Pertanika J. Sci. & Technol. 33 (S4): 1 - 25 (2025)

PERTANIKA JOURNALS

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Bibliometric Review on Geopolymer Modified with Nanomaterials Using VOS Viewer

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ABSTRACT

Geopolymer composites modified with nanomaterials have gained significant interest in recent years due to their improved properties. The nanoparticles can form extra C-S-H gel, reducing porosity and generating a denser microstructure. Manual reviews cannot effectively manage the immense bibliometric data. Therefore, this manuscript reviews nanomaterials in geopolymer by adopting a scientometric evaluation as a form of analysis via visualization of similarities software in the VOS viewer. A bibliometric network is created and depicted to analyze the annual distribution and growth pattern, prominent sources, frequent keywords, top articles, and leading countries of geopolymer modified with nanomaterials via the searched words in the Scopus database of "geopolymer" and "nanomaterial" that successfully achieved 529 documents from 2008 to October 2023. The results of the scientometric study indicate that *Construction and Building Materials* appears as the top publication source, in terms of article amount and citation count, and the most frequently utilized keywords in these publications are nanomaterial, geopolymers, and inorganic polymers. Furthermore, the countries that have demonstrated the highest levels of activity and contribution in terms of publications are China, India, and the United States. The inclusion of participating nations and researchers is facilitated through quantitative and graphical representations. This review has

ARTICLE INFO

Article history:
Received: 01 April 2024
Accepted: 10 April 2025
Published: 10 June 2025

DOI: https://doi.org/10.47836/pjst.33.S4.01

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e-ISSN: 2231-8526

the potential to provide valuable insights to academics in the field of forming collaborations and discussing novel ideas and methods. This is mostly due to the inclusion of visual and statistical depictions that showcase the participating nations and authors of the study.

Keywords: Geopolymer concrete (GPC), nanomaterial, VOS viewer, scientometric analysis

INTRODUCTION

Cement-based concrete is anticipated to be the most widely utilized substance worldwide after water, which contributes significantly to greenhouse gas emissions (Adesina, 2020). However, cement production is responsible for around 5%–8% of global carbon dioxide (CO_2) emissions (Teh et al., 2017). The annual consumption of cement exceeds 4000 million tons and is anticipated to exceed almost 6000 million tons by 2060 (Shahmansouri et al., 2020). Researchers have endeavored to develop substitute binders for concrete manufacturing to mitigate the environmental impact of CO_2 emissions on the Earth. Geopolymer concrete has developed as a promising replacement for ordinary concrete, demonstrating the potential for substitution (Shehata et al., 2022).

Portland cement is manufactured by heating limestone ($CaCO_3$) and clay at high temperatures (~1450 °C) in a kiln, resulting in significant CO_2 emissions from fuel burning and limestone decomposition. Conversely, geopolymer concrete employs industrial by-products like fly ash, slag, or metakaolin as its principal binder, which are activated with alkaline solutions (sodium hydroxide and sodium silicate). The absence of cement clinker production leads to significant CO_2 reduction. Geopolymers possess the ability to significantly decrease the carbon dioxide emissions associated with ordinary Portland cement (OPC) production by up to 80% (Duxson et al., 2007).

The word geopolymer was introduced in 1978 by a French scientist, Joseph Davidovits (Davidovits, 1979). It refers to a group of solid substances produced through the chemical reaction between an alumina silicate powder and an alkaline activator (Elie et al., 2021). Geopolymer has garnered more attention within the realm of academic research due to reduced CO_2 emissions (McLellan et al., 2011), reuse of waste materials (Kheimi et al., 2022), support for circular economy practices in solid waste management, enhanced thermal resistance (Turner & Collins, 2013), improved mechanical performance, resistance to acid and sulfate attacks (Zhao et al., 2021), decreased drying shrinkage, and increased resistance to freeze-thaw cycles (Davidovits, 1991; Matsimbe et al., 2022). Despite its numerous advantages, the utilization of geopolymer in technical applications remains limited because of its comparatively high porosity, inadequate interfacial bonding strength, and delayed development of strength during its final stages (Alomayri, 2019).

Recently, geopolymer composites modified with nanomaterials have gained significant interest. Nanomaterials can make more C-S-H gel, which reduces porosity and increases the

density of the microstructure (Jindal & Sharma, 2020; Mostafa et al., 2020) as illustrated in Figure 1. Nanomaterials enhance the formation of C-S-H gel, which reduces porosity and improves the density of the composite (Jindal & Sharma, 2020; Mostafa et al., 2020). Various types of nanomaterials used in geopolymers, such as nano-silica (Çevik et al., 2018), nano-alumina (Assaedi & Olawale, 2022), nano-titanium oxide (Jagadesh & Nagarajan, 2022), carbon nanotubes (Jagadesh & Nagarajan, 2022), and nano-clay (Li et al., 2022), are used to enhance their properties (Raj et al., 2023). Figure 1 illustrates the benefits of nanomaterial-based geopolymers. Nano silica is a specific type of nanomaterial that is most impactful due to its high reactivity with geopolymer compared to other nanomaterials.

Conventional literature reviews are insufficient and subject to bias in establishing an integrated and systematic relationship between different domains of scholarly work. The bibliometric analysis method illustrates the current trajectory of geopolymer concrete modified with nano materials knowledge development in numerous fields of science, furnishes data on the most productive writers and nations, and offers insight into past trends and projected futures of research areas worldwide. This approach is especially valuable as it permits researchers to identify new trends, cross-disciplinary collaborations,

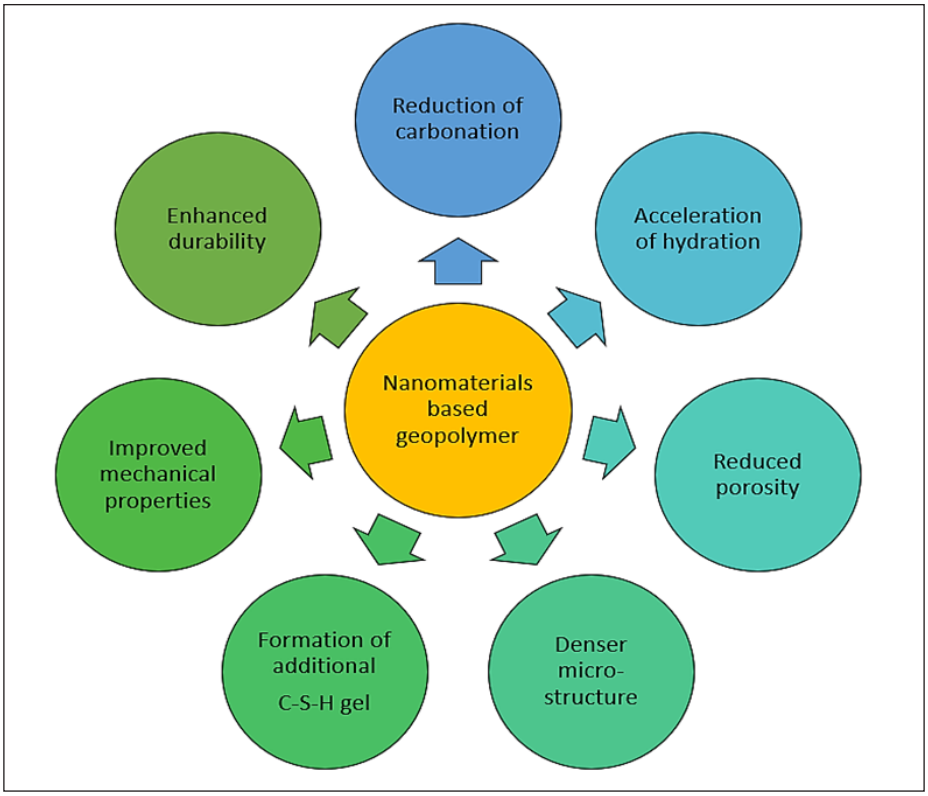

Figure 1. Benefits of nanomaterial-based geopolymers (created by the author)

and technological innovations essential to handling global sustainability obstacles in construction materials.

Several researchers use VOS viewer software to conduct bibliometric studies of geopolymers in various fields, developed in 2010 by Nees Jan van Eck and Ludo Waltman. The software was selected over other bibliometric tools, such as CiteSpace, R Bibliometrix and Google Scholar, because of its ability to visualize and exhibit maps that are easy to interpret. Besides, VOS viewer collects data from various scientific sources such as the Web of Science and Scopus. This enables users to share their maps as dynamic visualizations on the web. VOS viewer is also available on many devices and operating systems, and is free to access (Martins et al., 2024).

Matsimbe et al. (2023) carried out a bibliographic analysis study of geopolymer research in Sub-Saharan Africa using VOS viewer software. The researchers discovered that the terms exhibiting the most frequent occurrences are geopolymers, inorganic polymers, and compressive strength. Furthermore, the *Construction and Building Materials* journal is widely regarded as a prominent scholarly publication, with 41 published articles and an impressive citation record of around 1488. Cameroon, Nigeria, and South Africa are the nations that exhibit the largest volume of publications. Khan et al. (2022) conducted a review of research on the scientometric analysis of the research growth on geopolymers. The keywords used are geopolymer, fly ash, and compressive strength. The scientometric analysis shows that *Construction and Building Materials* publishes the most articles and citations. China, India, and Australia have published extensively. The quantitative and graphical depiction of the participating countries and scholars in this study may foster academic collaboration and creativity.

Tian et al. (2022) found that fly ash-based geopolymer development has three stages: replacing Portland cement, developing multifunctional materials, and reducing environmental impact through solid waste conversion. The author found that China, Australia, India, and the United States emerged as the leading nations in terms of articles, with 16.45%, 10.14%, 7.67%, and 6.68% of the 4352 total articles, respectively.

On the other hand, Yang et al. (2022) carried out a bibliometric analysis of geopolymer composites. The analysis revealed a significant growth in publications on geopolymer composites, particularly between 2011 and 2021, highlighting an increasing interest in eco-friendly construction materials. The top keywords, such as inorganic polymers, geopolymers, and geopolymer, emphasize sustainability and mechanical properties. *Construction and Building Materials* led with 666 publications, followed by Ceramics International. India, China and Australia emerged as top contributors. The bibliometric analysis identified Van Deventer J. S. J. as the most prolific author with 79 publications and 16,125 citations, followed by Chindaprasirt P. (77 publications) and Provis J. L. (70 publications, 13,382 citations).

Geopolymer technology solves environmental contamination by replacing Portland cement with a sustainable alternative. Elmesalami and Celik (2022) comprehensively reviewed Engineered Geopolymer Composites (EGCs). The report commences with a scientometric analysis employing science mapping techniques to summarize the current state of study advancements in EGCs. The review has uncovered the intriguing potential of EGCs as materials that possess both low-carbon and ultra-high-performance characteristics in the application field of construction. Nevertheless, the current phase of research on EGCs remains in its nascent stages, necessitating future inquiries to fully comprehend and use the complete capabilities of EGCs.

Ji and Pei (2019) conducted a review paper on the bibliographic and graphical analysis of the application of geopolymers in the immobilization of heavy metals. The data show that geopolymer research has grown fast in recent years and has been applied to various technical sectors. Geopolymers are manufactured from fly ash and metakaolin. The toxicity characteristic leaching procedure (TCLP) is the most commonly used leaching method because it is a standardized method recommended by the U.S. Environmental Protection Agency (EPA) to evaluate the leaching potential of heavy metals under simulated landfill conditions, heavy metals like Pb, Cr, Cu, Cd, and Zn are toxic elements commonly found in industrial by-products like fly ash. These metals pose environmental risks due to their potential to leach into soil and groundwater, contaminating ecosystems. Therefore, using this method makes it an ideal choice for this research.

Another study conducted by Firas et al. (2024) and Al-Baldawi (2024) on the "Performance of Hybrid Fiber Reinforced Geopolymer Composites (HFRGC): Scientometric and Conventional Review". The outcome indicated that India, China, and Australia were the most active countries in HFRGC research, revealing India as the leading contributor with 35 documents and 333 citations. *Construction and Building Materials* emerged as the most influential journal, publishing 15 articles with 441 citations, significantly outpacing others like *Lecture Notes in Civil Engineering* (10 articles, four citations) and *Materials* (five articles, 34 citations). Frequently used keywords include "geopolymers" and "inorganic polymers," each with 51 occurrences, and "compressive strength" with 31 occurrences. The analysis shows fluctuating publication growth, peaking in 2023 with 20 documents. These findings underscore key research hubs, journals, and trends, aiding collaboration and strategic direction for future HFRGC studies.

There has been a notable lack of studies of geopolymers modified with nanomaterials in bibliometric reviews and bibliometric studies. This deficiency extends to the search strings that have not been sufficiently broad to yield a comprehensive dataset. Consequently, there is a need for an impartial and less subjective illustration of the trends and advancements in this field. This study aims to elucidate the patterns and advancements observed in the most significant sources of publishing, keywords, publications, and nations in the field of geopolymer modified with nanomaterials from 2008 to 2023. The bibliometric analysis

conducted in this study offers significant statistical insights into the development and implementation of geopolymer modified with nanomaterials.

Consequently, it effectively highlights the prevailing and prospective research trends in this field. Furthermore, it clarifies the key issues and noteworthy contributions made by eminent publications and authors to the development of the discipline and enhances comprehension of the theoretical framework and core subjects of the subject area. Using network visualization in bibliometric co-occurrences and co-citations can help academics and research institutions share research skills and creative technologies, work together on unique research projects, and create new business partnerships. Therefore, this study aims to address this deficiency by performing a bibliographic evaluation of the geopolymer modified with nanomaterials research trends to establish empirical benchmarks for future studies.

RESEARCH STRATEGY AND DATA SOURCES

The current investigation employed a scientometric strategy-based review of geopolymers modified with nanomaterials to analyze scientific findings and generate bibliometric geographical maps. The chosen methodology is suitable for this type of assessment as it effectively examines and evaluates the progression of the study during a certain timeframe, utilizing an extensive collection of bibliographic data (Hosseini et al., 2018). Several articles have been released on the topic, and choosing a trustworthy search engine is crucial. Scopus and Web of Science are both highly accurate search platforms that are ideal. (Chadegani et al., 2013; Pranckutė, 2021). The bibliographic data for the geopolymer composite modified with nanomaterials study was acquired using Scopus, which academics highly recommend (Meho, 2019).

Scopus was selected as the principal data source because of its extensive coverage and thorough indexing of scientific literature compared to the Web of Science (Visser et al., 2021). Scopus indexes more than 20,000 journals, exceeding WoS's 13,600, thereby providing a more extensive overview of global research outputs (Mongeon & Paul-Hus, 2016). Nevertheless, the accuracy of citation data differs, as WoS faces issues with missing and incorrect references, while Scopus struggles with duplicate publications. These elements make Scopus preferred for larger disciplinary coverage, although both platforms have limitations impacting citation reliability (Liu et al., 2021).

VOS viewer, created by Eck and Waltman (2021), is a popular data visualization software. It is able to generate visualizations of researchers, journals, documents, and keywords using citations and co-occurrence data. Table 1 illustrates the selection standards applied when obtaining data in the Scopus database from 2008 until October 2023. The timeframe of 2008–2023 was selected because research on the application of nanomaterials in geopolymer technology began gaining significant interest around 2008. Furthermore, collecting literature up to the time of manuscript submission in October 2023

ensures the Review reflects the most recent advancements and trends.

This research focuses on the annual publication of documents, Science mapping of top publication sources, science mapping of co-occurrence keywords, authors, top-cited articles, and contributing nations. The words searched in the Scopus database of Geopolymer and nanomaterial successfully achieved 529 of 914 articles as of October 2023, after applying filtration to eliminate unnecessary papers. The journal article and journal review document types were chosen. The constraint of the language was specified as English. Non-English articles are excluded to prevent misleading data due to translation, interpretation, and accessibility issues because the VOS viewer gives metadata in English.

Table 1
Filter applied for extracting data from the Scopus website

Option	Filter used
Publication date	2008–2023
Language	English
Subject area	Material Science Engineering
Document type	Article Review

The subject areas of engineering and material science were chosen because Geopolymer and nanomaterials are categories in these two. By limiting the scope to these categories, the study ensures a focused and comprehensive bibliometric analysis that is feasible and relevant to the research objectives. The geopolymer data modified with nanomaterials obtained from the Scopus database have been retained in the comma-separated values (CSV) form to facilitate assessment via an appropriate program. The scientific map and visualization tool utilized in this study was VOS viewer (version 1.6.17). Figure 2 illustrates a diagram representing the scientometric strategy.

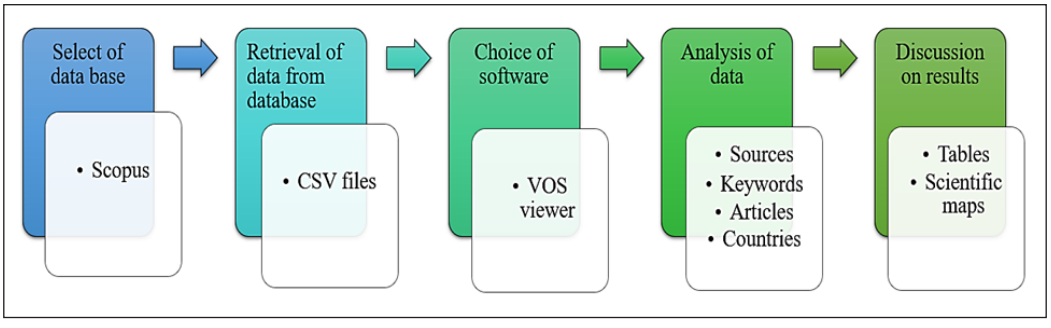

Figure 2. The Sequences of scientometric analysis followed in the geopolymer modified with nanomaterials research

RESULTS AND DISCUSSION

Annual Publication of Documents

The annual publication trend for the subject area is illustrated in Figure 3. The searched keywords, geopolymer and nanomaterial, resulted in 914 documents from 2008 to 2023.

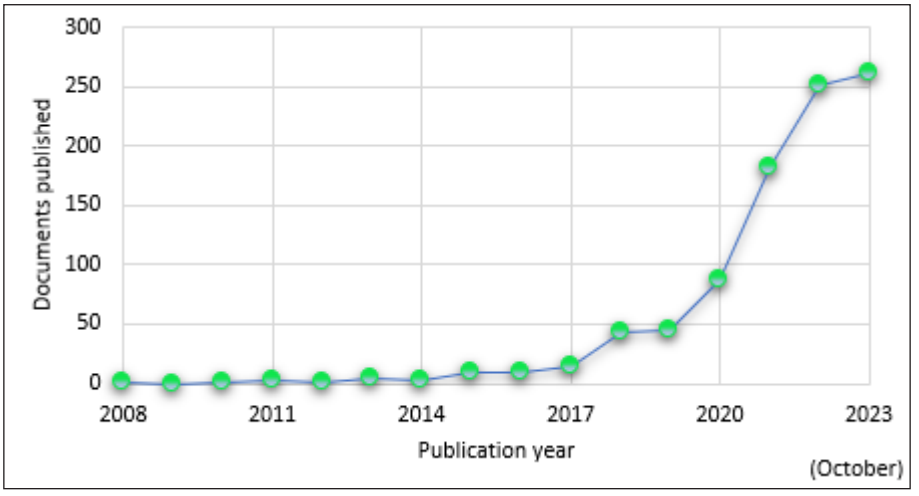

Figure 3. Annual publication trend on geopolymer modified with nanomaterials corpus from 2008 until 2023

According to the study conducted by Chen et al. (2022), the annual volume of publications can indicate the development path within a certain topic. According to the Scopus journal database, there have been a few research investigations on nanomaterial-based geopolymers between 2008 and 2017. Nevertheless, starting in 2018, there was a noticeable rise in published works, with a growth rate of over 50% compared to 2017. Since then, there has been an annual increase in the total and cumulative amount of documents on nanomaterial-based geopolymers, which peaked in 2023. The quantity of scholarly articles within the specific study domain is increasing yearly, with a total publication of 262 (October 2023).

Science Mapping Top Publication Sources

The use of source mapping techniques facilitates the analysis of innovation and development. These sources offer access to data that has some clearly stated limitations. The analysis was conducted using the VOS viewer software, which utilized bibliometric data from Scopus. The analysis type selected for this study was "bibliographic coupling" with the analysis unit "sources". The thresholds were fixed at a minimum number of five documents and a minimum citation source of 21. After the analysis, 203 publications met the conditions. Using 203 publications, the most related journals are identified by considering their total link strength, published related papers, and citation count. The result of the 10 most related journals is demonstrated in Table 2. *Construction and Building Materials*, *Materials,* and *Journal of Cleaner Production* are the three highest publication sources with 59, 25, and 20 research papers, respectively.

The aforementioned academic journals, *Construction and Building Materials*, *Journal of Cleaner Production*, and *Materials*, have received citation counts of 1918, 671, and 490,

Table 2
Top publication sources in the related research area

No.	Source	Number of publications	Citations	Link Strength
1	Construction and Building Materials	59	1918	496
2	Materials	25	490	138
3	Journal of Cleaner Production	20	671	105
4	Journal of Materials in Civil Engineering	14	93	64
5	Materials today: Proceedings	14	39	30
6	Case Studies in Construction Materials	12	142	301
7	Journal of Building Engineering	11	274	216
8	Polymers	11	97	12
9	Nanomaterials	10	198	140
10	Cement and Concrete Composites	10	294	102

respectively. This examination would establish a basis for future scientometric inquiries in geopolymer-modified nanomaterials research. Furthermore, previous conventional evaluations were incapable of producing visualizations of science maps. Figure 4(A) displays a network visualization of the journals that have been published.

The impact of the journal on the number of documents in the present research topic is reflected in the size of the node; a larger node indicates a greater impact. For instance, *Construction and Building Materials* have a bigger node size than the other categories, meaning they are a highly important source in the study. The artwork consists of five distinct clusters, each depicted using a unique color, namely red, green, blue, yellow, and purple. Groups are established according to the scope of the study sources or the frequency with which the sources are co-cited within similar works (Wuni et al., 2020). The number of connections among the research sources indicates the quantity of publications within the present study domain that feature co-citations.

Furthermore, the measure of connection strength provides insight into the frequency with which two journals are referenced in the same scholarly publication. For example, Construction and building materials had the most references compared to other studies (total link strength: 496). The relationships among the nodes in a cluster that are situated close together are more powerful compared to those that are farther apart. For instance, *Construction and Building Materials* are directly linked to case research studies on building materials compared to others. Different colors in Figure 4(B) represent different densities found in a journal. The largest concentration is red, followed by yellow, green, and blue.

The red hue of *Construction and Building Materials* represents the greater significance of the current study. Some journals related to the topic, such as the *International Journal of Geopolymer & Green Chemistry, Journal of Nano Research and Applications*, and *International Journal of Nanotechnology and Application*s, are worth mentioning. However, these journals are not in the Scopus database, so they are not captured in this research.

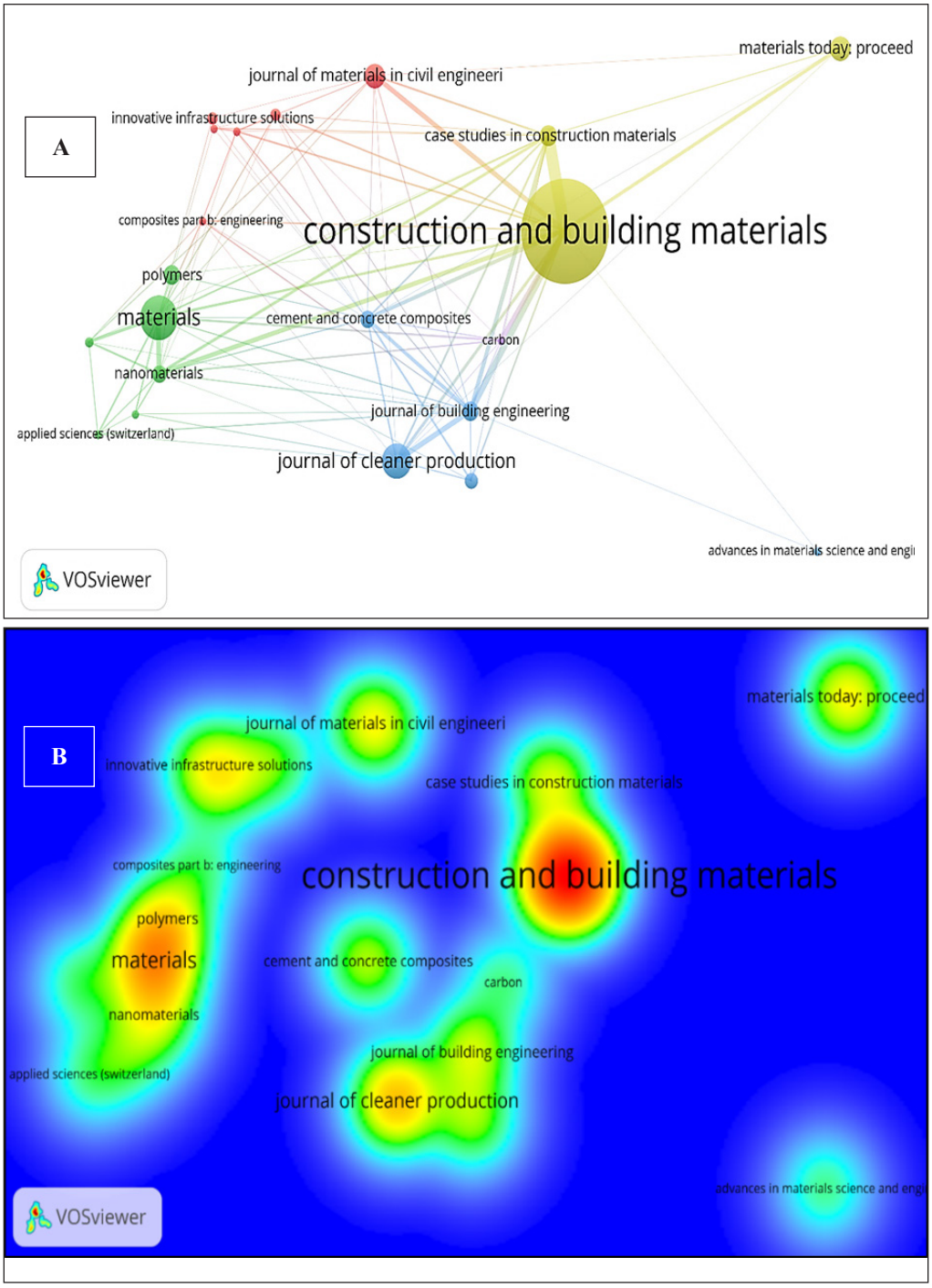

Figure 4. Science mapping of publication sources: (A) Network visualization; and (B) Density visualization

Science Mapping of Co-occurrence Keywords

Keywords have an essential function in academic study as they help to differentiate and demonstrate the fundamental topic of the studied area (Su & Lee, 2010). In the assessment, the data analysis type chosen was "co-occurrence," and the unit of analysis was specified as "all keywords." The minimum threshold for keyword repetition was maintained at 10, preserving 125 out of the total 5216 keywords. Table 3 displays the predominant keywords observed in geopolymer research modified with nanomaterials. Nanomaterials, geopolymers, and inorganic polymers are the top three most occurring keywords, with 59, 41, and 41 occurrences, respectively.

Table 3
The most frequent keywords in the research area

No.	Keywords	Occurrences	Total link strength
1	Nanomaterial	59	355
2	Geopolymers	41	365
3	Inorganic polymers	41	365
4	Nanoparticles	41	198
5	Geopolymer	36	299
6	Nanocomposites	35	186
7	Sustainable development	27	186
8	Nano silica	26	243
9	Nanomaterials	26	163
10	Titanium dioxide	25	156

Figure 5 (A) illustrates the visual representation of the main keywords within the research areas. The network visualization identifies four clusters: red, green, blue, and yellow. Moreover, the scientific visualization presented in the study reveals that the aforementioned keywords display larger nodes when compared to the other keywords. This observation indicates the importance of these keywords in the research area. In Figure 5(B), the varying colors indicate the dense concentration of keywords. The colors red, yellow, green, and blue are organized in ascending order based on their respective densities, with red having the highest density and blue having the lowest density.

The red zones, which include nanomaterial, geopolymer, "inorganic polymer, and nanoparticles, indicate areas of increased research activity, reflecting a substantial emphasis on nanomaterial and geopolymer collectively. Simultaneously, yellow zones that include terms like graphene oxides, composite materials, and sustainability represent emerging topics with moderate research activity that necessitate further exploration, particularly concerning their combined effects on mechanical and microstructural performance. The outer green and blue zones, which include composite material, nanotechnology, and polymer, represent underrepresented but important areas in

composite material and nanotechnology, highlighting opportunities to merge geopolymer research with polymer goals.

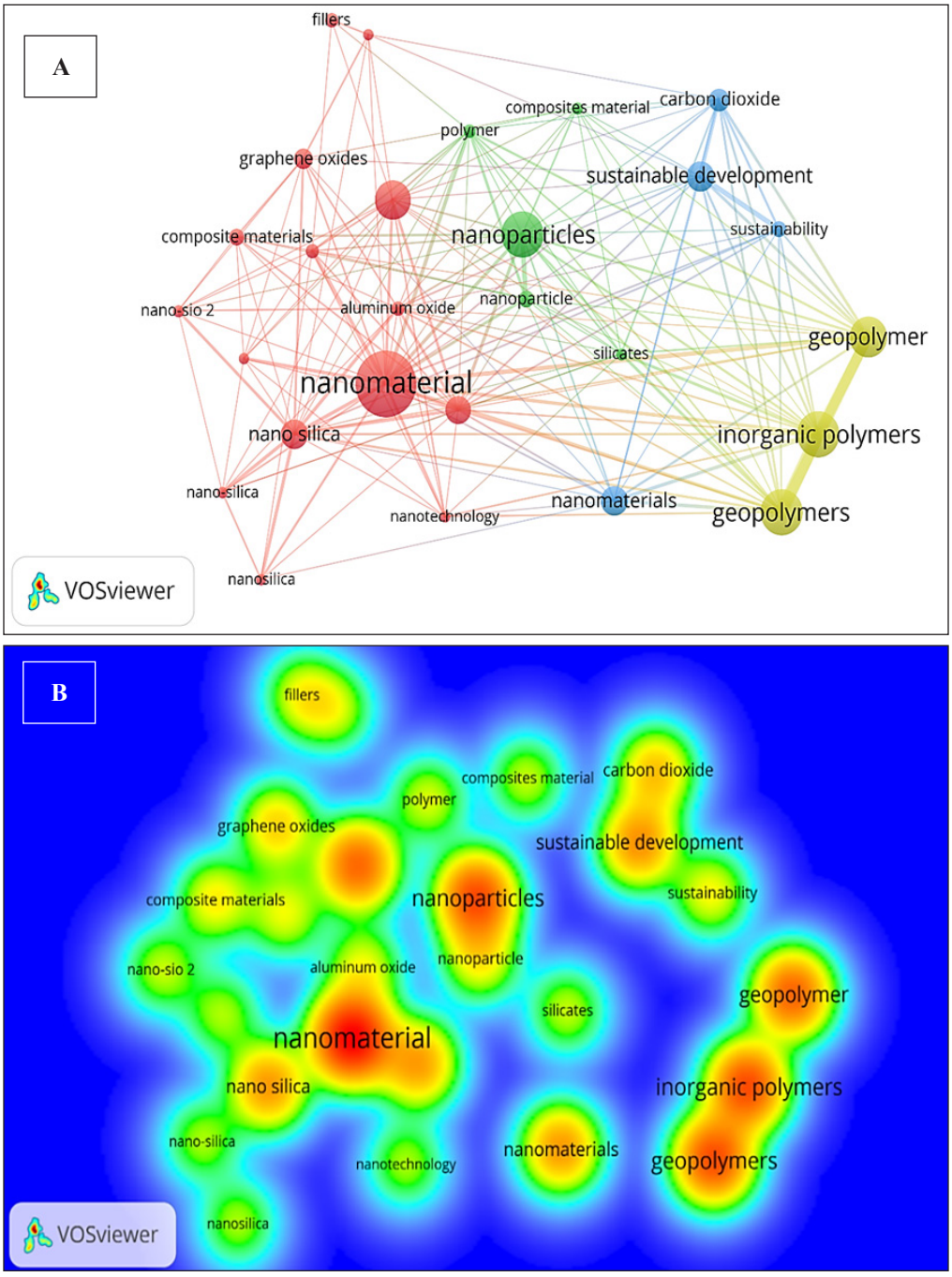

Figure 5. Science mapping of frequent keywords: (A) Network visualization; and (B) Density visualization

High-density topics such as nanomaterials, nanoparticles, and geopolymers suggest the need for deeper exploration into optimizing their properties and scalability for industrial applications. Medium-density areas, including sustainable development, carbon dioxide, and graphene oxides, point toward opportunities for interdisciplinary research on integrating nanomaterials with sustainable practices to address environmental challenges like carbon emissions. Low-density topics, such as fillers, silicates, and composite materials, represent emerging fields that could benefit from novel approaches to improve the performance and adaptability of geopolymers. Future research should focus on bridging these gaps, enhancing the synergy between sustainability and material science, and expanding the practical applications of nanomaterials in geopolymers for infrastructure, energy, and environmental solutions.

Science Mapping of Top-cited Articles

The total number of citations obtained by a document reflects its significance in the field of research. The evaluation of papers involved selecting "bibliographic coupling" as a method of analysis and "documents" as the investigation unit. Table 4 presents a compilation of the 10 most highly cited publications in the field of geopolymer modified with nanomaterials, encompassing the authors' names and relevant citation details. Liu et al. (2020) received 159 citations for their article “Review on the research progress of cement-based and geopolymer materials modified by graphene and graphene oxide" (Mohajerani et al., 2019), and Korayem et al. (2017) received 134 and 123 citations, respectively, selecting them among the top three most cited works.

Liu et al. (2020) addressed a substantial knowledge deficiency by integrating cementitious and geopolymer systems developments. The article’s broad scope, relevance, and ability to connect emerging nanotechnology with sustainable materials research made it particularly impactful at a time of growing interest in advanced material science. This is measured by the high citation index of 159. Other papers are less impactful because the discussion is on the specified research output, lacks a comprehensive synthesis, and is not in an interdisciplinary area, with a smaller scope. Hence, the citation index is lower.

Liu et al. (2020) provide an innovative overview of graphene-based nanomaterials, including graphene and graphene oxide, for improving cement-based and geopolymer materials, emphasizing notable progress in mechanical strength, durability, thermal stability, and microstructure. Their research addressed a substantial knowledge deficiency by integrating developments in cementitious and geopolymer systems, emphasizing graphene-based materials' revolutionary capabilities for sustainable, high-performance construction applications. The article’s broad scope, relevance, and ability to connect emerging nanotechnology with sustainable materials research made it particularly impactful at a time of growing interest in advanced material science.

Table 4
The most cited articles in the research area

No.	Article	Title	Citations
1	Liu et al., 2020	Review of the research progress of cement-based and geopolymer materials modified by graphene and graphene oxide	159
2	Mohajerani et al., 2019	Nanoparticles in construction materials and other applications, and implications of nanoparticle use	134
3	Korayem et al., 2017	A review of dispersion of nanoparticles in cementitious matrices: A Nanoparticle geometry perspective	123
4	Khater & Abd El Gawaad, 2016	Characterization of alkali-activated geopolymer mortar doped with MWCNT	122
5	Vishwakarma & Ramachandran, 2018	Green Concrete mix using solid waste and nanoparticles as alternatives. A review	112
6	Shah et al., 2015	Nano-modification of cementitious material: Toward a stronger and durable concrete	109
7	Faried et al., 2021	Mechanical and durability properties of ultra-high-performance concrete incorporated with various nano-waste materials under different curing conditions	108
8	Ebrahimi et al., 2018	A review of the impact of micro- and nanoparticles on freeze-thaw durability of hardened concrete: Mechanism perspective	98
9	Hajimohammadi et al., 2011	Time-resolved and spatially resolved infrared spectroscopic observation of seeded nucleation controlling geopolymer gel formation	94
10	Ahmed et al., 2022	The role of nanomaterials in geopolymer concrete composites: A state-of-the-art review	74

In contrast, other highly cited works like Mohajerani et al. (2019) and Korayem et al. (2017), although valuable, concentrated on more specialized subjects, such as the environmental implications of waste materials or particular impacts of nanomaterials on cementitious systems, lacking the comprehensive synthesis, interdisciplinary insights, or prospective analysis that Liu et al. provided. The context of the influence of this article is the transformative potential of nanomaterials in the construction and building industry, focusing on enhancing the performance of cement-based and geopolymer materials. The research by Liu et al. (2020) and Mohajerani et al. (2019) emphasizes the innovative application of materials like graphene and graphene oxide (GO) to address critical challenges in structural engineering, such as improving mechanical properties like (tensile and compressive strength), durability, and resistance to environmental stresses like freeze-thaw cycles and cracking. The important gap that the research found includes unresolved challenges such as variability in optimal content and gaps in the microstructural understanding of these materials.

Figure 6(A) demonstrates the map of related works according to citations and the relative importance of these articles in the current subject of study. The investigation showed that 359 papers were connected through citations. In addition, the density mapping depicted in Figure 6(B) illustrates a heightened concentration of articles among the top-ranked ones.

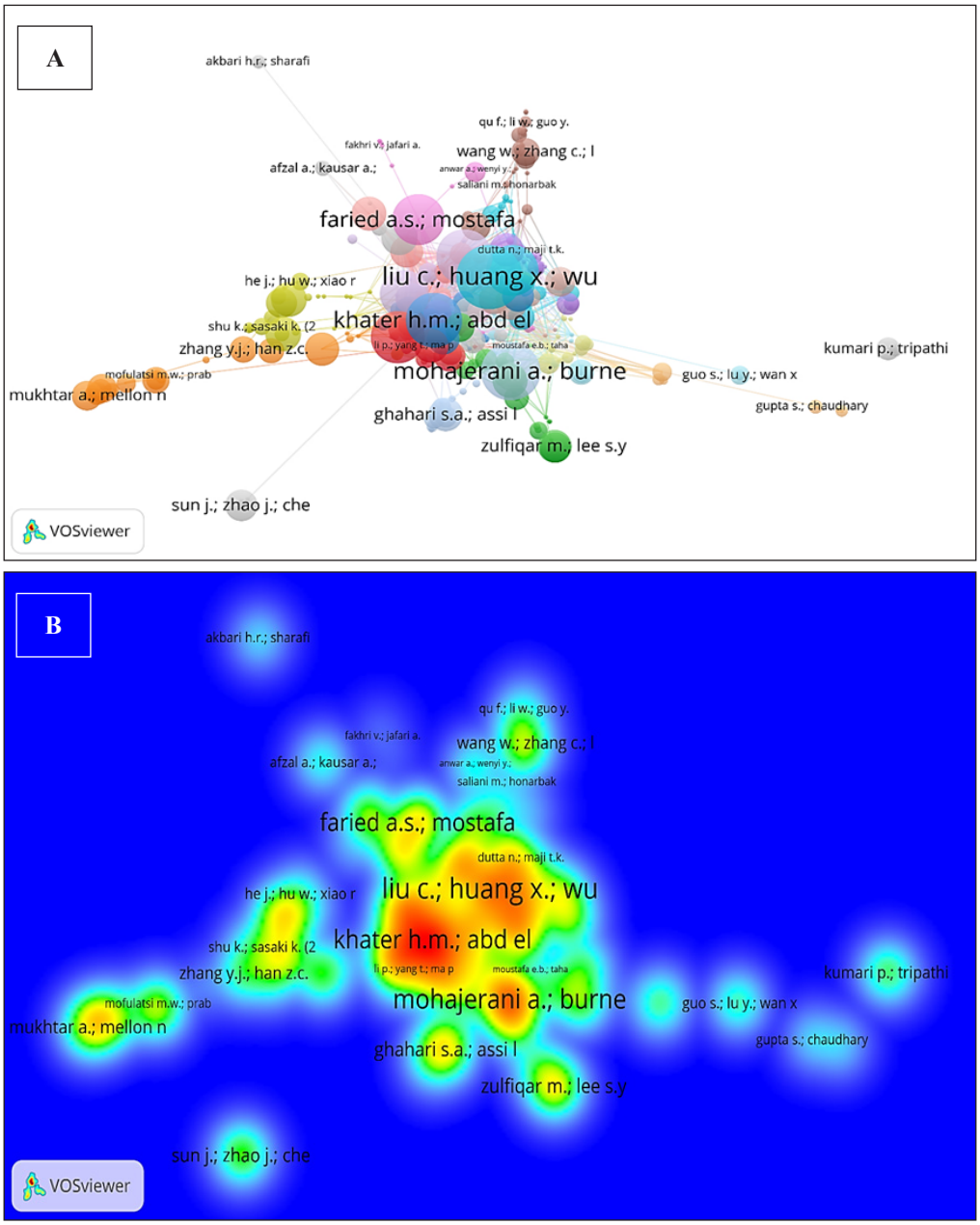

Figure 6. Science mapping of cited articles: (A) Network visualization; (B) Density visualization

Science Mapping of Country Contributions

Certain states have exhibited higher involvement and ongoing contributions in geopolymers modified with nanomaterials than others. The network was visualized to provide readers with a visual representation of the regions dedicated to the research domain. “Bibliographic coupling” was adopted as the “method of analysis”, and “countries” as the “unit of analysis". The minimum number of documents restricted for a country was 5, and 32 of the 75 nations met the criteria.

The countries enumerated in Table 5 have produced at least ten publications on the present study subject. China, India, and the United States provided the most documents, with 164, 89, and 59, respectively. Moreover, the countries that received the most citations were China, the United States, and Australia, which received 4024, 2942, and 1319, respectively. The number of publications, references, and total link strength indicate the degree of influence each nation has had on the evolution of the subject area. Figure 7(A) depicts the science mapping visualization of nations joined through citations. The node size relates to the nation's contribution to the area of research. Four clusters of countries were found on the visualization network, each with its color. As shown in Figure 7(B), the countries with the highest level of participation possessed a larger density. The geographical trends highlight the significant influence of major hubs such as China, India, and the United States in promoting geopolymer research involving nanomaterials, facilitated by robust global and regional collaborations.

The four colors denote clusters of countries participating in regular collaboration within the study topic, with each hue indicating a unique group based on co-occurrence or similarity. The blue cluster, led by China, shows significant regional cooperation with nations including Saudi Arabia, Iraq, and Egypt. This indicates common interests in geopolymer concrete enhanced with nanomaterials in rapidly developing regions. China is a critical

Table 5
The top ten documents in the research area

No.	Country	Documents	Citations	Total link strength
1	China	164	4024	18336
2	India	89	683	5343
3	United States	59	2942	8511
4	Saudi Arabia	51	1097	17247
5	Malaysia	43	872	7242
6	Iran	38	1072	4860
7	Australia	35	1319	6967
8	Egypt	32	424	6645
9	Iraq	24	681	10365
10	Pakistan	23	280	5652

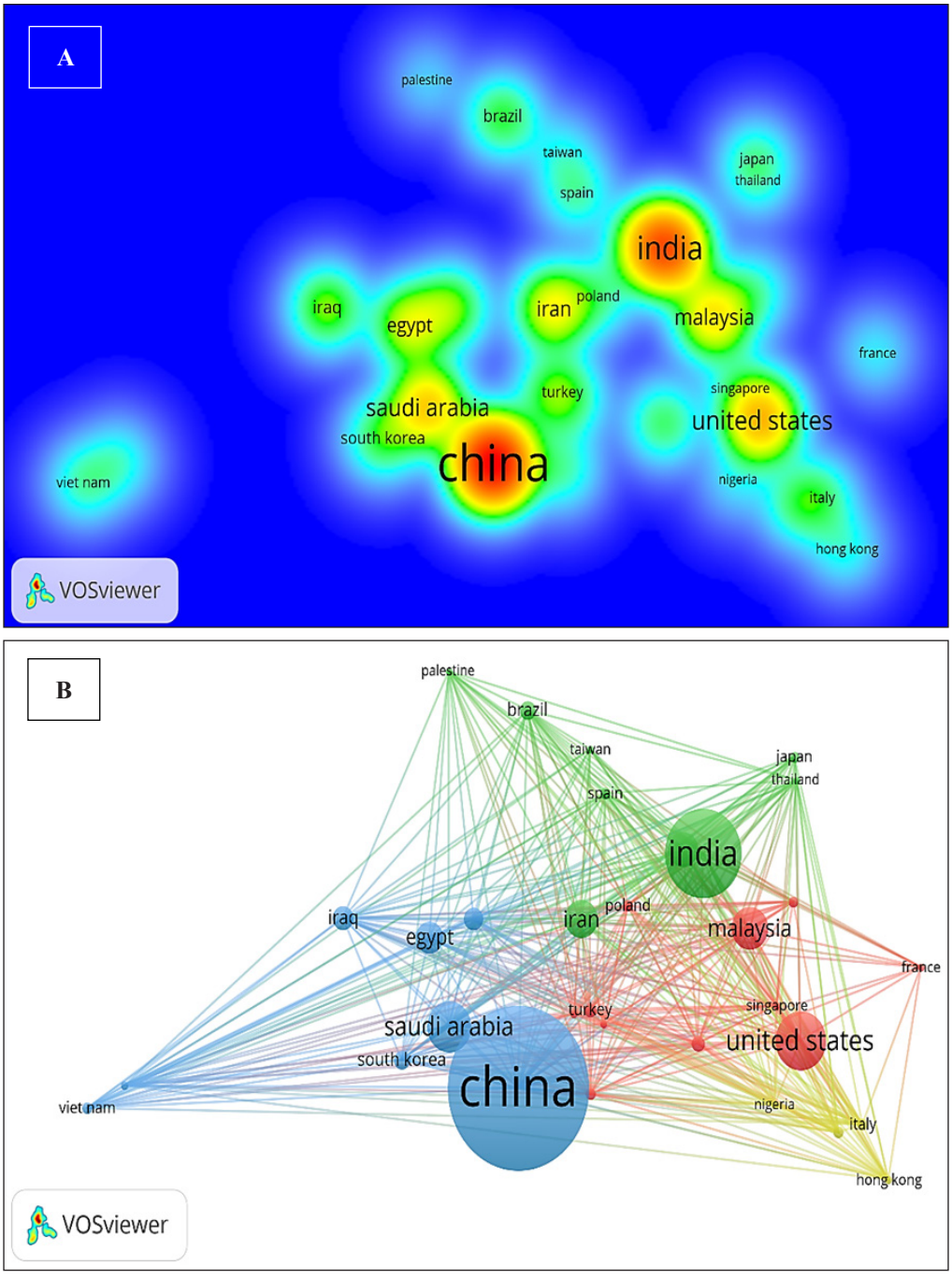

Figure 7. Science mapping of countries' contributions: (A) Network visualization; (B) Density visualization

hub, linking this group with multiple clusters via significant international collaborations. The green cluster, led by India, displays collaboration among developing countries such as Brazil and Iran, while also connecting with bigger hubs that incorporate international innovations. In contrast, based in the United States, the red cluster demonstrates advanced collaborations with countries such as Malaysia and Singapore, highlighting the importance of innovative nanomaterial uses and commercialization.

This cluster acts as a crucial link to the green and yellow clusters, facilitating information and technology transfer. The yellow cluster, which includes countries like Italy and Hong Kong, reflects smaller-scale contributions. While these countries play a less prominent role, they maintain connections with larger clusters, facilitating the exchange of innovative techniques and specialized knowledge. The connections between clusters, depicted by lines in the graphic, indicate the level of collaboration; larger lines imply stronger partnerships. The linkage among clusters illustrates a balanced global network, wherein regional centers such as China and India are crucial in linking developing academic fields with advanced technological centers like the United States, thus creating a collaborative environment for advancing geopolymer concrete incorporating nanomaterials.

The trends highlight the necessity of inclusive policies, investments in developing regions, and knowledge-sharing to enhance global advancements in geopolymer-nanomaterial innovations. The visual representation and data documentation of all the countries involved will facilitate young scientists in establishing scientific relationships, initiating collaborative initiatives, and sharing innovative methodologies and ideas. Academic researchers hailing from different countries with a vested interest in advancing the study of geopolymer modified with nanomaterials have the opportunity to engage in fruitful collaborations with established experts in this domain, thereby gaining valuable insights and benefiting from their extensive knowledge and experience.

DISCUSSIONS

The scientometric review conducted a comprehensive statistical evaluation and mapping of the available bibliographic data about research on geopolymers modified with nanomaterials. Prior literature reviews have demonstrated limitations in their ability to comprehensively and accurately establish connections between various research domains. Hence, the VOS viewer presents the connections within various domains.

The output of the present study has discovered the top sources of publications, such as the *Construction and Building Materials Journal*, which has produced 59 documents. The frequently utilized keywords are nanomaterial, geopolymers and inorganic polymers. Furthermore, this analysis also includes the top-cited article, Liu et al. (2020), which received 159 citations. The most important countries in this work are China, India, and the United States. The statistics and visualizations of the contributing countries will help

young researchers form scientific partnerships, start collaborative businesses, and share novel concepts and methods to achieve knowledge.

1. A comprehensive assessment of scholarly journals, encompassing studies on incorporating nanoparticles in geopolymers, has indicated that *Construction and Building Materials, Materials, and Journal of Cleaner Production* are the leading publication journals, including 59, 25, and 20 publications, respectively. *Construction and Building Materials, Journal of Cleaner Production,* and *Materials* have been identified as the top three in total citations, with citation counts of 1918, 671, and 490, respectively.
2. The analysis of keywords within the study field indicates that the most frequently used keywords are nanomaterials, geopolymers, and inorganic polymers, with 59, 41, and 41 occurrences, respectively. The keyword evaluation discovered that nanomaterials have mostly been studied for developing environmentally friendly building materials and enhancing the properties of geopolymer compounds.
3. The top-cited article is Liu et al. (2020), which received 159 citations. Mohajerani et al. (2019) and Korayem et al. (2017) received 134 and 123 citations, respectively, making them among the top three most cited works.
4. The investigation of the countries' contributions found that China, India, and the United States displayed the most papers, with 164, 89, and 59 papers, respectively. Moreover, the countries that received the most citations were China, the United States, and Australia, which received 4024, 2942, and 1319, respectively.

LIMITATION

This work provides a scientometric evaluation of nanomaterials in geopolymer, utilizing visualization of similarity software in the VOS viewer for analysis. A bibliometric network is constructed and illustrated to examine the annual distribution and growth trends, sources, keywords, leading articles, and prominent countries related to geopolymer modified with nanomaterials, based on the search terms "geopolymer" and "nanomaterial" in the Scopus database. The network yielded 529 documents from 2008 to October 2023.

The quality of VOS viewer outcomes is significantly influenced by the dataset employed. Incomplete or biased data, such as that derived from a singular database like Scopus, can result in misleading outcomes.

VOS viewer cannot evaluate the quality of research papers, as it depends only on bibliometric data like citation counts, which do not reflect the significance of a study. While self-citation may affect individual citation measurements, its overall effect on VOS viewer analyses is relatively minimal. Studies have shown that the median self-citation rate is usually below 15% across areas, resulting in just a tiny percentage of total citations (Frontiers in Research Metrics and Analytics, 2023; IJHS, 2023).

The VOS viewer does not analyze the research content, focusing only on bibliometric relationships such as citations, Authors, keywords and countries. This may limit detailed insights; hence, a traditional review should be made. Despite these limitations, the VOS viewer remains a powerful tool for visualizing bibliometric networks, relationships, and collaborations, provided its outputs are interpreted alongside other complementary analyses.

The findings based on reading showed that the utilization of nanomaterials in geopolymer composites shows considerable promise due to their ability to substantially enhance the mechanical properties of the materials with only a small quantity of nanoparticles. Further investigation is necessary to ascertain the exact number of nanocomposites in the geopolymer composite mixture. Additional research is required to investigate the impact of nanomaterials on both human health and the environment (Tortella et al., 2020).

Furthermore, conducting a comprehensive investigation into the mathematical modelling or artificial intelligence of nanomaterial-based geopolymer behavior is still possible. Because of the high cost of nanomaterials (Grieger et al., 2012) and the alkaline activator of geopolymers, there are further obstacles to their widespread use in the building industry (Mendes et al., 2021). Moreover, incorporating sufficient nanomaterials into geopolymers has enhanced their performance, decreased porosity, and enhanced mechanical qualities. Therefore, proper selection of the nanoparticle dosage is very important to attain optimal mechanical properties in the geopolymer composite (Dylla & Hassan, 2012). For example, when a greater quantity or proportion of nanoparticles is incorporated into the concrete mixture, a reduction in mechanical strength can be noticed due to the conglomeration of the nanoparticles with other components.

CONCLUSION AND FUTURE PERSPECTIVES

The current research paper conducts a scientometric review of the existing literature on geopolymers modified with nanomaterials to evaluate the annual distribution and growth pattern, prominent sources, frequent keywords, top articles, and leading countries on geopolymers modified with nanomaterials where the previous literature reviews have shown shortcomings in their ability to extensively and completely establish connections among different research domains. A search was conducted in the Scopus database using the VOS viewer, resulting in the finding of 529 publications that were relevant to the research topic.

The searched keywords, geopolymer and nanomaterial, resulted in 914 documents from 2008 to 2023, while the *Construction and Building Materials* journal was the highest publication source with 59 research papers and 1918 citations. Nanomaterials, geopolymers, and inorganic polymers are the top three most occurring keywords, with 59, 41, and 41 occurrences, respectively. Liu et al. (2020) received 159 citations for their article "Review on the research progress of cement-based and geopolymer materials modified by graphene

and graphene oxide China, India, and the United States provided the biggest number of documents, with 164, 89, and 59 documents, respectively.

Based on this VOS review, the reader could visualize the overall picture of the bibliographic data on geopolymers modified with nanomaterials. The scientometric analysis will aid researchers to identify important keywords, the highest-cited paper and key researchers in this area. Countries that contribute to the research are also identified. Based on these outputs, the future direction of research collaboration shall explore other continents, such as Africa, to enhance cooperative research, exchange ideas and expertise, and create joint ventures in research. The study reveals underrepresented areas, notably in Africa and smaller states, that require targeted research funding and collaboration to increase participation. Additionally, unexamined subfields encompass the environmental sustainability of nanomaterial-based geopolymers and their extensive industrial uses.

Future research based on the output of conventional research and application will find that the elevated expense of nanomaterials and alkaline activators presents a considerable obstacle to their extensive application in the construction sector. Practical obstacles, like the expansion of production and the assurance of cost-effectiveness, remain unaddressed. Connecting laboratory research with practical applications is crucial to address these problems and facilitate real-world implementation. By addressing these constraints, bridging data deficiencies, and surmounting practical obstacles, the next research can realize the complete potential of nanomaterial-modified geopolymers for sustainable and economical construction solutions.

ACKNOWLEDGEMENT

The authors express gratitude for the financial support for this research by the Ministry of Education, Malaysia, under the Fundamental Research Grant Scheme (FRGS/1/2020/TKO/UPM/02/32) with Vote no: 5540372 for research work entitled 'An investigation of characterization and parametric effect of kenaf bast fiber in the properties of geopolymer kenaf reinforced concrete.'

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