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Sustainability in Geotechnical Engineering: A Bibliometric Analysis

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Abstract

Within the ever-expanding field of sustainability research in geotechnical engineering, scholars need to fully grasp its breadth. This complexity often results in redundancies and delays in research progress. In order to have a more scientific grasp of the development of the field of geotechnical engineering sustainability, we tried to use innovative bibliometric methods to scientifically review the contemporary landscape and evolution of geotechnical engineering sustainability research. This study uses the R package bibliometrics to analyse bibliometric data visualizations regarding geotechnical sustainability in contemporary landscapes. Therefore, it conducted a follow-up analysis: examining annual publication trends, identifying the most contributing authors, the most productive countries, the most cited papers, popular journals, prolific affiliations, frequently occurring keywords and network analysis. Bibliometric methods can provide relevant researchers with a reference for the current status of research in this field. Based on the findings, sustainable geotechnical engineering research was initiated in 1998 and has continued to advance since then, especially surging in 2019. The field of geotechnical sustainability research is dynamically expanding and in a transformational phase, which indicates a significant increase in related research. Since the data will continue to change, replication may be required in the future.

Keywords: Geotechnical Engineering, Sustainability, Bibliometric, Topic Detection

Introduction

When building buildings on land or in the ocean, the engineering involving the underground part is called geotechnical engineering. Geotechnical engineering is the guarantee for the long-term normal use of buildings. Scientific and sustainable ideas are adopted in design, clean and reliable materials are used in construction, and low-cost and efficient methods are used in maintenance. This is increasingly closely related to sustainability. Geotechnical engineering, characterized by its substantial environmental footprint and resource utilization, underscores the imperative for sustainable practices (Basu et al., 2015). Research suggests that civil engineering is one of the principal factors contributing to environmental pollution, with geotechnical engineering being an indispensable component thereof (Tiza et al., 2023).

As sustainable research in geotechnical engineering continues to advance, it becomes imperative to conduct a comprehensive analysis of the current research landscape to support subsequent investigations. Given the vast quantity of relevant literature and the wide-ranging scope of research in this field, it poses significant challenges to transition from geotechnical engineering to sustainability analysis. Traditional literature reviews struggle to encapsulate the key aspects of existing research. To advance the sustainable evolution of geotechnical engineering, researchers have undertaken extensive investigations across diverse realms within the discipline, including roadway construction (Celauro et al., 2017), foundation excavations (Gao et al., 2020), tunnels (Lombardi et al., 2023), sustainable materials (Pang et al., 2024).

Indeed, in the initial phases of civil engineering projects, adopting sustainable practices in geotechnical design and construction can establish paradigms for subsequent project components, thereby substantively advancing sustainable development. The field of civil engineering exerts influence across endeavours directed towards human manipulation, modification, and governance of natural and ecological systems. Estimates suggest that the construction sector contributes approximately 40% to global energy usage and consumes substantial quantities of sand and stone reserves annually (Labaran et al., 2021). Construction activities contribute to a spectrum of challenges including climate change, ozone depletion, desertification, deforestation, soil erosion, and alterations in land and water dynamics, among others. Geotechnical engineering not only engenders the aforementioned adverse impacts on Earth's resources and environment but also precipitates shifts in longstanding land use patterns, impacting the social and ethical fabric of communities. Consequently, geotechnical engineering projects encompass a multitude of social, environmental, and economic considerations, making the enhancement of sustainability within geotechnical engineering processes imperative for achieving comprehensive sustainable development (He et al., 2020). Despite the increasing recognition of the role of geotechnical engineering in sustainable development, there persists a general paucity of understanding regarding the precise contributions of geotechnical engineering processes to overarching sustainable development objectives.

The study framework comprises several sections. Section 2 provides a comprehensive review of literature pertaining to geotechnical engineering sustainability. Section 3 outlines the methodologies employed for data collection and analysis. The primary findings are delineated in Section 4, while Section 5 delves into the implications of the research findings.

Literature Review

Sustainability in geotechnical engineering

The concept of sustainability in geotechnical engineering has gained significant attention in recent years. Basu et al. (2015) underscores the importance of sustainability within geotechnical engineering and its influence on infrastructure development (Basu et al., 2015). Their study examines the extent to which geotechnical engineering contributes to the promotion of sustainable development in civil infrastructure. Vieira et al. in 2016 presents an educational experience involving undergraduate students in determining the engineering properties of recycled materials for geotechnical applications (Vieira et al., 2016). This study sheds light on the potential of using recycled materials to enhance sustainability in geotechnical engineering practices. Lee et al. focused on the integration of resilience and

sustainability in geotechnical engineering, highlighting the need to incorporate resilience alongside sustainability for improved infrastructure development (Lee et al., 2018). Several recent studies by Guzman et al. in 2019, Sleep et al. in 2019, Lal et al. in 2019, and Ahirwar et al. in 2021 all explore sustainability in geotechnical engineering, indicating a growing interest in this area (Guzman et al., 2019, Sleep et al., 2019, Lal et al., 2019, & Ahirwar et al., 2021). Roque in 2021 discusses the movement toward sustainability in geotechnical engineering, highlighting the importance of incorporating sustainable practices in this field (Roque, 2021). These studies likely delve into various aspects of sustainability practices, challenges, and opportunities within geotechnical engineering. Murashev in 2021 discusses sustainability aspects of geotechnical engineering specifically in New Zealand, emphasizing the importance of managing resources, energy, and human capital for future generations (Murashev, 2021). Raza et al. in 2011 focused on the engineering aspect of sustainability assessment for geotechnical projects, highlighting the need for a comprehensive sustainability assessment framework in geotechnical engineering (Raza et al., 2011). Sochanik in 2020 reviews the current status of geotechnical sustainability in the United Arab Emirates, proposing practical solutions to improve sustainability practices in geotechnical engineering (Sochanik, 2020). This study also identifies opportunities for further research and development in geotechnical engineering sustainability. Overall, the literature indicates a growing recognition of the importance of sustainability in geotechnical engineering and the need for continued research and development in this area.

Bibliometric Analysis For Exploring Research

Bibliometric analysis has become a valuable tool for assessing trends and developments in various fields of engineering. In a study on intelligent compaction practices and development, researchers utilized bibliometric analysis to explore the growth trends in the field (Liu et al., 2020). Similarly, in a study on microcapsule-enabled self-healing concrete, the emergence of civil engineering fronts from interdisciplinary research was examined through bibliometric analysis (Zhou et al., 2023). Geotechnical engineering has also been the subject of bibliometric analysis in recent research. A review paper on the global research trend on microbially induced carbonate highlighted the importance of bibliometric analysis in understanding the intersection of geotechnical/structural engineering and environmental engineering (Omoregie et al., 2022). Additionally, a bibliometric review on the stability and reinforcement of special soil in building science and engineering demonstrated the impact of detailed analysis in this area of geotechnical engineering (Wang et al., 2022). Furthermore, a critical review and bibliometric analysis on applications of engineering sustainability emphasized the significance of analyzing journals, authors, publications, author keywords, and collaboration between countries in understanding the field (Elshaboury et al., 2023). This type of analysis provides valuable insights into the current state of research and helps identify key areas for future exploration. Overall, bibliometric analysis has proven to be a valuable tool in understanding trends, developments, and interdisciplinary connections within geotechnical engineering and related fields. By examining citation patterns, growth trends, and collaboration networks, researchers can gain a deeper understanding of the current landscape and potential future directions for research in this area.

Research Methodology

We review the research area (publications) and the state of the literature on sustainable development in geotechnical engineering. We conducted a comprehensive search of the Web

of Science database to retrieve all relevant articles addressing the intersection of geotechnical engineering and sustainability, spanning from 1998 to 2024.

We conducted a search within the Web of Science database, which encompasses a broad array of scholarly publications, Altimetric data, patents, grants, clinical trials, and policy documents, constituting one of the most comprehensive collections of interconnected data (Bergeron et al., 2018). In our search for English-language documents, we employed the terms "Sustainability" and "Geotechnical engineering" across all fields, including titles, abstracts, and keywords.

In order to conduct analysis using the Bibliometrix software, documents sourced from the WoS database were retrieved in BibTeX format and subjected to filtration (Bouchard et al., 2020). The Bibliometrix program offers a wealth of pertinent data and embodies scientific rigor, while also providing visualization capabilities, thus aligning effectively with the principles of human-machine interaction. According to Yurui et al., it stands as the most comprehensive, integrated, and user-friendly bibliometric tool of type A currently available, serving as an open-source solution for bibliometric measurement in scientific quantification and research (Yurui & Abdullah, 2024).

Results and Discussions

Descriptive Analysis

The primary details of the chosen collection of articles obtained from the "Biblioshiny Tool for R-Package" are presented in Table 1.

Table 1
Demographic Profile of Respondents

Description	Results
Timespan	1998:2024
Sources (Journals, Books, etc)	116
Documents	288
Annual Growth Rate %	11.99
Document Average Age	4.87
Average citations per doc	10.01
References	12795
Keywords Plus (ID)	675
Author's Keywords (DE)	1025
Authors	917
Authors of single-authored docs	20
Single-authored docs	20
Co-Authors per Doc	3.72
International co-authorships %	28.12

The data shows the status of geotechnical and sustainability research over time. The data includes documents from 1998 to 2024, with a total of 288 articles covering 116 sources. The annual growth rate of documents is approximately 11.99%, the average number of citations is 10.01, and the average age of documents is 4.87 years. The total number of cited documents is 12,795 times, the number of keywords is 675, and the number of author keywords is 1,025. A total of 917 authors participated in the creation of these documents, 20 of which were created by a single author, and there were 20 single authors in total. Each document has an average of 3.72 collaborators, of which 28.12% are international collaborations.

This shows the research situation in the field of geotechnical engineering and sustainability in recent years. From 1998 to 2024, there were a total of 288 documents involving this field, among which the number of citations was relatively high, with an average of 10 citations per document. Research shows a continuous growth trend, and the average age of literature is approximately 5 years, indicating that the research field is constantly updated. The proportion of international cooperation is relatively high, accounting for about 28%, reflecting the international and cooperative nature of this field.

Table 2
Annual Publication Trends for Sustainability in Geotechnical Engineering

Year	Articles	Mean TC per Year	CitableYears
2024	19	0.26	1
2023	51	0.53	2
2022	55	1.5	3
2021	26	2.09	4
2020	29	4.82	5
2019	14	4.04	6
2018	12	0.67	7
2017	6	3.35	8
2016	17	2.05	9
2015	16	1.89	10
2014	4	0.82	11
2013	10	0.54	12
2012	4	1.46	13
2011	12	0.49	14
2010	3	2.4	15
2009	2	0.75	16
2008	2	1.38	17

The data provides detailed insights into recent trends in the field of geotechnical engineering and sustainability. Let's break it down year by year:

- 2024: 19 articles were published, with an average of 0.26 citations per article. It is a calculable year with only one year, so the average number of citations is low.
- 2023: 51 articles were published, with an average of 0.53 citations per article. It is a calculable two-year period. The number of articles has increased, but the average number of citations is relatively low.
- 2022: 55 articles were published, with an average of 1.5 citations per article. This is one of the highest numbers of articles published in a three-year calculable period, and the average number of citations is high.
- 2010 to 2021: Both the number of articles and the average number of citations fluctuated during this period. Among them, the number of articles in 2019 and 2020 is relatively high, and the average number of citations is also high, indicating that the research in these two years has a greater impact on the field.
- 2008 to 2009: The number of articles in these two years was smaller, but the average number of citations was relatively high, which may reflect the higher quality of research in this period.

  Overall, while there are fluctuations in the number of articles and average citations per year, the overall trend shows a steady increase, reflecting the continued growth in interest and research in the fields of geotechnical engineering and sustainability.

Table 3
Most Productive Authors for Sustainability in Geotechnical Engineering

Authors	Articles	Articles Fractionalized
DEJONG JT	6	1.53
RAYMOND AJ	6	1.70
BASU D	5	2.08
CONSOLI NC	5	1.37
DA ROCHA CG	5	1.28

In the field of geotechnical engineering and sustainability, DEJONG JT and RAYMOND AJ lead with 6 articles published, but BASU D's articles have the highest average number of citations, reaching 2.08 times, showing high influence. Although other authors CONSOLI NC and DA ROCHA CG have published more articles, their average number of citations is low, and they may need to further improve their research impact.

Table 4
Most Cited Papers for Sustainability in Geotechnical Engineering

Paper	Total Citations	TC per Year	Normalized TC
MOHAJERANI A, 2020, RESOUR CONSERV RECYCL	266	53.20	11.04
CHANG I, 2016, SUSTAINABILITY	212	23.56	11.51
IKEAGWUANI CC, 2019, J ROCK MECH GEOTECH ENG	167	27.83	6.90
VIEIRA CS, 2015, RESOUR CONSERV RECYCL	162	16.20	8.58
CHANG I, 2020, TRANSP GEOTECH	142	28.40	5.89
BASU D, 2015, CAN GEOTECH J	95	9.50	5.03
KUMARI WGP, 2019, EARTH-SCI REV	92	15.33	3.80
SOUKISSIAN TH, 2017, ENERGIES	88	11.00	3.28
DU H, 2020, CONSTR BUILD MATER	81	16.20	3.36
O'ROURKE TD, 2010, GEOTECHNIQUE	78	5.20	2.17

These data show the citation status of selected papers in the fields of geotechnical engineering and sustainability. Among them, the papers by MOHAJERANI A and others performed better in terms of total citations and average annual citations. The normalized citations were also relatively high, showing high academic influence. The citations of other papers also have their own characteristics. Although some papers have more total citations, their average annual citations are lower, reflecting that they have achieved a higher number of citations in a shorter period of time, while some papers have a lower average number of citations. Steady citation trend. These data help assess the influence and importance of these papers in the academic community.

Table 5
Most Productive Countries for Sustainability in Geotechnical Engineering

Country	Articles	MCP_Ratio
CHINA	56	0.232
USA	42	0.19
UNITED KINGDOM	27	0.037
INDIA	17	0.176
AUSTRALIA	11	0.636
BRAZIL	11	0.364
CANADA	11	0.455
MALAYSIA	10	0.6
PAKISTAN	8	0.5
PORTUGAL	8	0.375

The data presents the number of published articles by different countries in the field of geotechnical engineering and sustainability and the multi-country collaboration ratio (MCP Ratio) per article. China ranks first with 56 articles, but its multinational cooperation ratio is 0.232. Other leading countries include the United States (42 articles, MCP ratio 0.19), India (17 articles, MCP ratio 0.176), and the United Kingdom (27 articles, MCP ratio 0.037). However, although countries such as Australia, Brazil, Canada, and Malaysia have fewer articles, their proportions of multi-national cooperation are relatively high, which are 0.636, 0.364, 0.455, and 0.6 respectively, indicating that researchers in these countries are more inclined to engage in cross-border cooperation.

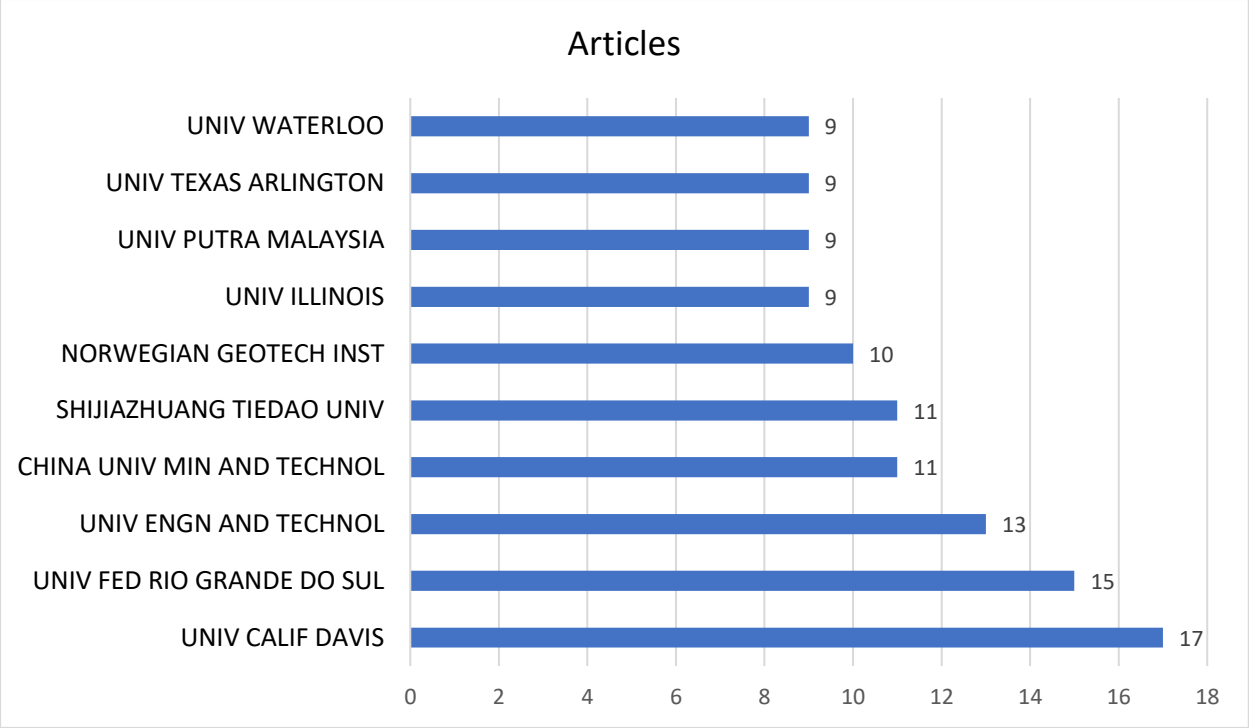

Figure 1. The Most Relevant Affiliations

As can be seen from Figure 1, the United States: University of California, Davis and University of Illinois Urbana-Champaign published 17 and 9 articles respectively, showing the important position of the United States in this field. This reflects the United States' advantages in scientific research resources and academic output.

Brazil: Universidade Federal do Rio Grande do Sul is a Brazilian university that published 15 articles showing Brazilian research activities in the field of geotechnical engineering and sustainability.

China: China University of Mining and Technology and Shijiazhuang Tiedao University published 11 articles each, showing how active China is in this field. China's participation demonstrates the country's growing research investment and influence in the fields of geotechnical engineering and sustainability.

Malaysia: Universiti Putra Malaysia published 9 articles showing Malaysia's research activities in the field, especially in areas related to sustainability.

Norway: Norwegian Geotechnical Institute published 10 articles showing Norwegian research activities in the field of geotechnical engineering. Norway has a certain reputation in the field of geological engineering research.

Based on the above, it can be seen that the United States, Brazil, China, Malaysia, Norway, etc. are more active in research activities in the field of geotechnical engineering sustainability. Among them, the United States and China are the top two economies in the world and have relatively large investments in infrastructure. Brazil has formulated A series of infrastructure investment policies have been implemented. Malaysia has attached great importance to the

topic of sustainable development in recent years. The frozen soil in Norway is widely distributed. Among them, the Norwegian Institute of Geotechnical Technology has long been committed to geotechnical engineering research, so it has published many documents.

Table 6
Most Frequent Journals for Sustainability in Geotechnical Engineering

Sources	Articles
SUSTAINABILITY	81
PROCEEDINGS OF THE INSTITUTION OF CIVIL ENGINEERS-GEOTECHNICAL ENGINEERING	18
PROCEEDINGS OF THE INSTITUTION OF CIVIL ENGINEERS-ENGINEERING SUSTAINABILITY	14
ENVIRONMENTAL GEOTECHNICS	5
FROM FUNDAMENTALS TO APPLICATIONS IN GEOTECHNICS	5
INDIAN GEOTECHNICAL JOURNAL	5
JOURNAL OF ROCK MECHANICS AND GEOTECHNICAL ENGINEERING	5
COUPLED PHENOMENA IN ENVIRONMENTAL GEOTECHNICS: FROM THEORETICAL AND EXPERIMENTAL RESEARCH TO PRACTICAL APPLICATIONS	4
GEO-CHICAGO 2016: SUSTAINABLE GEOENVIRONMENTAL SYSTEMS	4
GEOTECHNICAL ENGINEERING IN THE XXI CENTURY: LESSONS LEARNED AND FUTURE CHALLENGES	4

These data provide the number of published articles in several important journals and conference proceedings in the field of geotechnical engineering and sustainability. Among them, the SUSTAINABILITY journal published the largest number of articles, with a total of 81 articles, highlighting the importance of sustainability in this field. Other journals and proceedings have a smaller number of published articles, but still cover different aspects of the geotechnical engineering and sustainability fields, providing a platform for academic exchanges and research.

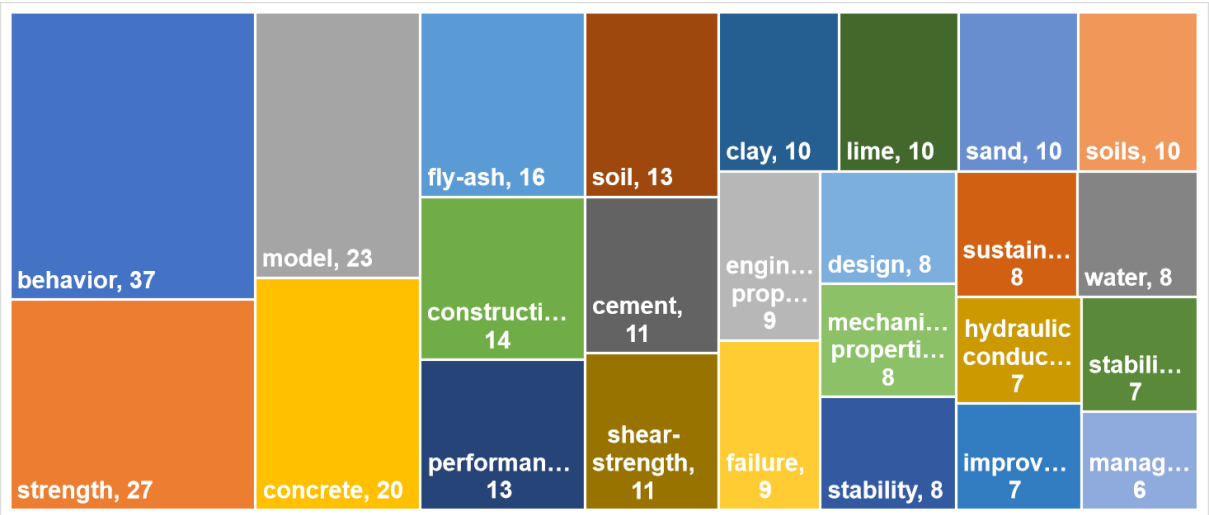

Figure 2. Most Frequent Keywords for Sustainability in Geotechnical Engineering Figure

Based on the data analysis provided, the field of geotechnical engineering and sustainability presents several key characteristics:

First, the term that appears most frequently in the data is "behavior," which indicates the importance of studying the behavioral properties of materials or structures in this field. This may involve the study of deformation, failure, and load-deformation relationships of materials such as soil and concrete, which are essential for engineering design and analysis. Second, the terms "strength" and "shear-strength" also appear more frequently, reflecting the study of the strength characteristics of materials and structures in geotechnical engineering. These studies are of great significance for evaluating the stability, bearing capacity, and seismic performance of engineering structures. In addition, the high frequency of the term "model" indicates that in the field of geotechnical engineering and sustainability, there is an emphasis on the development of appropriate numerical, experimental, or theoretical models to describe and predict the behavior of engineering structures or materials. In addition, the frequency of the terms "concrete" and "cement" is also significant, reflecting the importance of concrete materials in geotechnical engineering and the study of concrete properties and applications.

To sum up, research in the field of geotechnical engineering and sustainability covers material behavior, strength characteristics, simulation modeling, concrete materials, and other aspects, which are of great significance for the development of engineering practice and the improvement of sustainability.

Discussion

Over the past few decades, the field of geotechnical engineering and sustainability has shown a continuous growth trend, with increasing research activities, increasing international cooperation, and sustainability becoming one of the important topics of research. However, as society, environment, and technology continue to change, the field may face some challenges and changes in the future.

First, as populations grow, urbanization accelerates, and natural resources continue to be consumed, the field of geotechnical engineering and sustainability will face more complex engineering and environmental issues. For example, issues such as land use pressure, water management, and waste disposal due to urbanization require more innovative and sustainable solutions.

Second, climate change and the frequency of natural disasters are likely to place greater demands on the design, construction, and management of geotechnical engineering and infrastructure. Engineers and scientists need to consider the effects of climate change on geology and soil, and how to incorporate more adaptability and disaster resilience into their designs.

Future thematic trends may include more attention to the following:
Smart and sustainable infrastructure: Future research is likely to focus more on leveraging advanced technologies and intelligent systems to build more sustainable, intelligent infrastructure to meet the challenges posed by urbanization and population growth.

Ecological restoration and biodiversity conservation: With the increasing awareness of environmental protection, future research may focus more on the restoration of ecosystems and the protection of biodiversity, improving environmental quality through ecological engineering and biotechnology.

Renewable energy and low-carbon technologies: Future research is likely to focus more on the development and utilization of renewable energy sources, as well as the application of low-carbon technologies in geotechnical engineering and infrastructure construction to reduce environmental impact.

Digitalization and Big Data analytics: As digital technologies evolve, future research is likely to focus more on leveraging technologies such as big data analytics and artificial intelligence to optimize the design, construction, and management of infrastructure for greater efficiency and sustainability.

In summary, there are many challenges and opportunities ahead in the field of geotechnical engineering and sustainability. Through interdisciplinary collaboration and innovation, we are expected to find more sustainable and environmentally friendly solutions that promote social, environmental, and economic sustainability.

Conclusions

Developments in the fields of geotechnical engineering and sustainability have shown a continuous growth trend over the past decades. Research activity continues to increase, with an annual growth rate of approximately 11.99%, reflecting the academic community's continued focus and investment in this field. This growth is reflected not only in the number of documents but also in the increase in international collaborations, which account for approximately 28.12% of research activities. International cooperation in this field promotes the sharing and exchange of knowledge and promotes research progress. At the same time, the fields of geotechnical engineering and sustainability are increasingly paying attention to sustainability issues. The frequent occurrence of keywords and journal names in journals and papers reflects this trend. Many countries have actively participated in research activities in this field, and countries such as China, the United States, and Brazil have published a large number of research papers, showing the global characteristics of this field. Finally, research in the field of geotechnical engineering and sustainability exhibits interdisciplinary characteristics, involving multiple disciplines such as engineering and environmental science, and requires cooperation and communication between different disciplines to solve complex problems. In summary, the development trends in this field show vitality and diversity, providing important academic support for solving today's social and environmental challenges.

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