A Bibliometric Review of the Literature on Soil Stabilization Using Nanomaterials

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ABSTRACT

The stabilization of soil is a critical aspect of geotechnical engineering, addressing challenges such as soil strength, durability, and load-bearing capacity. The incorporation of nanomaterials into soil stabilization processes has emerged as a revolutionary approach that leverages the unique properties of nanotechnology to enhance soil performance in a sustainable and efficient manner. This study investigates the bibliometric network landscape of soil stabilization using nanomaterials (SSN), offering a comprehensive review of publication trends, key contributors, and influential works. By analyzing 431 publications retrieved from the scopus database, the study identified articles (74.7%) as the predominant document type, followed by conference papers (18.6%) and review articles (4.4%), emphasizing the centrality of journal-based research. This analysis reveals exponential growth in research output, with publications surging from 1 in 1999–2001 to 176 in 2020–2022, reflecting the field's dynamic evolution and increasing global interest. Among the most-cited works, Behnood, A.'s 2018 publication in transportation geotechnics had 270 citations, followed by Bahmani, S.H. (2014) with 234 citations, underscoring the impact of these foundational studies. Leading journals include Construction and Building Materials, which ranks first with 32 publications. Wang, W. (China) emerges as the most productive author with 13 publications, followed closely by Gallagher, P.M. (United States) with 12 publications, showcasing the contributions of global researchers, particularly from China, India, and the United States. Current interests and future research can be better understood using this systematic mapping, which visually depicts the evolution of publications over time. The results provide a clear roadmap for further investigation. The diverse range of research contributions underscores the field's dynamic evolution. However, although the study highlights the global interest in SSN and its potential, a more in-depth critique of the methodological gaps, challenges related to scalability, and practical applications would enhance the conclusions.

KEYWORDS

Bibliometric Analysis, Co-occurrence Analysis, Soil Stabilization, Nanomaterials.

1. Introduction

In civil engineering and construction, nanomaterials have greatly improved the main characteristics of materials, such as their cost, environmental effect, and energy consumption of structures [1-3]. Nanotechnology, which involves manipulating matter below 100 nm, provides more sustainable alternatives for soil stabilization using nanomaterials (SSN) readily interact with soil particles and fill soil pore media due to their high surface area and reactivity [4].

Nanotechnology has emerged as a promising field, offering innovative solutions to longstanding geotechnical problems. Nanomaterials, characterized by their particle sizes ranging from 1 to 100 nanometers, exhibit unique physical, chemical, and mechanical properties that distinguish them from conventional additives. For instance, their high surface area-to-volume ratio and superior reactivity enable them to interact at the microscopic level with other soil particles, leading to profound changes in soil behavior and properties [4, 5]. The application of SSN offers several advantages over the traditional additives. First, nanomaterials such as nano-silica and nano-clay can significantly enhance the compressive strength, cohesion, and durability of soils while reducing permeability and shrink-swell potential. Nano-silica, for instance, has been widely studied for its ability to improve soil microstructure by filling voids and creating denser soil matrices, thereby reducing water absorption and increasing load-bearing capacity [6, 7]. Similarly, carbon-based nanomaterials like graphene oxide and carbon nanotubes offer exceptional tensile strength, enabling soils to better withstand dynamic loading and resist cracking under stress [8]. Second, nanomaterials offer sustainability benefits by reducing the reliance on traditional stabilizers and the quantities required for effective soil improvement. For example, studies have demonstrated that small dosages of nano-silica can achieve stabilization results comparable to or even exceeding those of conventional cement treatments, but with significantly lower environmental impact [9]. This makes nanomaterials an attractive alternative for projects aiming to align with global sustainability goals, such as the reduction of greenhouse gas emissions and resource conservation. Third, nanomaterials exhibit unique interactions with soil particles at the molecular level. These materials can chemically bond with soil components and enhance soil structure, making them effective tools for SSN [١٠]. Their small size allows them to penetrate soil pores and chemically bond with clay minerals, altering soil structure in ways that are impossible with traditional stabilizers. For instance, nano-aqueous adhesives have been shown to enhance water retention in sandy soils, improve thermal insulation properties, and provide resistance to erosion, making them ideal for projects in arid or semi-arid regions [9]. Finally, nanomaterials can address specific geotechnical challenges, such as the stabilization of expansive soils. Expansive soils, characterized by their tendency to swell when wet and shrink when dry, are particularly problematic in construction. Nanomaterials, such as nano-silica and nano-clay, have been shown to significantly improve the mechanical properties and reduce the swelling potential of expansive soils [11]. The application of nano-material-based stabilizers, such as nano-silica or nano-titanium dioxide, has been shown to mitigate these issues by reducing plasticity and improving soil load-bearing capacity [12].

Numerous studies have been published on SSN, according to a literature review [13-16]. To the best of our knowledge, no bibliometric studies on SSN have been conducted. Consequently, employing the scopus database for this topic would aid in determining the global research trends in this area of interest. Numerous similar bibliometric analyses have been published in top journals [17] [18] [19]. Bibliometric network analyses are valuable tools in engineering research as them:

- Identify key trends, gaps, and emerging topics in the field to guide future experimental and applied research.
- Provide a roadmap for researchers to focus their efforts on understudied or high-potential areas to foster innovation and new developments in this field of study.
- Highlight influential studies, researchers, and collaborations that inspire and inform laboratory or fieldwork.

This study aims to conduct a bibliometric analysis to identify annual publications, thematic clusters, leading countries, and publications in SSN. This bibliometric network analysis is a novel study in the field of geotechnical engineering, serving as a framework and model for future research by other scholars in this domain. In other words, this bibliometric study outlines the path forward for researchers, identifying which aspects have been addressed, highlighting the most significant topics, and indicating which countries have contributed and produced the most highly-cited articles. This article can serve as an excellent guide for researchers aiming to study this field.

2. Materials and methods

2.1 Data source

In this study, the scopus database was used to collect relevant publications on SSN. The main search to find related publications was conducted in December 2024.

Fourteen keywords (nano, colloidal silica, laponite, soil, sand, clay, enhanc*, stabilis*, stabiliz*, improvement, strength, durability, mechanical, properties) were retrieved to search strings focusing on the title, abstract, and keyword sections of the Scopus database. Records that did not focus on the application of nanomaterials in geotechnics were sieved. In addition, the research database was limited to English records. Accordingly, 431 publications were selected for this study. Of a note, The clear description of search strings and filters ensures transparency. However, relying solely on scopus and English-language records may introduce bias by underrepresenting non-English and regional studies. A comparative analysis incorporating additional databases or regional publications could improve the comprehensiveness of the analysis.

2.2. Bibliometric Network Analysis

Visualization of similarities (VOS) viewer software (version 1.6.18) was used to conduct a detailed bibliometric network analysis. This tool leverages the mapping technique to effectively present large bibliometric maps in an intuitive manner [20] It facilitates the generation and examination of maps derived from bibliometric network data. By organizing the results into clusters, the software enables the visualization of connections among the analyzed data [21]. Through its distance-based mapping approach, VOS viewer represents the strength of relationships between items, with shorter distances indicating stronger connections [22] This method contrasts with graph-based mapping, as the proximity of items directly reflects their relational strength [23]. Table 1 provides an overview of the key technical terms utilized by the software. To generate distance-based network maps, analyses of coauthorship, cooccurrence, and citations, illustrating: (1) coauthorship among researchers and collaborations between countries, (2) keyword co-cooccurrences, and (3) citations of scientific journals.

Table 1. Key Terminologies Defined in the VOS viewer Manual (Version 1.6.18)

Term	Definition
Items	Objects of interest (e.g., publications, researchers, terms) included in a map. Usually of one type only.
Links	Connections or relationships between items (e.g., bibliographic coupling, co-authorship, co-occurrence). Each link has a strength value indicating the degree of connection.
Network	A set of items and their links. Sometimes referred to as a graph.
Clusters	Groups of items in a map. Clusters are non-overlapping (each item belongs to one cluster only) and may not cover all items.
Attributes	Properties of items, such as weights (indicating importance) or scores (representing numerical properties). Weight attributes influence visualization prominence; score attributes are used in overlay visualizations.
Links attribute	Number of items' links with other items.
Total link strength Attributes	Sum of the strengths of an item's links with other items.
Custom weight Attributes	User-defined weights for items to indicate their importance.
Custom score Attributes	User-defined numerical values indicating various properties used for coloring items in overlay visualizations.

3. Results and discussion

3.1 Publication types

The bibliometric review of the literature on SSN highlights the distribution of document types contributing to the body of knowledge in this field, as summarized in Table 2: Types of publications regarding SSN from 1999 to 2024. The analysis reveals that articles constitute the predominant type of publication, accounting for 322 documents and representing 74.7% of the total output. This reflects the central role of peer-reviewed journal articles as the primary medium through which original research findings are disseminated. Conference papers are the second most common type of publication, accounting for 80 papers, and contributed 18.6% to the total. This underscores the importance of academic conferences as platforms for presenting cutting-edge research, fostering collaboration, and disseminating preliminary findings within the SSN research community. Review articles, representing 19.4% of the total publications, provide critical syntheses of existing research and identify trends, gaps, and future directions in the field. These contributions play a crucial role in consolidating

knowledge and guiding subsequent studies. The other document types included notes (7 documents, 1.6%) and book chapters (3 documents, 0.7%). Although these forms of publication are less common, they reflect additional avenues for communicating specialized or supplementary insights into the field of SSN.

Table 2. Types of publications regarding SSN from 1999 to 2024.

Rank	Document Types	Numbers	Percentage (%)
1	Articles	322	74.7
2	Conference Papers	80	18.6
3	Review Articles	19	4.4
4	Note	7	1.6
5	Book Chapters	3	0.7

3.2 Annual publications

Figure 1 displays the annual increase in the number of SSN publications. The first relevant publication dates back to 1999. It examined the effect of dilution and contaminants on sand grouted with colloidal silica [24]. This trend demonstrates the growing importance of this topic in geotechnical and material sciences. From 1999 to 2004, only a minimal number of publications were recorded (1 and 3, respectively), indicating the nascent stage of research in this field. In the following intervals, research activity began to gain momentum, with 8 publications between 2005 and 2007 and 7 publications between 2008 and 2010. The period from 2011 to 2013 also saw a modest rise, with 7 publications, reflecting a steady but slow growth phase in early exploration. A significant turning point is observed from 2014 onwards, with 33 publications recorded between 2014 and 2016. This period marked a considerable surge in interest, which further accelerated in subsequent intervals. Between 2017 and 2019, the number of publications more than doubled to 73, indicating an increasing recognition of the potential of nanomaterials in SSN. The growth trend reached its peak in 2020–2022, with an impressive 176 publications, highlighting a period of intensive research activity and scholarly focus. The most recent interval, 2023–2024, continues to show substantial progress, with 123 publications already recorded, signaling sustained interest and ongoing advancements in this domain. The exponential rise in publications reflects the field's growing recognition. However, the sharp increase in recent years may also indicate a trend-driven focus, raising concerns about the depth and originality of newer studies. An analysis of qualitative advancements alongside publication quantity would offer a more nuanced understanding of progress.

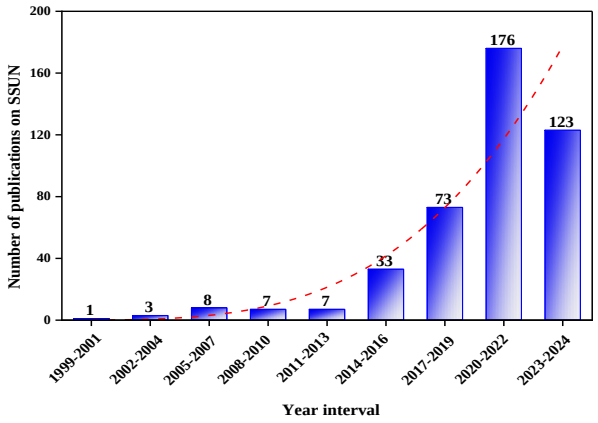

Figure 1. Growth pattern of SSN journal publications from 1999 to 2024

3.3 Leading countries and collaboration network analysis

A bibliometric analysis using VOS viewer was conducted to identify the collaboration and research trends among countries focusing on the application of nanomaterials in soils within geotechnical engineering. By applying bibliometric coupling at the country level, this study highlights the connections and contributions of different nations to this emerging research domain. The analysis settings used countries as the unit of analysis, with a threshold requiring a minimum of 5 publications per country and no restrictions on the minimum number of citations. Out of 45 countries, 25 met these criteria and were included in the network map visualization. Figure 3 shows that the network map illustrates the bibliometric coupling between countries based on shared references, signifying overlapping research interests and collaboration potential. Countries like India, Iran, and China emerge as central nodes in the network, indicated by their larger node sizes and high degree of connectivity, demonstrating that these countries have produced a significant volume of research in the field and fostered widespread bibliometric coupling with other nations.

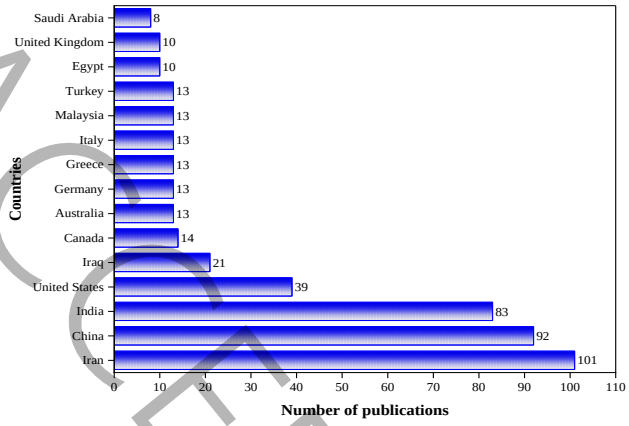

Figure 2. Top 15 countries with the highest number of publications from 1999 to 2024

The map displays distinct clusters of countries, which can be analyzed as follows: Red Cluster (India, Iran, Iraq, etc.): Represents a tightly-knit group of countries, with India and Iran acting as primary hubs. This cluster indicates active regional collaborations and shared research priorities in Asia and the Middle East. Green Cluster (United States, Germany, Italy, etc.): This cluster highlights significant contributions from Western countries. The United States appears prominently, with connections to European nations like Germany, Italy, and Greecesuggesting transatlantic research collaborations. Blue Cluster (Saudi Arabia, Egypt, Canada, etc.): This grouping suggests collaboration primarily among Middle Eastern and North American nations, possibly driven by shared challenges in soil improvement technologies. Yellow Cluster (China and neighboring countries): China forms its own cluster with strong links to neighboring countries, emphasizing its role as a leader in this research field.

The network highlights the global nature of research on nanomaterials in geotechnical engineering: cross-continental collaborations are evident, with countries from Asia, Europe, North America, and the Middle East interacting through shared citations.

The Americans were the first researchers to publish articles on SSN, but they eventually shifted their focus, allowing other countries to step into the field of SSN research. These countries began publishing articles and initiating SSN research and are currently actively developing and working in this area. The progression of SSN research has been updated to reflect trends up to 2024 and beyond. Iran, in particular, has been very active in the field of nanotechnology and has independently advanced its capabilities in this field.

The analysis underscored the limited concentration of countries engaged in SSN research, resulting in a constrained collaboration network. This underscores the necessity for future studies to explore avenues for expanding international cooperation and involving a broader array of nations in this field. Additional numerical details regarding Figure 3 are provided in Table S2 of the supplementary data.

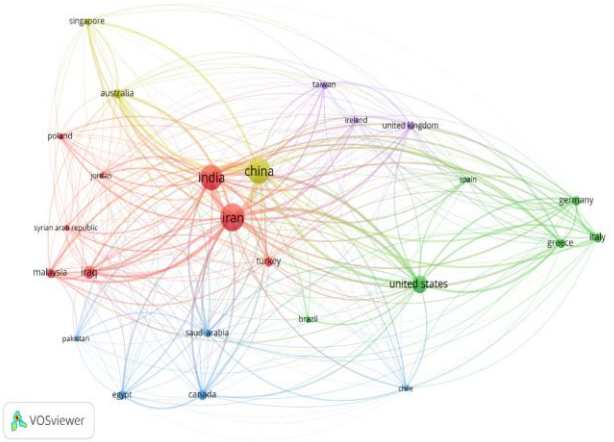

Figure 3. Collaborative networks in geotechnical nanomaterials research: Insights from bibliometric coupling analysis

3.4 Most cited authors

A bibliometric analysis was conducted using VOSviewer. The parameters included the type of analysis (co-citation analysis), unit of analysis (cited authors), and minimum citation threshold of 20 citations. The dataset analyzed represents a co-citation network in which nodes represent cited authors, and links indicate co-citation relationships. The size of the nodes corresponds to the number of citations received by the author, while the thickness of the links reflects the strength of the co-citation relationships. The network is divided into clusters, identified by different colors, representing thematic or disciplinary groupings (Figure 4). Gallagher, P.M. has 406 citations and a total link strength of 850, indicating significant individual influence in the field. Taha, M.R. has 329 citations and a total link strength of 2286, reflecting both a strong impact and notable connectivity within the research network. Choobbasti, A.J. has 221 citations but stands out with the highest total link strength of 2588, demonstrating a central role in bridging collaborations across different clusters in SSN research. The bibliometric analysis underscores the pivotal contributions of key authors (Table 3) and identifies distinct thematic clusters within the SSN domain. The interconnected network of researchers forms a strong foundation for advancing the field through collaborative and multidisciplinary approaches.

The high citation count for foundational works emphasizes their influence. However, citation analysis primarily focuses on quantity rather than transformative impact of cited studies.

Table 3. Top cited authors and their influence in SSN research from 1999 to 2024

Author	Citations	Total link strength
Gallagher, P.M.	406	850
Taha, M.R.	329	2286
Choobbasti, A.J.	221	2588
Haddad, A.	216	1984
Kutanaei, S.S.	210	2459
Changizi, F.	190	1809
Wang, W.	176	993
Horpibulsuk, S.	166	1363
Asadi, A.	164	1754
Aarzadnia, N.	164	1536

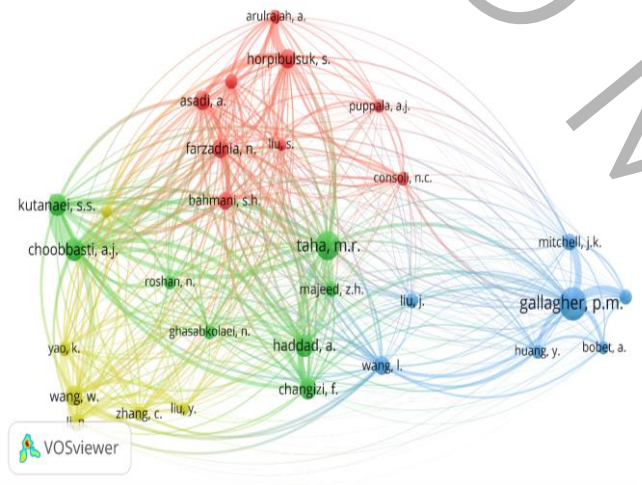

Figure 4. Co-Citation network of authors in SSN research from 1999 to 2024

3.5 Authors and collaborations network analysis

The bibliometric analysis of the literature on SSN highlights the most productive authors in this research domain (Figure 5: Most productive authors are ranked by the number of publications. The data reveal that Wang, W., from China, is the most prolific author, with 13 publications, indicating his prominent role in advancing this field. Gallagher, P.M., from the United States, follows closely with 12 publications, demonstrating significant contributions from North America. Three researchers, Krishnan, J., Li, N., and Shukla, S., from India are each credited with 11 publications, underscoring the substantial output from researchers based in Asia, particularly China and India. In addition, Spagnoli, G., from Germany has authored 9 publications, indicating notable contributions from Europe. Lang, L., from China, with 8 publications, further solidifies China's leading position in this research area. Similarly, Chen, B. from China and Chen, Q. from Singapore have each contributed 7 publications, highlighting collaborative research efforts across Asia. Finally, Azadi, M. from Iran has 6 publications, representing valuable contributions from the Middle East. This information is encapsulated in Figure 5 and provides a visual representation of the most productive authors in the field ranked by the number of their publications. This underscores the global and multidisciplinary nature of SSN research, with notable contributions from China, India, the United States, and other regions. The ranking offers insight into the key researchers driving progress in this field.

The analysis emphasizes China's dominance in this field while showcasing collaborative efforts among Asian authors. The findings underscore the global and multidisciplinary nature of SSN research, with important implications for future research directions and collaborative opportunities across regions.

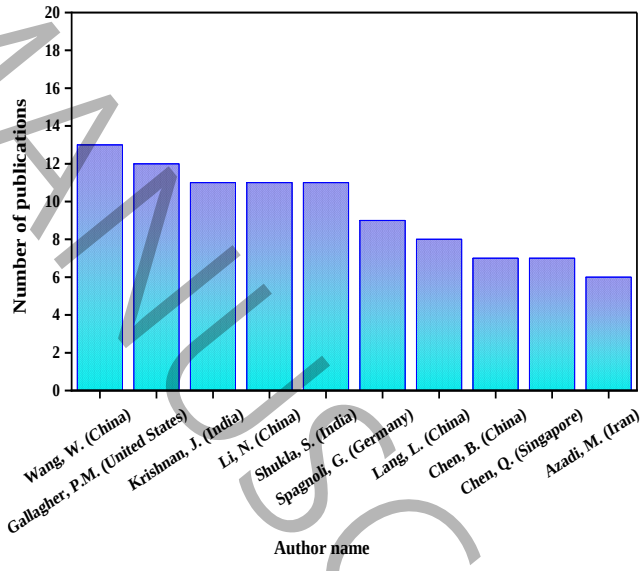

Figure 5. Most productive authors ranked by number of publications

3.6 Journal network analysis

The bibliometric review of the literature on SSN highlights the leading journals that serve as primary outlets for research dissemination (Figure 7. Leading journals publishing production considering SSN. The analysis identifies Construction and Building Materials

as the most prominent journal, with a total of 32 publications, solidifying its position as a key platform for advancing knowledge in the application of nanomaterials in geotechnical and construction engineering. Lecture Notes in Civil Engineering, which contains 16 publications, ranks second, reflecting its significant role in documenting academic advancements and innovative approaches in civil engineering. The Geotechnical Special Publication follows closely, contributing 14 publications that emphasize its focus on geotechnical advancements, including nanomaterial applications. The Journal of Materials in Civil Engineering includes 13 publications, highlighting its alignment with material innovations tailored for civil engineering solutions. Journal of Geotechnical and Geoenvironmental Engineering, and Materials Today Proceedings each contribute 11 publications, highlighting their multidisciplinary roles in integrating geotechnical, geological, and materials sciences for SSN research. Furthermore, the International Journal of Geosynthetics and Ground Engineering and Materials each account for 10 publications, underscoring their influence in areas such as ground improvement and material science innovations. Lastly, the Bulletin of Engineering Geology and the Environment, with 9 publications, bridges geological and environmental perspectives in the context of nanomaterial-enhanced SSN.

The analysis underscores the multidisciplinary nature of SSN research, with contributions from journals that integrate materials science and environmental studies. This overview emphasizes the importance of these leading journals in disseminating knowledge and fostering collaborative efforts across various scientific domains to advance the field.

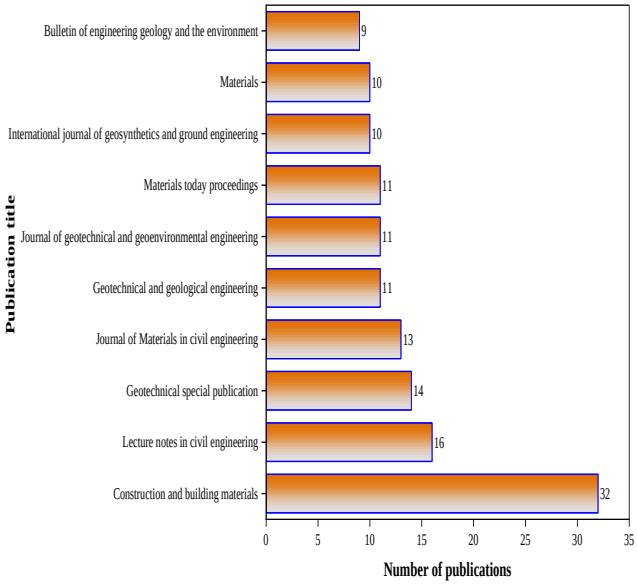

Figure 7. Leading journals publishing production considering SSN

3.7 co-occurrence Analysis

An extensive study using the VOSviewer software was conducted to construct a cooccurrence. The results of this study indicated that the most popular keywords along with the number of publications (N) were "soil stabilization" (N=203; 9.4%), "UCS (unconfined compressive strength)" (N=166; 7.7%), "soil" (N=158; 7.3%), "silica" (N=150; 7.0%), and "soil testing" (N=127; 5.9%).

Additional numerical information regarding this figure is provided in Table S1 (see supplementary data).

The arrangement and links between terms in Figure 8 enabled researchers to identify and group the most relevant thematic clusters in the selected literature. The results of the co-occurrence analysis revealed three main clusters in SSN studies, forming thematic clusters (Figure 8). The node size indicated the keyword frequency, and the thickness of the links was proportional to the strength of the connections among them.

The red cluster, named "nanomaterials in soil stabilization", focused on SSN. The most commonly

observed term in this cluster was "soil stabilization", with 203 appearances and 1027 total links. Subsequently, the term "UCS" appeared 166 times and had 912 connections. This demonstrated that the cluster was centered around the topic of soil stabilization, with a particular focus on the use of nanomaterials (referred to as SSN).

The green cluster, called "material testing methods". Keywords in this cluster were related to the materials used for soil stabilization and the methods for testing and evaluating their effectiveness. "Cement," "nanosilica," and "polymer" represented various stabilizing agents, while "UCS (unconfined compressive strength)" and "compression testing" reflected the emphasis on assessing mechanical properties. The occurrence of "microstructure", "XRD" (X-ray Diffraction) and "SEM" (Scanning Electron Microscopy) indicated the importance of understanding the material's internal structure and composition. The blue cluster was appropriately named the "Silica-soil stabilization".

The term "silica" emerged as the most frequently occurring term within the cluster, with 150 occurrences. This indicated its central role in this field. "colloidal silica" with 106 occurrences underscores the importance of this nanomaterial in the context of SSN. The high frequency of "soil mechanics" and "geotechnical engineering" reflected the foundational scientific disciplines that underpin the application of SSN.

This analysis identifies key research trends in SSN, focusing on soil stabilization using nanomaterials, testing methods, and silica's role. While static testing methods like UCS and compression are well-explored, there is a gap in cyclic testing, which is crucial for understanding the performance of stabilized soils under real-world conditions. The results suggests that future research should focus on cyclic loading, long-term durability under environmental stressors, and interdisciplinary approaches to further advance SSN. Bridging these gaps would provide a more comprehensive understanding of the effectiveness and longevity of soil stabilization techniques.

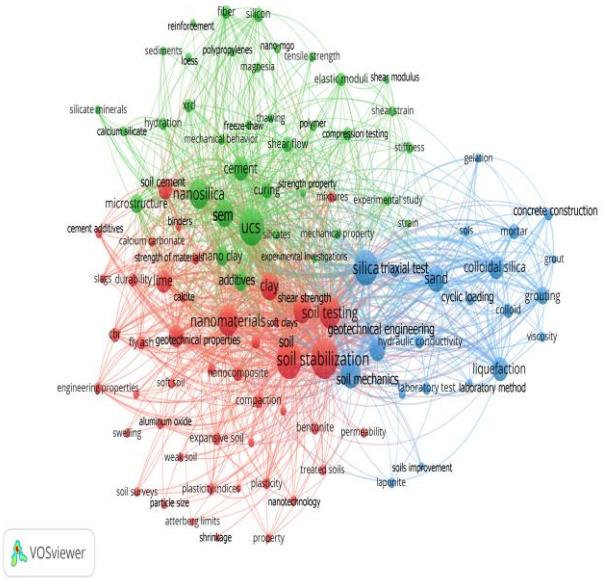

Figure 8. Keyword co-occurrence network map.

Table 4. Top 10 keywords and Network Strength of Keywords in the field of SSN.

Keyword	Occurrences	Total link strength
Soilstabilization	203	1027
Ucs	166	912
Soil	158	895
Silica	150	899
Soil testing	127	759
Nanoparticles	114	619
Nanosilica	114	627
Soil mechanics	107	689
Clay	91	484
SEM	89	540

3.8 Most cited publications

The analysis covers the top 10 most frequently cited publications in the field of SSN, spanning 2000 to 2022. Table 1 summarizes the top 10 most cited articles in the field of SSN during the selected period of this study. and highlights the foundational and impactful studies that have shaped research in this domain. The publication by Behnood, A. [25], published in Transportation Geotechnics (United States, 2018), emerges as the most-cited work with 270 citations, indicating its critical contribution to advancing knowledge in the application of nanomaterials in geotechnics. The second-highest cited work, authored by Bahmani, S.H. [26], was published in Construction and Building Materials (Malaysia, 2014) and has received 234 citations, highlighting its influence in

integrating nanotechnology within construction materials research. The third position is occupied by Taha, M.R. [27], whose work published in the Journal of Nanoparticle Research (Malaysia, 2012) garnered 189 citations, reflecting the importance of nanoparticle-based advancements in SSN. Another significant contribution is from Gallagher, P.M. [28], published in Soil Dynamics and Earthquake Engineering (United States, 2002), with 179 citations, indicating early recognition of the potential of nanotechnology in geotechnical applications. The work of Choobbasti, A.J. [29], featured in the Journal of Rock Mechanics and Geotechnical Engineering (Iran, 2019), has received 169 citations, reflecting the strong representation of Iranian research in this field. Lang, L. [30] contributed a highly cited paper with 148 citations, published in Construction and Building Materials (China, 2020), further emphasizing the journal's prominence as a platform for SSN research.

Table 5. Top 10 most cited publications from 1999 to 2024.

Title/Reference	Source Title/Firs author	Citation
Soil and clay stabilization with calcium- and non-calcium-based additives: A state-of-the-art review of challenges, approaches and techniques [25].	Transportation Geotechnics/ Behnood, A.	270
Stabilization of residual soil using SiO_2 nanoparticles and cement [26]	Construction and building materials/ Bahmani, S.H.	234
Influence of nano-material on the expansive and shrinkage soil behavior [27]	Journal of nanoparticle research/ Taha, M.R.	189
Influence of colloidal silica grout on liquefaction potential and cyclic undrained behavior of loose sand [28].	Soil Dynamics and Earthquake Engineering/ Patricia, M.G.	179
Microstructure characteristics of cement-stabilized sandy soil using nanosilica [29].	Journal of Rock Mechanics and Geotechnical Engineering/ Choobbasti, A.J.	١٦٩
Strength development of solidified dredged sludge containing humic acid with cement, lime and nano-SiO_2 [30].	Construction and building materials/ Lang, L.	١٤٨
Strength properties of soft clay treated with mixture of nano-SiO_2 and recycled polyester fiber [31].	Journal of Rock Mechanics and Geotechnical Engineering/ Changizi, F.	143
Stabilization of expansive soils using chemical additives: A review [32].	Journal of Rock Mechanics and Geotechnical Engineering/Barman, D.	١٣٦
Laboratory investigation and field evaluation of loess improvement using nanoclay – A sustainable material for construction [33].	Construction and building materials/Tabarsa, A.	١٣٤
Mechanical properties soil stabilized with nano calcium carbonate and reinforced with carpet waste fibers [34].	Construction and building materials/Choobbasti, A.J.	١٢٩

Other notable publications include works by Changizi, F. [31] (Iran, 2017) with 143 citations in the Journal of Rock Mechanics and Geotechnical Engineering, Barman, D. [32] (India, 2022) with 136 citations, and Tabarsa, A. [33] (Iran, 2018) with 134 citations, both published in Construction and Building Materials. Lastly, Choobbasti, A.J. [34]. appears again with a 2017 contribution in Construction and Building Materials, accumulating 129 citations, showcasing their recurring influence on the field.

This section shows a progression from early foundational work to more applied studies. However, as explained in Section 3.7, there is a gap in exploring the dynamic behavior of stabilized soils under cyclic loading, suggesting an area for future investigation in SSN research.

4. Conclusions

This bibliometric review examined the literature on soil stabilization using nanomaterials (SSN), revealing critical trends, contributors:

• It discovered three main thematic clusters: (1) nanomaterials in soil stabilization, (2) materials testing methods and (3) silica-soil stabilization.
• The study revealed exponential growth in SSN research, with publications increasing from 1 in 1999–2001 to 176 in 2020–2022, highlighting the rising global interest in nanomaterials for geotechnical applications.
• Articles (74.7%) were the most common document type, followed by conference papers (18.6%) and

review articles (4.4%), emphasizing the dominance of journal-based research in this field.
• The most-cited publication by Behnood, A. (2018) received 270 citations, demonstrating its foundational influence in SSN research, while Wang, W. emerged as the most productive author with 13 publications.
• Leading journals, such as Construction and Building Materials (32 publications), served as primary platforms for disseminating SSN research, highlighting their importance in the field.
• China, India, and the United States were identified as leading SSN research countries, supported by strong international collaborations and bibliometric coupling networks.
• Co-occurrence analysis identified "soil stabilization" (203 occurrences) and "UCS (unconfined compressive strength)" (166 occurrences) as the most frequently studied topics, with thematic clusters focusing on nanomaterials, materials testing methods, and silica-based stabilization.

5. References

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