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Research Trends in the Use of Eggshell Powder for Soil Stabilization: A Review-Based Analysis

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Abstract: *The objective of this study is to perform a thorough bibliometric analysis of scholarly publications that concentrate on the utilization of eggshell powder (ESP) for soil stabilization. The research identifies key contributors, thematic clusters, influential publications, and evolving research trends from 2010 to 2024 by utilizing bibliometric tools such as VOSviewer and Biblioshiny, as well as data retrieval from Scopus and Web of Science. The network, overlay, and density visualizations demonstrate that ESP research is deeply rooted in geotechnical engineering, with a growing emphasis on life cycle assessments, chemical performance, and sustainability. Thematic mapping identifies emerging and underexplored research areas, as well as well-developed motor themes. The central role of ESP as a sustainable stabilizer is underscored by the findings, which also identify opportunities for future research. These opportunities include the integration of multi-waste stabilization systems, long-term durability assessments, field validations, and standardized testing.*

Keywords: Eggshell powder, Soil stabilization, Geotechnical engineering, and Sustainable materials

1. INTRODUCTION

Soil stabilization is a fundamental practice in geotechnical engineering that is designed to improve the engineering properties of soil to enhance its overall performance, durability, and strength [1]. Traditionally, stabilization has been accomplished using chemical additives, including bitumen, cement, or lime [2]. However, the growing demand for sustainable engineering practices has resulted in a surge of interest in alternative, eco-friendly stabilizing materials. Eggshell powder (ESP), a calcium-rich agricultural waste product, has emerged as a promising additive capable of improving soil characteristics while simultaneously addressing waste management issues [3].

The principles of the circular economy and sustainable development are embodied using eggshell powder in soil stabilization [4]. Discarded eggshells, which are often treated as waste in the food industry, are now being reimaged as functional construction materials. Their high calcium carbonate content, like that of lime, facilitates pozzolanic reactions that enhance soil cohesion, reduce plasticity, and increase load-bearing capacity [5]. Furthermore, the economic feasibility of utilizing eggshells in geotechnical applications is enhanced by their widespread availability in countries with high poultry consumption.

The physical and chemical performance of ESP-treated soils has been extensively studied in recent years. Parameters such as compaction behavior, unconfined compressive strength, permeability, and durability have been examined under various environmental conditions [6]. However, despite the growing number of investigations, no comprehensive bibliometric study has mapped global research trends, key contributors, and thematic evolution in this emerging niche of geotechnical engineering.

Bibliometric analysis is a quantitative research method used to analyze the structure, dynamics, and patterns of academic publications within a specific field [7]. Tools such as VOSviewer and Bibliometrix allow researchers to identify high-impact papers, emerging research hotspots, and visualize relationships among authors, keywords, institutions, and countries [8]. Applying these tools to the study of eggshell powder in soil stabilization facilitates the synthesis of current knowledge and the identification of trends that may inform future research directions.

This investigation aims to address the existing gap by conducting a thorough bibliometric analysis of scholarly publications relating to the use of eggshell powder in soil stabilization. The analysis focuses on identifying thematic clusters, influential articles, key contributors, and publication trends within the literature. By doing so, the study seeks to provide a deeper understanding of the scientific progression of this subject and to identify areas that warrant further investigation.

Targeted search strategies were employed to retrieve data for this bibliometric analysis from reputable databases, including Scopus and Web of Science [9]. Filters and criteria were applied to ensure the inclusion of peer-reviewed journal articles, conference papers, and reviews specifically addressing the use of eggshell powder for geotechnical soil treatment. Bibliometric tools were subsequently used to process the extracted data, generating visual and quantitative insights into the structure and evolution of the research landscape.

This paper enhances the understanding of the increasing prominence of waste-based soil stabilization materials in engineering research through a focused bibliometric

analysis. Furthermore, it offers a strategic perspective for researchers, policymakers, and practitioners aiming to promote sustainable construction materials. Ultimately, the objective is to encourage the broader adoption and innovation of agricultural waste products, such as eggshell powder, for enhancing soil behavior in geotechnical engineering applications.

2. METHODOLOGY

The methodology for conducting a bibliometric analysis on the applications of eggshell powder in soil stabilization research is summarized in Figure 1. The process commences with the initial step of Start and proceeds through a sequence of stages. The initial step is Data Acquisition, which entails the collection of pertinent scientific publications from established academic databases [7]. The following step is Data Processing, which involves the organization, cleaning, and standardization of the extracted bibliographic data to prepare it for analysis [10]. The subsequent stage, Network Visualization, involves the development of visual representations, including co-occurrence networks and collaboration maps, to identify relationships among authors, institutions, and keywords [11]. Cluster Analysis is subsequently implemented to organize research themes that are related and to emphasize the primary areas of focus in the field [12]. The temporal evolution and emerging patterns of research topics are subsequently analyzed using Trend and Thematic Evolution Analysis [8]. The process culminates in the Discussion of Results, which involves the interpretation of the generated visualizations, the summarization of key findings, and the proposal of future research directions.

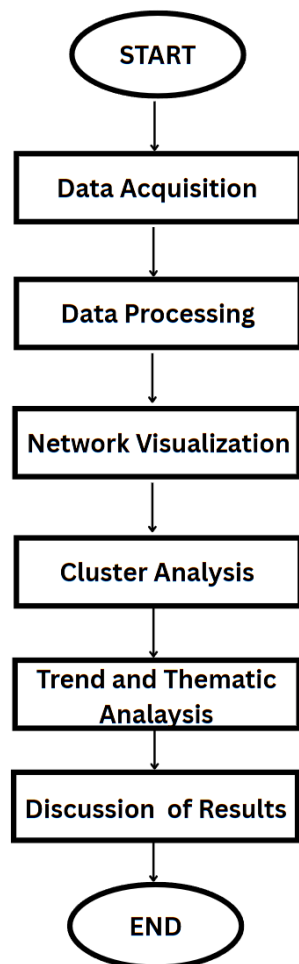


Fig. 1. Methodology of the Study

2.1 Data Acquisition

The bibliometric analysis for this study was conducted by systematically retrieving scholarly publications from two major scientific databases: Scopus and Web of Science. The search strategy employed a series of keywords pertinent to the research focus, such as "eggshell powder," "soil stabilization," "waste-based stabilizer," and "geotechnical engineering" [6]. Peer-reviewed journal articles, conference proceedings, and review papers published between 2010 and 2024 were considered for inclusion. Only publications specifically written in English and addressing the application of eggshell powder in soil stabilization were included. Metadata including publication titles, authors, keywords, abstracts, source titles, and publication years were extracted for analysis.

2.2 Data Processing

To guarantee reliability and consistency, the gathered bibliographic data underwent an exhaustive cleaning procedure [10]. Duplicate entries were identified and eliminated. Variations in author names, institutional affiliations, and keyword phrasing were standardized to maintain consistency. Subsequently, the refined dataset was exported in formats compatible with bibliometric software processing (e.g., CSV, RIS). Critical fields such as author names, country of origin, keywords, titles, citation counts, and source information were extracted.

2.3 Network Visualization

VOSviewer and Biblioshiny (an interface of the Bibliometrix package in RStudio) were employed to conduct network visualization [11]. Co-occurrence analyses were performed on keywords to identify thematic relationships within the research domain. Research clusters and influential contributors were mapped by examining collaboration networks between authors and institutions. Network graphs, density maps, and co-authorship maps were employed to illustrate the structure and dynamics of research activities.

2.4 Cluster Analysis

To identify significant thematic areas within the literature, cluster analysis was applied to the co-occurrence network of keywords [12]. Clusters were formed by grouping keywords that frequently appeared together, reflecting specific research themes relevant to the use of agricultural waste in soil stabilization. The relevance and centrality of each cluster to the field were analyzed and color-coded, facilitating the understanding of core areas, interdisciplinary linkages, and peripheral research topics in the eggshell powder domain.

2.5 Trend and Thematic Evolution Analysis

To monitor the progression of research themes over the designated period, temporal trend analysis was conducted [8]. Sankey diagrams and thematic evolution maps were created to demonstrate the transition of research focus across three distinct time periods: 2010–2014, 2015–2019, and 2020–2024. Themes were categorized into motor themes, niche themes, emerging or declining themes, and basic themes, based on their density and centrality using thematic mapping techniques [12]. These visual tools facilitated the identification of emerging research areas and future directions for the

application of waste-based stabilizers such as eggshell powder.

2.6 Discussion of Results

The final phase entailed interpreting the quantitative outputs and visualizations to derive meaningful insights [7]. Key research themes were identified, collaborative networks among researchers and institutions were mapped, and shifts in research focus over time were analyzed. The discussion offered a structured narrative regarding the evolution of research on eggshell powder in soil stabilization, highlighting significant trends, existing research gaps, and opportunities for future investigations [3].

3. RESULTS AND DISCUSSION

3.1 Network Analysis

A cluster-based co-occurrence map of keywords extracted from scholarly literature that is specifically focused on geotechnical engineering and, by extension, research related to eggshell powder (ESP) in soil stabilization is depicted in Figure 2. The network is dominated by the term "geotechnical engineering," suggesting that research on ESP is firmly rooted in this broader field. It is surrounded by related terms such as shear strength, bearing capacity, soil reinforcement, and slope stability, which are critical performance indicators for evaluating the efficacy of any soil stabilizer, including ESP.

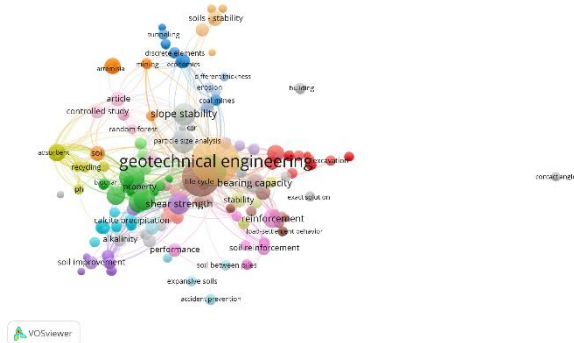


Fig. 2. Network Visualization

The green cluster's presence of the calcite precipitation and alkalinity nodes is particularly noteworthy. These terms are directly related to the chemical reactions that take place when ESP, which is abundant in calcium carbonate, interacts with soils to improve cohesion and decrease plasticity. In the same vein, the yellow and orange clusters contain biochar, recycling, and adsorbent, all of which are consistent with ESP's status as a sustainable, waste-based material. These connections further solidify the classification of ESP research within environmentally conscious soil improvement techniques.

The red cluster, which is centered on reinforcement and excavation, emphasizes the overlapping nature of ESP applications and structural support systems, including embankments and retaining structures. ESP research is intersected with both performance evaluation and sustainability metrics, as evidenced by terms such as slope stability, life cycle, and soil improvement. This is consistent with its appeal as a low-cost, circular-economy material.

Ultimately, Figure 2 demonstrates that the research on eggshell powder is deeply ingrained in the broader body

of geotechnical engineering literature. The growing academic traction and the significance of ESP in addressing performance, sustainability, and waste reduction challenges in modern civil engineering are indicated by the clear association of ESP-relevant concepts with high-frequency nodes.

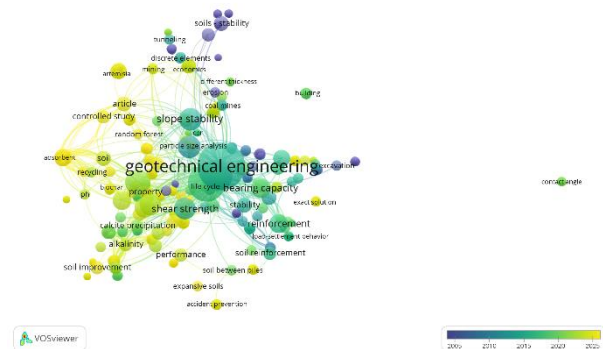


Fig. 3. Overlay Visualization

Figure 3 augments the previous co-occurrence network by incorporating a temporal layer that demonstrates the progression of research themes over time, with a particular emphasis on the period between 2005 and 2025. The appearance of keywords associated with foundational geotechnical engineering concepts, such as shear strength, bearing capacity, and slope stability, in cooler shades (blues and greens), suggests their prior presence in the literature. These serve as the foundation of ESP research, which is founded on established principles of soil behavior.

The yellow-hued nodes—recycling, biochar, life cycle, and calcite precipitation—which have emerged more recently are particularly noteworthy. These terms are consistent with the utilization of eggshell powder and are indicative of recent research trends (2018–2025). ESP is frequently investigated in the context of environmental impact and life cycle analysis, as it is a waste-derived material that is rich in calcium. This places it within the sustainability movement in geotechnical research.

The increasing prevalence of experimental design and data-driven methods in the evaluation of alternative stabilizers such as ESP is evidenced by the positioning of random forest and controlled study in the more recent layers. Additionally, the emergence of terms such as "soil improvement" and "adsorbent" in more recent time zones indicates that researchers are currently investigating ESP for its potential to mitigate environmental contaminants, in addition to its structural benefits, due to its high pH and sorptive properties.

Consequently, this overlay map substantiates the notion that eggshell powder applications are a component of a broader transition in geotechnical research, which is to transition from classical mechanical testing to sustainable material integration, life cycle performance, and data-driven decision-making. The inclusion of ESP in the most recent cluster of terms indicates that it is a topic that is both timely and emerging in the field of civil and environmental engineering scholarship.

demonstrated potential in reducing their swelling behavior. Similarly, energy dissipation may be associated with the damping properties of ESP under dynamic loading, an area that has yet to be thoroughly investigated.

Finally, the central region of the map encompasses terms such as alkalinity, calcite, performance, and controlled study, which seem to connect multiple quadrants. These terms emphasize the increasing interest in investigating the chemical and experimental aspects of ESP stabilization. ESP's intermediate positioning implies that they are gaining momentum and may eventually transition to the Motor Themes quadrant as additional studies investigate the pozzolanic activity, long-term durability, and sustainability metrics of ESP in controlled laboratory environments.

In conclusion, this thematic map confirms the significant centrality of ESP in conventional geotechnical domains and identifies underdeveloped or peripheral areas with untapped potential. The significance of linking specialized applications to broader engineering objectives, expanding experimental studies, and balancing mechanical and chemical perspectives is emphasized by the visualization. Researchers who are interested in advancing the stabilization of ESP soil can utilize this map to identify both core and emerging areas that are available for impactful contributions.

3.3 Influential Contributors and Trends

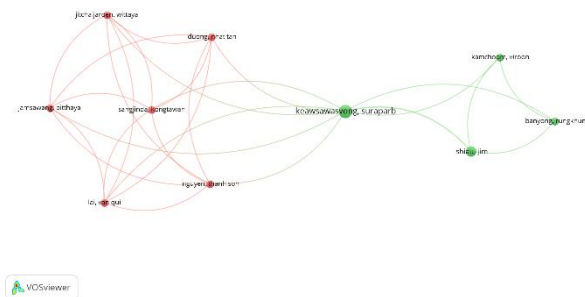


Fig. 6. Network Visualization of Authors

The collaborative landscape among researchers who are working on soil stabilization using waste-based materials such as eggshell powder (ESP) is illustrated by the co-authorship network in Figure 6. The links indicate co-authorship connections in published works, while each node represents an author. The color-coding is used to differentiate between various research clusters or groups, while the size of each node is indicative of the number of publications or influence (as determined by citation metrics). This visualization discloses the structure of their collaborative relationships in addition to the active research contributors.

The network is divided into two major clusters—one red and one green—which represent two distinct groups of collaborators. The **red cluster** is centered on authors such as *Duong, Nhat Tan*, *Jitchaijaroen, Wittaya*, and *Nguyen, Thanh Son*, who all seem to have strong internal collaborative ties. Their interconnected structure suggests consistent co-authorship, which may suggest joint institutional affiliations or region-specific research

efforts, likely within Southeast Asia. This group's emphasis may be more experimental or restricted to soil types and stabilization contexts.

Conversely, the **green cluster** is organized around *Keawsawasvong, Suraparb*, who serves as a liaison between the two research groups. This individual exhibit a high level of connectivity, which implies that they are involved in numerous international or interdisciplinary collaborations. The tight connections between collaborators *Kamchoom, Viroon*, *Shiao, Jim*, and *Banyong, Rungkun* suggest a focused sub-network that is likely dedicated to the mechanical or chemical behavior of ESP in geotechnical applications.

The significance of collaborative research in the advancement of sustainable soil stabilization is underscored by this network visualization. Strong intra-cluster connections facilitate in-depth investigations within specific domains, while inter-cluster links—particularly through the bridging of researchers—enable knowledge transfer and interdisciplinary innovation. In the future, the integration of environmental and structural performance outcomes, a broader validation of ESP applications, and the development of more standardized methodologies could be facilitated by the enhancement of cross-cluster collaboration.

3.4 Methodologies and Applications

Most of the studies employed laboratory-scale experimental setups, in which soil samples were mixed with varying percentages of ESP and analyzed for properties such as unconfined compressive strength (UCS), maximum dry density (MDD), and California Bearing Ratio (CBR). Standard geotechnical testing protocols were implemented, and numerous investigations implemented chemical analysis through scanning electron microscopy (SEM) and X-ray diffraction (XRD) to enhance comprehension of soil-ESP interactions at the microstructural level.

The applications of these discoveries are expanding. ESP-treated soils have been suggested for use in subgrade layers of roads, embankment fills, and slope stabilization projects, particularly in regions where cement and lime are either environmentally undesirable or expensive. Its appeal for future infrastructure developments is further bolstered by the versatility and dual function of ESP as both a stabilizer and a sustainable waste management solution.

3.5 Future Research

Future research should prioritize the standardization of testing methodologies for the stabilization of ESP. Cross-study comparisons are challenging since current studies differ in terms of particle size preparation, curing times, dosage rates, and testing parameters. The establishment of best practices would be more reliable, and the synthesis of results would be improved by the development of a standardized framework.

The transition to field-scale trials is another significant venue. Although laboratory results have consistently demonstrated improvements in soil properties because of ESP treatment, validation under real-world environmental and loading conditions is still uncommon. Critical practical insights would be obtained through

pilot projects that evaluate ESP-treated soils in actual roadbeds or slope stabilization projects.

It is also essential to conduct long-term durability studies. The reliability of ESP-stabilized soils must be thoroughly evaluated across a variety of climates and usage scenarios by evaluating their performance under cyclic loading, freeze-thaw conditions, wet-dry cycles, and chemical exposure.

Moreover, the systematic integration of Cost-Benefit Analysis (CBA) and Life Cycle Assessment (LCA) into ESP research is advisable. The argument for the widespread adoption of ESP in civil engineering projects could be significantly strengthened by quantifying the environmental benefits of reducing waste and replacing cement-based stabilizers.

Lastly, there is potential for the development of hybrid stabilization systems, in which eggshell powder is combined with other waste materials, such as rice husk ash, fly ash, or biochar. These multi-waste systems have the potential to optimize mechanical performance and improve sustainability outcomes, thereby making soil stabilization even more eco-efficient and accessible on a global scale.

4. CONCLUSION

This bibliometric study offers a structured overview of the research landscape related to the use of eggshell powder (ESP) in soil stabilization. The analysis indicates that ESP applications are deeply rooted in the geotechnical engineering domain, with a particular emphasis on enhancing soil reinforcement properties, bearing capacity, and shear strength. Recent research trends have underscored an increasing emphasis on environmental sustainability, circular economy practices, and chemical interactions, including calcite precipitation, in addition to mechanical performance. The results confirm that ESP is a promising alternative to traditional soil stabilizers, as it is situated at the intersection of sustainable engineering and performance enhancement.

The study also identifies several gaps that future research must address, despite the positive outlook. It is imperative to maintain the standardization of testing methodologies to enable the replication and comparability of results across various studies. Additionally, it is evident that laboratory findings must be validated under real-world environmental and loading conditions through large-scale field trials. To establish the reliability of ESP-treated soils over time, it is imperative to conduct long-term performance evaluations that include assessments under cyclic loading, freeze-thaw actions, and chemical exposure.

Lastly, the incorporation of Cost-Benefit Analysis (CBA) and Life Cycle Assessment (LCA) into ESP studies could offer more compelling evidence to support its implementation in the field of mainstream engineering. It is also possible to explore hybrid stabilization systems by combining ESP with other agricultural or industrial waste materials, which presents new opportunities for innovation. The academic and engineering communities can more effectively leverage the potential of eggshell powder to advance sustainability goals in geotechnical

engineering and improve soil behavior by addressing these research needs.

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