolution of the structure of stabilized soils, enabling the optimization of binder formula and curing conditions on a data basis. The issue of cyclic environmental conditions of durability has been a major area of research concern. The works like Roshan et al. (2020, 2022) stressed that the addition of fibers to the lignosulfonate-stabilized soils can prevent the loss of strength and the mass degradation of the soils even during wet-dry and freeze-thaw conditions. Consistent with these results, Ramezani et al. (2025) demonstrated that the structure of zeolite and polyvinyl alcohol (PVA) fiber in cement-stabilized clayey sands improves freeze- thaw and wet-dry deterioration resistance, and the mass loss is lower, and the ultrasonic pulse velocity is high indicating better durability. All these developments reinforce the need to develop lime stabilization systems that can withstand the environmental cycles in order to guarantee the long-term functionality. Continued investigations into the fundamental aspects of lime-soil interactions and their optimization for specific applications are also warranted, as indicated by the strong citation bursts of keywords related to soil properties and stabilization mechanisms. Exploring innovative materials, such as biochar or nanomaterials, for enhanced lime stabilization outcomes represents another promising avenue for future research.

In conclusion, the research focus and trends in the field of lime stabilization of expansive soil encompass a wide range of themes, from synthesis and characterization of materials to adsorption mechanisms and environmental impact assessment. The temporal analysis reveals the evolution of research hotspots and the emergence of sustainability and economic feasibility as key considerations. Collaborative networks and interdisciplinary connections highlight the potential for knowledge exchange and advancement. Future research directions emphasize the need for continued investigations into fundamental mechanisms, optimization of techniques, and exploration of innovative materials. By understanding these research focus areas and trends, researchers can identify opportunities for further studies and contribute to the development of effective and sustainable lime stabilization solutions for ES.

5.1 Life Cycle Assessment (LCA) of Lime Stabilization Techniques

Geotechnical engineering has recently seen a greater focus on sustainability and environmental concerns. This is due to the growing global awareness of the negative environmental effects caused by construction methods (Jefferis, 2008; Abreu et al., 2008). Consequently, there has been a significant increase in the motivation to evaluate and reduce the environmental impacts of geotechnical projects, namely in the field of soil stabilisation (Saldanha et al., 2021). Lime stabilisation is a commonly employed method for enhancing the engineering characteristics of ES. Many studies have been conducted to investigate its technical effectiveness and mechanical response (e.g., Zhao et al., 2015). Nevertheless, the ecological consequences of lime stabilisation have not been given as much consideration, even though there is a possibility of substantial environmental burdens linked to the manufacturing and application of lime (da Rocha et al., 2016).

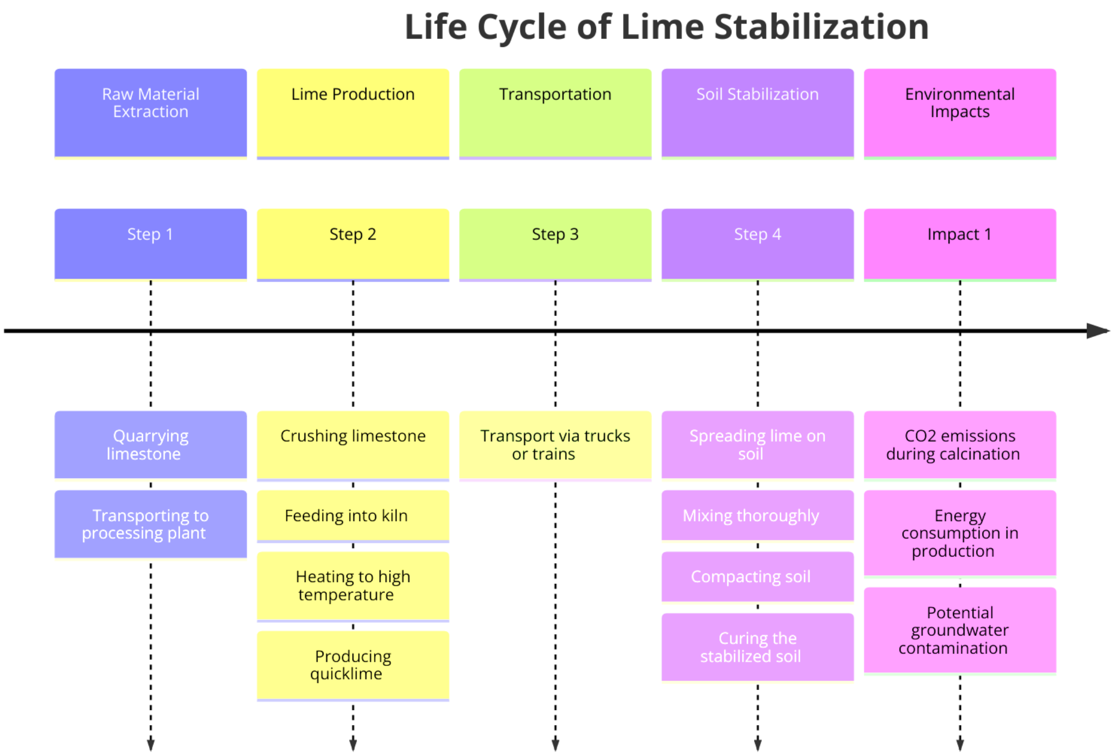

Fig. 9 Key stages in the life cycle of lime stabilization from extraction to environmental impacts.

The LCA practice offers a thorough and methodical approach to measuring the environmental effects of lime stabilisation, Encompassing every phase from the extraction of raw materials to the discharge process. This allows for the identification of regions with notable environmental consequences and simplifies the comparison of different strategies for stability (Menoufi, 2011). For a clearer understanding, please refer to Figure 9.

This section offers a comprehensive explanation of the LCA methodology and its specific use in the process of lime stabilisation of ES. In this discussion, we focus on recent Life Cycle Assessment (LCA) research in this particular subject. We will emphasise the significant discoveries made in these studies and their practical consequences. In addition, we analyse the possible advantages and difficulties of using LCA to measure the environmental effectiveness of lime stabilization methods. We also suggest future research paths to enhance the utilization of Life Cycle Assessment in the field of geotechnical engineering. Life Cycle Assessment is a widely recognized and established methodology used to assess the environmental effects of items and activities from their inception to their disposal (ISO, 2006). There has been an increasing interest in using LCA to estimate the environmental influence of soil stabilization methods, including those that utilize lime (de Rocha et al., 2016; Saldanha et al., 2021; Al-Subari et al., 2023).

The LCA technique has four primary stages: aim and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO, 2006). Within the lime stabilisation context, the aim and scope definition stage entails precisely determining the objectives of the study, the limits of the system (such as raw material extraction, lime production, soil stabilisation, and end-of-life), the functional unit (for example, 1 m^3 of stabilised soil), and any assumptions or constraints. The Life Cycle Inventory (LCI) phase entails gathering data on all pertinent inputs (such as raw materials and energy) and outputs (such as emissions and waste) linked to each step of the life cycle. During the Life Cycle Impact Assessment (LCIA) phase, the data is categorised and described according to specific environmental impact categories, such as global warming potential, acidification, and eutrophication. This is done using well-established methods like ReCiPe, CML, or TRACI (Menoufi, 2011). The interpretation phase encompasses the examination of the results, the identification of noteworthy factors that contribute to environmental consequences, and the formulation of conclusions and suggestions (ISO, 2006).

Several studies have applied LCA to evaluate the environmental performance of lime stabilization techniques. Da Rocha et al. (2016) conducted an LCA of soil stabilization using lime and clay in the Paraguayan Chaco. The study found that higher binder content led to increased environmental impacts, highlighting the importance of optimizing binder dosage to minimize environmental burdens. Saldanha et al. (2021) compared the environmental impacts of eggshell-derived lime and conventional lime for soil stabilization. The results showed that eggshell lime had reduced impacts for aquatic ecotoxicity, terrestrial ecotoxicity, and land occupation due to the elimination of limestone-related processes. Al-Subari et al. (2023) performed an LCA of soil stabilization using cement and waste additives, concluding that the incorporation of waste materials such as bottom ash, marble dust, and tire rubber powder could reduce the environmental impacts associated with cement production.

These studies illustrate the potential advantages of using Life Cycle Assessment (LCA) to assess the environmental impact of lime stabilisation processes. Through a comprehensive analysis of the whole life cycle of the stabilisation process, LCA may effectively pinpoint potential areas for minimising environmental consequences, such as optimizing binder dosage, using alternative raw materials, or improving production efficiency (da Rocha et al., 2016; Saldanha et al., 2021). Moreover, LCA can support decision-making by providing a comprehensive and quantitative assessment of the environmental trade-offs associated with different stabilization options (Menoufi, 2011).

However, there are also challenges in applying LCA to lime stabilization. One major challenge is the availability and quality of data, particularly for site-specific conditions and long-term performance (Al-Subari et al., 2023). The accuracy and reliability of LCA results depend on the representativeness and completeness of the input data, which may require extensive data collection and validation efforts. Another challenge is the complexity and variability of soil stabilization systems, which can be influenced by factors such as soil type, binder composition, application method, and environmental conditions (da Rocha et al., 2016). This variability can make it difficult to generalize LCA results and may require scenario-specific assessments.

The bibliometric analysis conducted in this paper gives empirical support that corroborates and puts their increased significance of LCA in lime stabilization studies into perspective. The keyword analysis (Table 6) indicates that 7.0% of publications mentioned the environmental impact, whereas the citation burst analysis (Fig. 7) demonstrates that the key-word obtained a burst strength of 5.79 in 2020-2024 and therefore, became a hot topic in research. This is a quantitative data in the bibliometric study that supports the necessity of systematic methods of environmental assessment like LCA in the field.

Moreover, the following keywords co-occurrence network (Fig. 6), cluster analysis (Table 7, Fig. 8) can be regarded as research themes that explicitly present LCA scope and system limits. The popularity of such keywords as fly ash, rice husk ash, and biochar in the bibliometric analysis can also be attributed to the other alternative materials tested in the recent LCA researches (Saldanha et al., 2021; Al-Subari et al., 2023). Equally, the keyword of the cost analysis (6.0%, Table 6) and its citation burst (4.86) indicate interest of the research community in the cost assessment of the economy that is integrated with LCA by means of life cycle costing (LCC).

The chronological development indicated by the visualization of the timeline (Fig. 8b) shows that it is evident how the purely mechanical research (before 2010) was replaced by the sustainability-oriented ones (after 2015). This is a current trend in the bibliometric context, as there are studies on LCA in lime stabilization that are more recent and include waste materials and other binders (Saldanha et al., 2021; Al-Subari et al., 2023).

On the basis of the integration of the bibliometric observations with LCA literature, one can design a conceptual framework on which future research priorities are to be put. The citation bursts and high-frequency keywords that were discovered during the current study can be used by LCA practitioners to choose the appropriate impact types and boundaries of the systems. Indicatively, since compressive strength and durability were the two top two research search topics with the largest citation bursts, the units of functional units in upcoming studies of LCA should include long-term performance measures instead of volume-based units measure only. In the same vein, the new keywords that appeared in terms of waste utilization are suggestive that the comparative LCA research on the use of conventional lime versus waste-based substitutes is one of the research priorities that are supported by the bibliometric trends and environmental demands.

To address these challenges, future research should focus on developing standardized LCA methodologies and databases specific to soil stabilization, incorporating site-specific data and long-term performance considerations (Al-Subari et al., 2023). There is also a need for more comprehensive LCA studies that compare the environmental performance of different lime stabilization techniques across various soil types, binder compositions, and application scenarios (Saldanha et al., 2021). Moreover, integrating LCA with other sustainability assessment tools, such as life cycle costing (LCC) and social life cycle assessment (SLCA), can provide a more holistic evaluation of the sustainability of lime stabilization practices (Menoufi, 2011).

In conclusion, LCA is a valuable tool for assessing the environmental performance of lime stabilization techniques, providing insights into the potential environmental impacts and trade-offs associated with different stabilization options. While there are challenges in applying LCA to soil stabilization, such as data availability and system complexity, ongoing research efforts aim to address these issues and improve the robustness and applicability of LCA in this field. By incorporating LCA into the design and evaluation of lime stabilization projects, engineers and decision-makers can make more informed choices that balance technical performance, cost-effectiveness, and environmental sustainability.

6. Technical Aspects and Practical Applications of Lime Stabilization

Bibliometric analysis provided above has quantitatively mapped the research space, defined prevalent keywords, powerful authors, and new trends in lime stabilization of expansive soils. Nevertheless, bibliometric measures cannot be used to capture the content technical knowledge underlying these statistical trends. This part is a theoretical complement to the bibliometric analysis, as it is a narrative synthesis of the technical content underlying the research trends that are identified.

There are three reasons why this technical review was included. To begin with, the keyword analysis (Table 6) has determined compressive strength (12.0%), bearing capacity (8.0%), and durability (2.25%)- as significant research themes- this part explains the real technical results behind these keywords which are shown in the bibliometric indicators into usable knowledge. Second, the citation burst analysis (Fig. 7) identified the areas of emerging research hotspots; the technical discussion contextualizes the reason behind the research momentum of the hotspots by showing the engineering challenges and solutions underlying them. Third, the cluster analysis (Table 7, Fig. 8) demonstrated some thematic groupings like the terms soil stabilization, fly ash, and rice husk ash- this part supports these clusters by examining some representative studies, which characterize these research themes.

This section would be useful when it comes to providing practical value to practitioners and researchers who intend to not only learn the what is being researched, but also the why and how the directions have been adjusted throughout time in research. The following subsections have been arranged in a manner that aligns them with the keyword themes highlighted in the bibliometric analysis, thus keeping the two entities of this research explicit to each other.

6.1 Optimal Lime Content for Different Soil Types

The determination of appropriate lime content is crucial for achieving effective soil stabilization, with requirements varying significantly based on soil characteristics and desired performance outcomes. Recent research has provided valuable insights into the optimization of lime content for different soil types. Driss et al., (2022) investigated the effects of lime addition on the geotechnical characteristics of expansive Algerian clayey soil, classified as CH according to the Unified Soil Classification System (USCS). Their study found that adding 6% lime resulted in significant improvements in unconfined compressive strength (UCS), swelling potential, and plasticity index, with the benefits amplified over a curing period of 28 days. These findings align with the work of Bell (1996), who reported that the optimal lime content for stabilizing clay soils generally falls between 4-6%.

Similarly, Saidate et al., (2022) studied the stabilization of gypsum-clay soil using lime. They identified an optimal lime content of 6%, which increased the UCS of the treated soil to 3.23 times that of the untreated soil after 28 days of curing. This highlights the importance of determining the appropriate lime content based on the specific soil type and its characteristics.

6.2 Effects of Lime on Geotechnical Properties

Lime treatment has been widely recognized for its ability to enhance various geotechnical properties of problematic soils. Salih and Shafiqu (2024) investigated the effects of lime on the engineering properties of expansive soil. Their study demonstrated that adding 9% lime decreased the swelling potential from 18.77% to 6.03% while increasing the UCS and California Bearing Ratio (CBR). These improvements can be attributed to the cation exchange, flocculation, and pozzolanic reactions that occur when lime is mixed with clay soils (Driss et al., 2022).

Naveed et al., (2024) further explained that the addition of lime enhances the mechanical strength of soils by promoting pozzolanic reactions and flocculation of soil particles. These processes lead to improved bearing capacity and reduced permanent deformation. The study also highlighted the reduction in plasticity index and increase in plastic limit resulting from lime treatment, which is consistent with the findings of Guney et al. (2007).

6.3 Long-Term Performance and Durability

Ensuring the long-term performance and durability of lime-stabilized soils is crucial for sustainable infrastructure development. Sivapriya et al., (2022) investigated the durability of lime-stabilized soils modified with eggshell ash (ESA) under wet-dry cycles. Their study found that using lime with 0.2% ESA resulted in optimal performance and improved durability. This demonstrates the potential of using auxiliary materials to enhance the long-term effectiveness of lime stabilization, as also highlighted by James et al., (2016).

Moreover, curing time plays a significant role in the long-term strength development of lime-treated soils. Naveed et al., (2024) reported that the UCS of lime-treated expansive soils increased by up to 523% with 4% lime after 28 days of curing. This emphasizes the importance of allowing sufficient curing time for the pozzolanic reactions to fully develop and contribute to the long-term strength gain of the stabilized soil.

6.4 Case Studies and Practical Applications

Several case studies and practical applications have demonstrated the effectiveness of lime stabilization in real-world scenarios. Vijayan et al. (2023) explored the use of lime in combination with palm kernel ash (PKA) for minor stabilization works. Their study showed promising results, with improved UCS and reduced Atterberg limits. This aligns with the findings of Nnochiri et al., (2017), who reported that PKA enhanced the strength of lime-stabilized lateritic soil.

In the context of road subgrade construction, Agate et al., (2024) investigated the stabilization of expansive black cotton soil using a combination of lime, bamboo charcoal, and quarry dust. The study achieved significant improvements in CBR and strength properties, demonstrating the viability of this approach for transforming problematic soils into suitable materials for rural road subgrades. These case studies highlight the versatility of lime stabilization and its potential to address diverse geotechnical challenges in practical applications.

6.5 Challenges and Innovations

Despite the well-established benefits of lime stabilization, challenges remain in optimizing its performance and sustainability. One major challenge is the variability in soil properties and environmental conditions, which can affect the effectiveness of lime treatment (Driss et al., 2022, Naveed et al., 2024). Researchers are continuously exploring innovative solutions to overcome these challenges and enhance the efficiency of lime stabilization.

The use of waste materials as auxiliary additives has emerged as a promising approach to improve the sustainability and performance of lime stabilization. For example, Sivapriya et al., (2022) demonstrated the potential of eggshell ash (ESA) in enhancing the durability of lime-stabilized soils, while Vijayan et al., (2023) explored the use of palm kernel ash (PKA). Other researchers have investigated the incorporation of rice husk ash and sugarcane bagasse ash (Sharma & Sivapullaiah, 2016) as supplementary materials in lime stabilization.

Moreover, advancements in characterization techniques are providing new insights into the mechanisms of lime-soil interactions. Driss et al., (2022) utilized X-ray diffraction (XRD) and scanning electron microscopy (SEM) to study the mineralogical and microstructural changes in lime-treated expansive soil. These advanced techniques help researchers better understand the underlying processes and optimize lime stabilization practices.

As research progresses, innovations in materials, design, and application methods are expected to further enhance the effectiveness and sustainability of lime stabilization. The development of novel binders, such as geopolymers (Zhang et al., 2016) and alkali-activated materials (Pourakbar et al., 2017), offers potential alternatives to traditional lime stabilization. Additionally, the integration of life cycle assessment (LCA) and environmental impact analysis (Saussaye et al., 2018) can guide the selection of sustainable stabilization techniques and materials.

In conclusion, lime stabilization has proven to be an effective approach for improving the geotechnical properties of problematic soils. The optimal lime content for stabilization typically ranges from 4-6%, depending on the soil type and its characteristics. Lime treatment significantly enhances strength, bearing capacity, and volume stability while reducing plasticity and swelling potential. The long-term performance and durability of lime-stabilized soils can be further improved by incorporating auxiliary materials and allowing sufficient curing time.

Case studies and practical applications demonstrate the feasibility and versatility of lime stabilization in various construction contexts, from minor stabilization works to road subgrade construction. However, challenges persist in optimizing the performance and sustainability of lime stabilization, particularly due to the variability in soil properties and environmental conditions.

Ongoing research and innovations in materials, characterization techniques, and design methods are paving the way for more efficient and sustainable lime stabilization practices. The use of waste materials as auxiliary additives, advancements in microstructural analysis, and the development of novel binders are promising avenues for future research and implementation. As the understanding of lime-soil interactions continues to grow, geotechnical engineers can leverage these findings to design resilient, cost-effective, and environmentally friendly solutions for infrastructure development. By embracing innovative approaches and sustainable practices, the field of lime stabilization can contribute to the creation of durable and eco-friendly geotechnical structures that meet the evolving needs of society.

Even though the field of research in lime and other alternative methods of soil stabilization has grown fast, there are still some gaps that have not been developed. The bibliometric mapping indicated that most of the studies are related to a few regions, which are located mainly in Asia and the Middle East, but there is little contribution made by Africa, Latin America, and Southeast Asia, meaning that their geographically different geocentric work should be conducted in these areas to employ different climatic and soil factors. Thematic analyses further revealed that despite the rapid growth in sustainability and nano-additive stabilization, studies that combine the life-cycle assessment (LCA), quantification of the carbon footprint and validation of the performance in the field remain scarce. Moreover, not many works have been able to associate microstructural observation in laboratory experiments with any long-term mechanical behavior or durability model in real environmental cycles. The interdisciplinary and regionally distributed approach to addressing these gaps would help to make an advance in the scientific and practical aspects of sustainable soil stabilization.

Lime Stabilization in Context of Emerging Techniques

Although the research is done on stabilization of lime, one should note that there are other methods of soil improvement that have developed in the recent years. The use of polyurethane and biopolymers as stabilizer polymers has a promising future in specific cases where speedy attainment of strength is required (Latifi et al., 2017). Alternatives to the traditional binders are geopolymerization, in which fly ash and slag serve as an alkali-activated material, and that is less carbon footprint-demanding (Zhang et al., 2016; Hoy et al., 2016). By-products of industries, such as ground granulated blast furnace slag (GGBS), silica fume, and rice husk ash, have been explored as an addition or a substitute of lime (Sharma and Sivapullaiah, 2016). Nevertheless, the lime stabilization is beneficial because it is cost-effective, common, has well-established mechanisms, and has been long-term performance in various soil types and climatic conditions. Future studies combining bibliometric analysis of these new methods with lime stabilization would offer an all-inclusive comparative paradigm of sustainable soil improvement methods.

7. Conclusion

This paper proposes in-depth research of the lime stabilization of expansive soils using three complementary components that include bibliometric analysis, life cycle assessment review, and technical synthesis. The next conclusions separate the results obtained directly based on the initial bibliometric analysis (the main contribution) and the implications based on the supporting narrative reviews:

1. The trends in publication show that it is growing considerably at a rate of about 15 yearly and the average of 33.17 citations per paper is evidence of the growing use and applicability of the field.
2. The other main research categories that emerge due to distribution of publications are Environmental Sciences and Ecology, Engineering and Geology.
3. China is at the forefront in terms of output in research followed by United States and India with international collaboration of the most productive countries.

4. The most fruitful institutions are the University of Sao Paulo and Federal University of Rio de Janeiro, though Consoli, Nilo Cesar, Caicedo, Andres Mauricio, and Saldanha, Rodrigo Beck are known as influential authors.
5. The keyword analysis recognizes soil stabilization, lime treatment, compressive strength, and geotechnical engineering as the most active research topics, whereas the citation burst analysis shows that the environmental impact and cost analysis are becoming hotspots (2020-2024).
6. The thematic groupings identified by cluster analysis are seven, and the temporal visualization shows that the shift between entirely mechanistic research (before 2010) and sustainability-oriented research (after 2015) transitioning took place.

The LCA review adds to the bibliometric results by putting the trends of sustainability found in the analysis of the key words and citation bursts into context. Among the most important lessons, it is possible to single out how the LCA methodology can be used to identify hotspots in the environment, how the dosage of the binder may be optimized, and how alternative materials, including eggshell-derived lime and waste additives, may be assessed. The issues associated with data availability and system complexity are pointing to the future methodological development.

The bibliometric themes are supported by the technical synthesis through explaining the optimal lime content (4-6%), its mechanisms of improvement (cation exchange, flocculation, pozzolanic reactions), and the long-term durability. The case studies show how it can be applied practically in the construction of subgrade and the use of auxiliary construction materials like fly ash, rice husk ash and eggshell ash, etc.

The novelty of the current research is that it is the first attempt to map the research in lime stabilization of expansive soils systematically, quantitatively defining the trends in publications, contributors to the research, thematic groups, and changes over time. The LCA and technical reviews are the contextual complements that put the bibliometric indicators into context into the areas of practical and environmental knowledge. Collectively, these elements can provide a clear asset to researchers, practitioners, and decision-makers to determine the future priorities in research, build partnerships, and generate sustainable lime stabilization solutions in the world.

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