Review Article

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Foamed geopolymers as low carbon materials for fire-resistant and lightweight applications in construction: A review

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Abstract: This study analyzed the research developments on foamed geopolymers (FGPs) in construction applications, aiming to evaluate advancements, challenges, and prospective future directions. Data for the review were collected using the Scopus database. The evaluation identified key publishing sources, keyword trends, leading authors in terms of citations and publications, most-cited papers, and regions actively involved in FGP research. Additionally, the study discussed the demand for FGP, the main challenges to its implementation, and potential solutions. A notable increase in publications on FGP was observed, indicating growing interest among researchers. Keyword trends emphasized the growing interest in FGPs for thermal insulation and fire-resistant applications, underscoring their potential to address critical sustainability challenges in the construction industry. An analysis of prominent authors and their extensively cited works showed the principal contributors driving innovation within this domain. The review highlighted current research gaps concerning the long-term performance and durability of FGPs when subjected to extreme environmental conditions. Furthermore, the necessity for advanced processing techniques to enhance material characteristics and cost-effectiveness for practical applications was discussed. This study might be valuable for both researchers and industry, providing recommendations to address existing gaps and promote the advancement and implementation of FGPs in sustainable construction.

Keywords: foamed geopolymer, construction material, fire resistance

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1 Introduction

As public consciousness regarding sustainability grows in relation to climate change and global warming, there has been a heightened focus on the recycling of solid refuse as a means to mitigate carbon dioxide emissions [1]. In the realm of low-carbon building material research, alkali activation technology has become a topic of intense interest due to its potential for the treatment and utilization of solid refuse. The term “geopolymer” was presented by Davidovits in 1978 [2]. Alkali activation technology is commonly employed to produce geopolymers from solid residues. From an academic standpoint, geopolymers are inorganic polymers that are created by the polycondensation of dissolved aluminosilicate in an extremely alkaline solution. These polymers possess a Si–O–Al network structure in three dimensions [3]. In contrast to cementitious materials, alkali-activated geopolymers are considered promising new low-carbon construction materials due to their favorable characteristics, such as rapid hardening, exceptional mechanical properties, long durability, resistance to high temperatures, and ability to effectively seal heavy metal ions [4–6].

An increasing number of individuals are considering the high-value-added consumption of foamed geopolymers (FGPs) on account of their exceptionally porous structures. Gas is typically introduced into a geopolymer mortar or slurry to produce spongy materials, which are also referred to as porous or cellular geopolymers [7,8]. FGPs are lightweight and possess exceptional acoustic and thermal insulation properties due to their porous structure [9–11]. Therefore, FGPs are extensively researched in various domains, including but not limited to high-strength, thermal insulation, lightweight [12], fire resistance [13], catalyst supports [14], and absorbents [15]. However, two fatal flaws continue to significantly impede the widespread implementation of FGPs. One aspect to consider is the lack of clarity surrounding the mechanism governing foam structures, which frequently leads to significant challenges in attaining the desired porosity configurations. Conversely, the majority of geopolymers have an inordinate amount of alkali in their matrix, which readily depletes with water and contributes to environmental contamination.

In light of recent developments in sustainable and lightweight materials, it is becoming increasingly vital for scientists to comprehend FGPs. However, a problem exists with regard to information voids that could hinder the establishment of new research avenues and the building of academic partnerships. Consequently, in order to simplify the acquisition of key data from sources that are extremely reliable, it is essential for researchers to establish a system that can facilitate this process. By utilizing scientometrics in the context of this matter, a workable solution may be achieved. The aim of the study is to provide a comprehensive scientometric analysis of FGP research trends, challenges, and future directions. This aim is achieved *via* investigating the records of FGP research, beginning with the period when the research was initially published in the literature until December 2023. Situated at the forefront of methodologies, scientometric analysis has the capacity to evaluate quantitative data from extensive bibliographic collections. Manual evaluation of research does not effectively and exhaustively establish connections between the various aspects of literature. Co-occurrence, scientific visualization, and co-citations are intricate components of advanced-level study [16,17]. The assessment using scientometrics highlights the regions that are vigorously engaged in a specific area of research, the most influential publications sources, the academicians with the greatest number of publications and citations, and the documents that receive the most references. In return for pertinent information, the Scopus database returned results from 361 results. This information comprised various types of information, including abstracts, citations, keywords, and bibliographic details. In addition, potential remedies to the limitations of FGP applications in the construction industry were examined and discussed in this study. Academics will be able to share new ideas and methods and enhance collaborative projects with the aid of this research, which utilizes quantitative and graphical recordings of researchers and locations.

2 Review strategy

By conducting analysis using scientometrics of the pertinent bibliographic records, this study revealed the diverse aspects of the literature. The mapping of scientific knowledge is a technique used in scientometric studies that was devised by experts to assess bibliographic records [18,19]. The information was acquired using the preferred reporting items for systematic reviews and meta-analyses (PRISMA) methodology. Given the probable abundance of scholarly articles pertaining to the subject matter being investigated, it is critical to employ a dependable databank. Scopus and Web of Science, two databases known for their high level of reliability, are suitable sources for retrieving data [20,21]. Bibliographic data on FGP investigations was compiled using Scopus's database. By using the Scopus index as the source of the data, documents were searched for and extracted. The comparison findings suggest that Scopus provides an extensive compilation of sources compared with the Web of Science [22,23]. Previous research has similarly suggested utilizing the Scopus database to perform comparable analysis due to its possession of more current information [17,24,25]. In December 2023, a Scopus search for "geopolymer foam" returned 420 results. Utilizing multiple keywords during a data search in Scopus is feasible; nevertheless, doing so may result in the retrieval of duplicate and irrelevant information, as confirmed during the search process. It has been determined from the literature that conducting this form of research with a single keyword search yields greater effectiveness [16,26,27]. A variety of filter options were implemented in order to exclude extraneous records. The comprehensive PRISMA method, encompassing data mining, analysis, and the myriad constraints and filters that are applied throughout the procedure, is illustrated in Figure 1. Previous research in a variety of other disciplines has employed a comparable approach [28,29]. In the end, 361 records underwent additional analysis utilizing suitable software. The VOSviewer software (version 1.6.20) was employed to generate a statistical evaluation and methodical depiction of the comma-separated values formatted bibliometric data. VOSviewer is a publicly accessible, open-source program [30–32]. Hence, VOSviewer assisted in the current study in achieving its goals. For additional analysis, the resulting records were imported into VOSviewer. For the scientometric evaluation, the highly cited articles, the active and contributing researchers and journals, and the region's

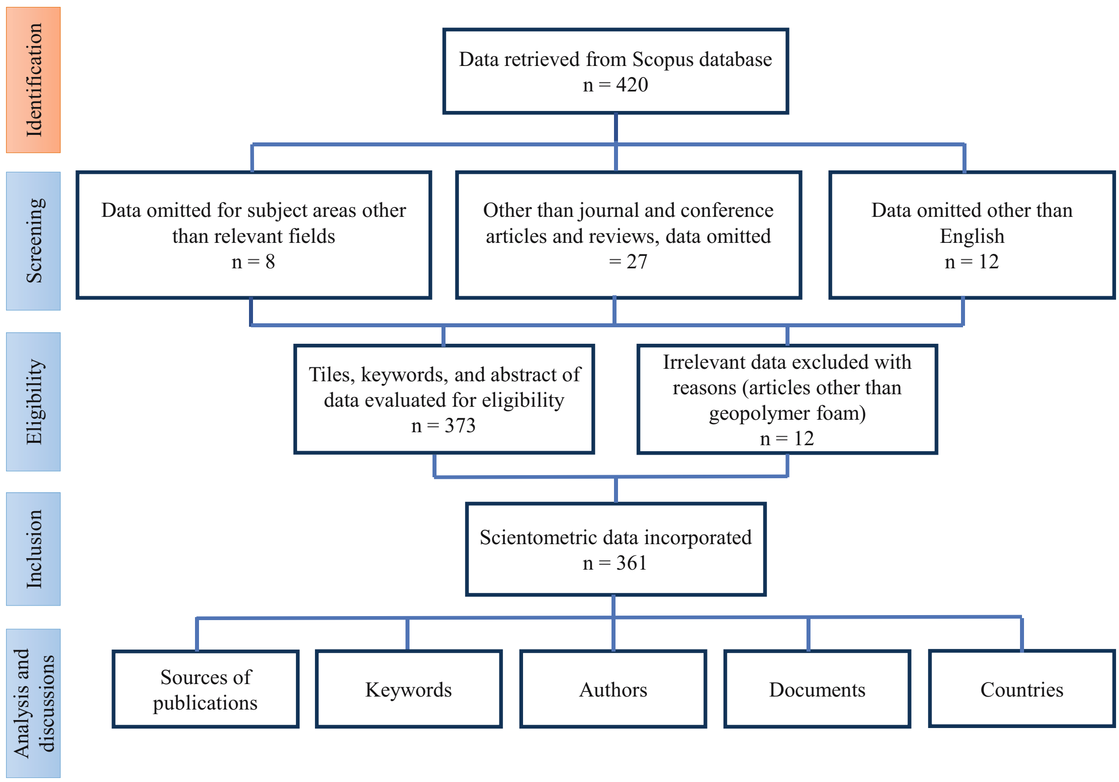


Figure 1: The sequence of data mining utilizing the PRISMA methodology.

participation were all assessed. The data were displayed in a tabular format, whereas graphical representations illustrated the features, their interactions, and their co-occurrence.

3 Results and discussion

3.1 Research development on FGPs

For research development evaluation, pertinent academic disciplines were identified through the Scopus analyzer. Figure 2 illustrates the disciplinary distribution of research on FGPs, with 36% of the studies originating from Materials Science, reflecting the field's focus on developing and characterizing innovative materials. Engineering (27%) follows, emphasizing structural applications, while Physics and Astronomy (10%) contribute theoretical frameworks. Chemical engineering accounts for 7%, highlighting its role in advancing geopolymerization processes and optimizing chemical formulations. Environmental Science (5%) and Chemistry (4%) underline the aspects of sustainability and chemical synthesis, respectively. The remaining 11% labeled as "other" highlights interdisciplinary contributions, showcasing the broad applicability of FGPs across scientific domains. Figure 3 categorizes the types of publications contributing to FGP research. It shows that 78% of the publications are journal articles, highlighting the dominance of peer-reviewed studies in advancing the field. Conference papers (14%) and reviews (5%) provide additional insights and summaries of current trends, while a smaller proportion of conference reviews

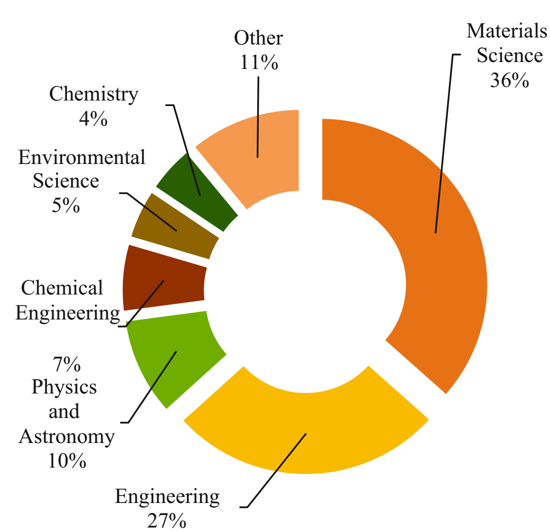


Figure 2: Subject areas that are relevant and featured articles on FGP studies.

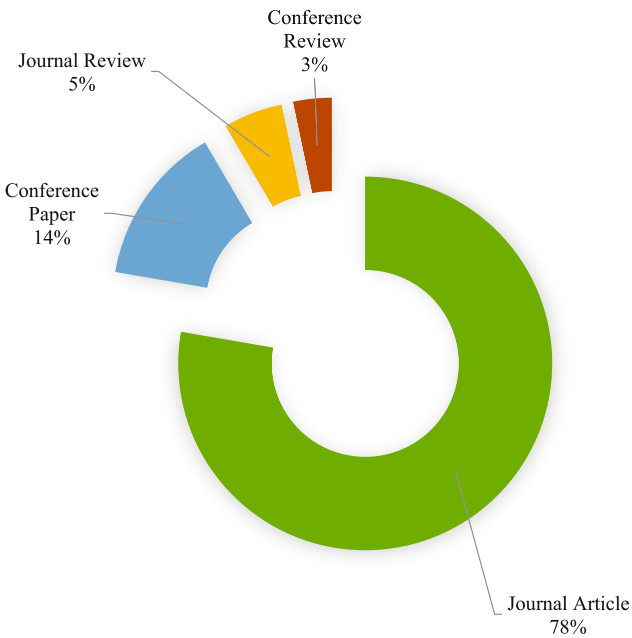


Figure 3: Document types pertaining to FGP studies.

(3%) reflect limited discussions on the topic in conference settings. This analysis underscores the advancement of the discipline, as evidenced by the number of published research and its dependence on academic journals to disseminate significant findings. The first document on FGP research was found in 2005. From 2005 to 2023, the yearly total of publications in the field of FGP research is depicted in Figure 4. Until 2011, there were very few publications on FGP study. However, the publication counts increased in 2012 but decreased in 2013. The number of publications was almost equal from 2014 to 2016. Then, the number of documents increased gradually from 2017 to 2020, increasing from 27 to 52. Again, there is a slight decrease in 2021 to a number of 44. Inconsistent progress was discovered in the investigation, and no period of consistent growth was observed during that time. Thereafter, annual publication rates increased from 2022 to 2023, with an annual number of publications equal to 58 and 64, respectively. The evaluation suggested that the development of FGP over the past 7 years has shifted the attention of researchers to FGP research.

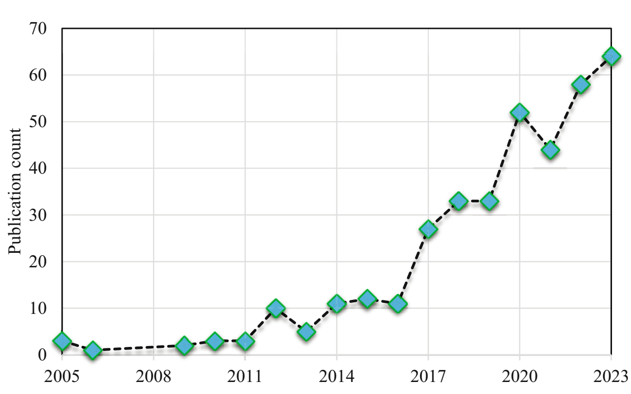


Figure 4: Publications on GPS research from 2005 to 2023.

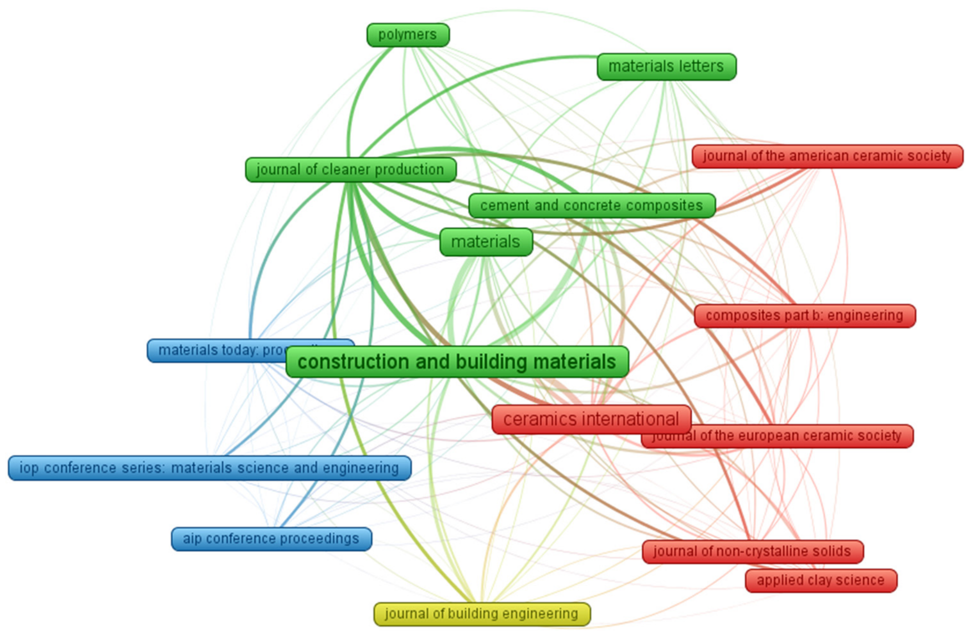
3.2 Science mapping of publication outlets

On the basis of bibliographical data, publishing sources (conferences/journals) were assessed using VOSviewer. A mere 16 out of 134 sources were found to have published a minimum of five articles pertaining to FGP research. The sources comprising a minimum of five articles on FGP studies as of 2023 are listed in Table 1, along with the citations record. The publishers that published the most articles overall were identified as *"Construction and building materials,"* with 46 articles, *"Ceramics International,"* with 27 articles, and *"Materials,"* with 22 articles. Additionally, as of 2023, "Construction and building materials" with 1,941 citations; *"Ceramics International,"* with 1,248 citations; and *"Cement and concrete composites,"* with 962 citations in terms of the number of citations obtained were the three most prominent journals. More specifically, the results obtained from this inquiry would establish the basis for subsequent scientometric assessments of FGP research. Standard review studies that were previously conducted were incapable of furnishing such information.

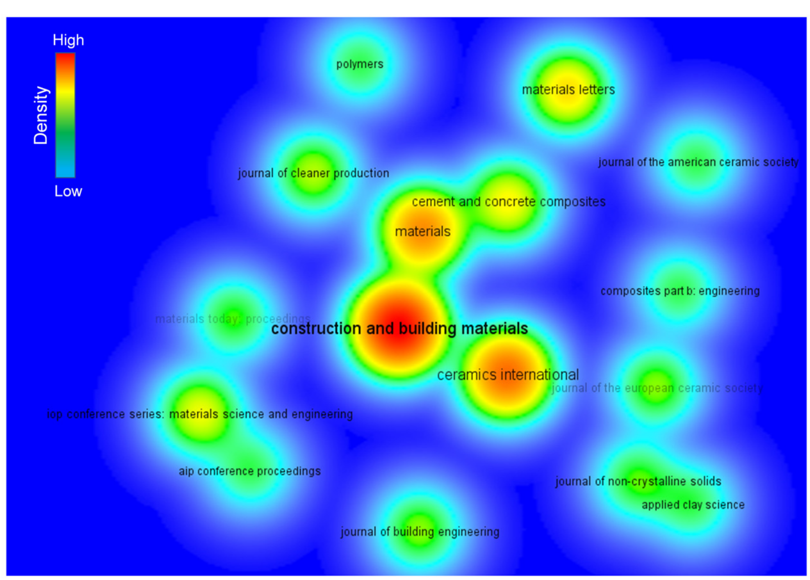
Table 1: List of top publication sources on FGP studies

S/N	Source name	Documents	Citations
1	Construction and Building Materials	46	1,941
2	Ceramics International	27	1,248
3	Materials	22	342
4	Materials Letters	13	264
5	Cement and Concrete Composites	11	960
6	IOP Conference Series: Materials Science and Engineering	10	46
7	Journal of Cleaner Production	8	259
8	Journal of The European Ceramic Society	7	612
9	Journal of Building Engineering	7	146
10	Journal of Non-Crystalline Solids	6	212
11	Materials Today: Proceedings	6	45
12	Applied Clay Science	5	456
13	Composites Part B: Engineering	5	247
14	Journal of The American Ceramic Society	5	102
15	Polymers	5	56
16	AIP Conference Proceedings	5	53

The mapping of publication sources containing a minimum of five FGP publications is illustrated in Figure 5. In Figure 5(a), the frame size indicates the relative significance of each source based on article quantity. For instance, "*Construction and Building Materials*" has a more substantial influence than other publications, rendering it a more significant source within the discipline. The map exhibits four discrete groupings, each of which is symbolized by a unique color: green, red, blue, and yellow. Groups are established based on the frequency of co-citations in articles or the scope of the research source [33]. In the case of VOSviewer, the sources were categorized according to their co-citation frequencies in articles. The green cluster, for instance, comprises six articles that have been co-cited on multiple occasions in publications of a similar nature. The strength of the links between adjacent frames is greater in a group than between frames that are far apart. Four clusters of journals



(a)



(b)

Figure 5: Publication sources that published a minimum of five documents: (a) network visualization and (b) density visualization.

were noted from the map. The green cluster, led by "*Construction and Building Materials*," includes journals emphasizing materials science and sustainability, such as "*Journal of Cleaner Production*," "*Cement and Concrete Composites*," and "*Materials*," highlighting the structural and environmental aspects of FGPs. The red cluster, centered around "*Ceramics International*," focuses on ceramics and composite materials, reflecting research on optimizing FGP properties like porosity and mechanical strength. The blue cluster represents conference proceedings (*e.g.*, "*IOP Conference Series: Materials Science and Engineering*"), which highlight ongoing discussions and emerging ideas. Finally, the yellow cluster features journals like the "*Journal of Building Engineering*," emphasizing practical engineering applications. This network illustrates the interdisciplinary nature of FGP research, spanning materials science, engineering, and sustainability domains.

As illustrated in Figure 5(b), different hues correspond to distinct densities of concentration at an outflow. As one progresses from red to yellow, green, and blue, the color intensity diminishes. The reddish-yellow hues observed in prestigious periodicals, including "*Construction and Building Materials*," "*Ceramics International*," and "*Materials*," indicate a greater commitment to FGP studies.

3.3 Science mapping of keywords

Keywords are essential elements of the research process as they function to differentiate and highlight the central topic of the study [34]. An analysis revealed that 92 out of 2,785 keywords contained at least 10 repetitions. Table 2 presents the 32 terms that are most frequently encountered in scholarly works. The five most regularly utilized keywords in FGP research articles are inorganic polymers, geopolymers, geopolymers, compressive strength, and thermal conductivity. According to the results of the keyword analysis, the majority of FGP research has been devoted to its application for thermal insulation and fire resistance material applications. Keywords such as "compressive strength" and "thermal conductivity" appear prominently, reflecting a significant emphasis on the mechanical and thermal performance of FGPs. This indicates that much of the research is directed toward evaluating and optimizing these critical properties to meet the demands of construction applications, particularly in thermal insulation and lightweight structural materials. Also, using FGP is a viable approach for reducing the carbon footprints of the construction industry.

Figure 6 presents a systematic map of keywords, illustrating their interrelationships, density, and connections.

Table 2: List of top 30 frequently occurring keywords in the study of FGP

S/N	Keyword	Occurrences
1	Inorganic polymers	273
2	Geopolymers	269
3	Geopolymer	224
4	Compressive strength	152
5	Thermal conductivity	105
6	Fly ash	101
7	Porosity	84
8	Foams	71
9	Geopolymer foam	49
10	Foam	45
11	Thermal insulation	45
12	Pore size	42
13	Silicates	40
14	Metakaolins	39
15	Scanning electron microscopy	37
16	Pore structure	36
17	Concretes	32
18	Geopolymer concrete	30
19	Slags	30
20	Fire resistance	28
21	Mechanical properties	28
22	Low thermal conductivity	27
23	Geopolymer composites	26
24	Sodium hydroxide	26
25	Microstructure	25
26	Fourier transform infrared Spectroscopy	24
27	Porous materials	24
28	Portland cement	24
29	Water absorption	24
30	Geopolymerization	22

The frequency of a keyword frame's appearance in articles is denoted by its magnitude in Figure 6(a), while the categories of content in which it appeared together are indicated by its position. In contrast to the remaining keywords, the most prominent ones exhibit more expansive frameworks on the map, indicating their significance in the FGP study. The figure highlights clusters to illustrate the frequency with which they occur in conjunction across multiple sources. The keywords are color-coded according to the frequency with which they co-occur in the articles. Five clusters of diverse colors are illustrated in Figure 6(a). Cluster 1 (red) contains 26 items, cluster 2 (green) contains 21 items, cluster 3 (blue) contains 19 items, cluster 4 (yellow) contains 15 items, and cluster 5 (purple) contain 11 items. Keywords like "thermal conductivity" and "fire resistance" (yellow cluster) highlight a focus on energy-efficient and fireproof construction materials. The red cluster emphasizes mechanical properties such as "compression strength" and "porous materials," crucial for lightweight and structural applications. The green cluster

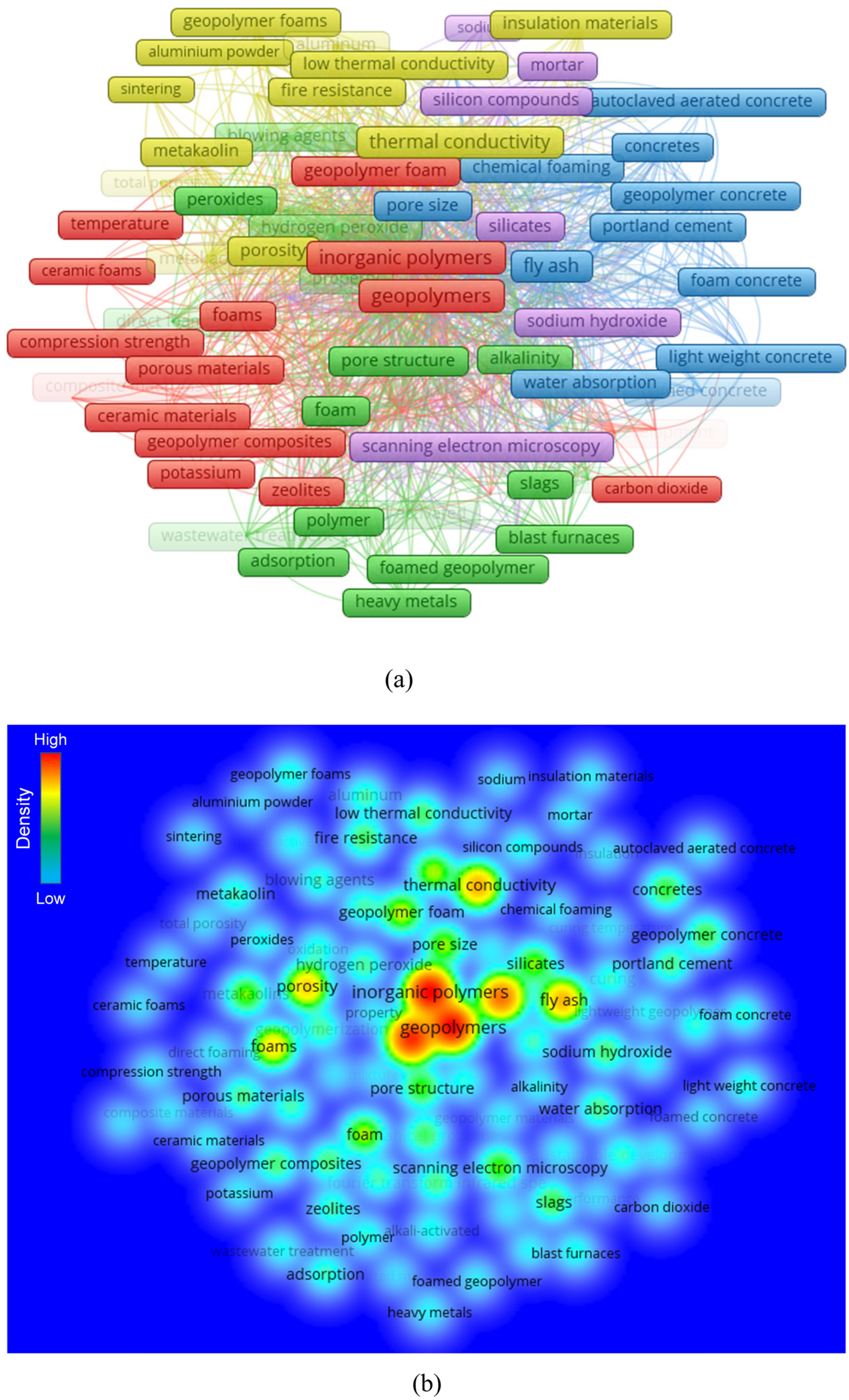


Figure 6: Visualization of keywords: (a) network and (b) density.

reflects environmental applications, with terms like "adsorption" and "heavy metals," showcasing FGPs' potential in remediation and carbon reduction. Meanwhile, the blue cluster compares FGPs with conventional materials like Portland cement, addressing sustainability advantages, and the purple cluster focuses on the fundamental chemical used for FGP production, such as "silicates," "sodium," and "silicon compounds." These clusters collectively underline the multidisciplinary nature of FGP research, addressing both performance optimization and environmental impact.

As illustrated in Figure 6(b), a spectrum of colors can be utilized to visually represent the density of keywords. The terms inorganic polymers, geopolymers, geopolymers, and other pertinent information are visually represented in red or yellow to indicate a higher frequency of usage. These results will support scholars in the process of choosing suitable keywords that will streamline the lookup for pertinent scholarly articles.

3.4 Science mapping of authors

The extent of one's scholarly impact can be gauged by the frequency with which their work is referenced [35]. Out of the 1,244 academicians who were examined, only 37 fulfilled the criterion of having a minimum of five publications. The authors of the most prolific FGP research are enumerated in Table 3. The average citations of individual authors were calculated using the ratio of the total citations and total articles. Assessing the productivity of a researcher becomes a complex task when every pertinent metric is taken into account, including the number of published papers, average citations, and cumulative citations. Total publications reflect the productivity of a researcher, while average citations per publication indicate the impact and quality of their work. Cumulative citations provide a broader measure of their overall influence in the field. Conversely, the scientist's performance shall be assessed impartially in accordance with all criteria. Based on statistical data, Colombo, Paolo emerges as the most prolific author, having authored 16 articles, while Bai, Chengying, and Rossignol, S. each contribute 12 papers. With a total of 1,139 citations, Zhang, Zuhua is the foremost authority in the field of FGP research, followed by Wang, Hao (1,072 citations) and Colombo, Paolo (1,045 citations). Conversely, with an average of 179 citations, Wang, Hao might rank first, Zhang, Zuhua might rank second with 163 citations, and Peyratout, C., Smith, A. might rank third with 86 citations. These prolific authors and their highly cited works have shaped key research directions in FGPs. For instance, their studies have driven advancements in thermal insulation properties, foaming techniques, and the use of sustainable precursors like fly ash and slag. By analyzing their contributions, readers can identify foundational studies and cutting-edge research trends.

Table 3: List of authors with a minimum of five publications in the research of FGP

S/N	Author	Documents	Citations	Average citations
1	Colombo, Paolo	16	1,045	65
2	Bai, Chengying	12	749	62
3	Rossignol, S.	12	685	57
4	Sanjayan, Jay	10	447	45
5	Louda, Petr	10	133	13
6	Pasupathy, Kirubajiny	9	337	37
7	Ramakrishnan, Sayanthan	9	337	37
8	Hajimohammadi, Ailar	8	645	81
9	Ngo, Tuan	8	645	81
10	Li, Hongqiang	8	479	60
11	Rossignol, Sylvie	8	229	29
12	?Ach, Micha?	8	176	22
13	Yan, Shu	8	130	16
14	Zhang, Zuhua	7	1,139	163
15	Joussein, E.	7	548	78
16	Michaud, P.	7	548	78
17	Prud'homme, E.	7	548	78
18	Wang, Hao	6	1,072	179
19	Hussin, Kamarudin	6	403	67
20	Medri, Valentina	6	241	40
21	Korniejenko, Kinga	6	145	24
22	Le, Van Su	6	83	14
23	Peyratout, C.	5	429	86
24	Smith, A.	5	429	86
25	Novais, Rui M.	5	259	52
26	Ferone, Claudio	5	203	41
27	Ricciotti, Laura	5	203	41
28	Roviello, Giuseppina	5	203	41
29	Liu, Ze	5	183	37
30	Abdullah, Mohd Mustafa Al Bakri	5	160	32
31	Chindaprasirt, Prinya	5	131	26
32	Qiao, Yingjie	5	131	26
33	Zhang, Fanyong	5	125	25
34	Li, Han	5	103	21
35	Peng, Xi	5	103	21
36	Liu, Yi	5	85	17
37	Xing, Pengfei	5	36	7

The correlation between the counts of published works and the prominence of authors is illustrated in Figure 7(a). The density map of connected authors is shown in Figure 7(b). The color gradient indicates author prominence and influence: red and yellow regions represent authors with high publication density and collaboration networks, such as Colombo, Paolo, Zhang, Zuhua, and Rossignol, Sylvie. In contrast, green and blue regions depict authors with lower activity or peripheral involvement. This visualization is significant for identifying leading contributors and collaboration hubs within the field and guiding new researchers in selecting potential mentors, collaborators, or influential studies to enhance their understanding and engagement with the FGP research community.

3.5 Science mapping of documents

An article's citation count is used in academics to determine its importance [24]. In their respective disciplines of study, the most frequently referenced works are frequently regarded as groundbreaking. Only 26 out of 361 articles, which were expected to have at least 100 citations, were kept. The top five articles in the FGP research are shown in Table 4, along with their citations. There were 584

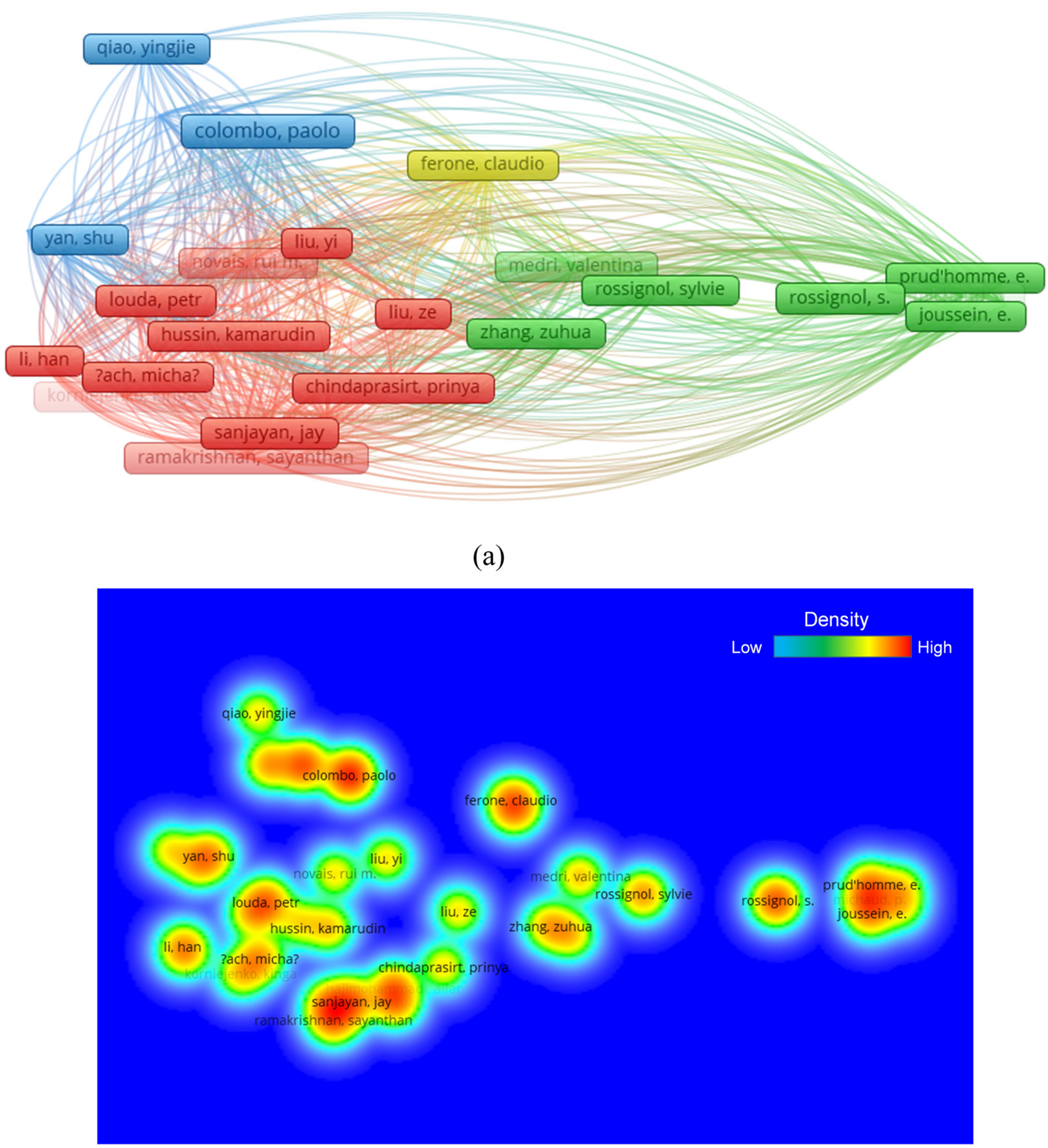


Figure 7: Science mapping of authors: (a) network visualization and (b) density visualization.

citations found in Zhang *et al.*'s [7] study, "Geopolymer foam concrete: An emerging material for sustainable construction." This study has become a cornerstone in FGP research due to its novel approach to developing lightweight, thermally insulating construction materials using industrial by-products such as fly ash and slag. By addressing key challenges in pore structure optimization and demonstrating significant environmental benefits, Zhang's work laid the foundation for integrating FGPs into sustainable construction practices. Additionally, Zhang *et al.* [36] and Liu *et al.* [37] ranked the best three for their articles with 397 and 320 citations, respectively. Only 6 articles had received more than 200 citations as of 2023, though. The evolution of citation trends in FGP research reflects the growing interest and advancements in the field over time. Early studies in the 2000s focused on the potential of geopolymers as sustainable alternatives to traditional cement, but it was not until Zhang *et al.*'s [7] landmark study in 2014.

The article network map based on citations is shown in Figure 8. A network of publications with a hundred or more citations through 2023 is displayed in Figure 8(a). A graph displaying the citation density of related publications may be found in Figure 8(b). The color gradient indicates the citation density, with red and yellow areas representing articles with a high number of citations, highlighting their significant impact on the field. For instance, the studies of Zhang *et al.* [7,36] appear as highly cited works, reflecting their foundational contributions to the development of sustainable geopolymer materials. Articles in green and blue regions have lower citation densities, indicating less academic attention but potentially emerging areas of research. This visualization helps researchers identify key landmark studies that shape the field and understand the evolution of research priorities in FGP development, aiding new researchers in locating influential studies and guiding future investigations.

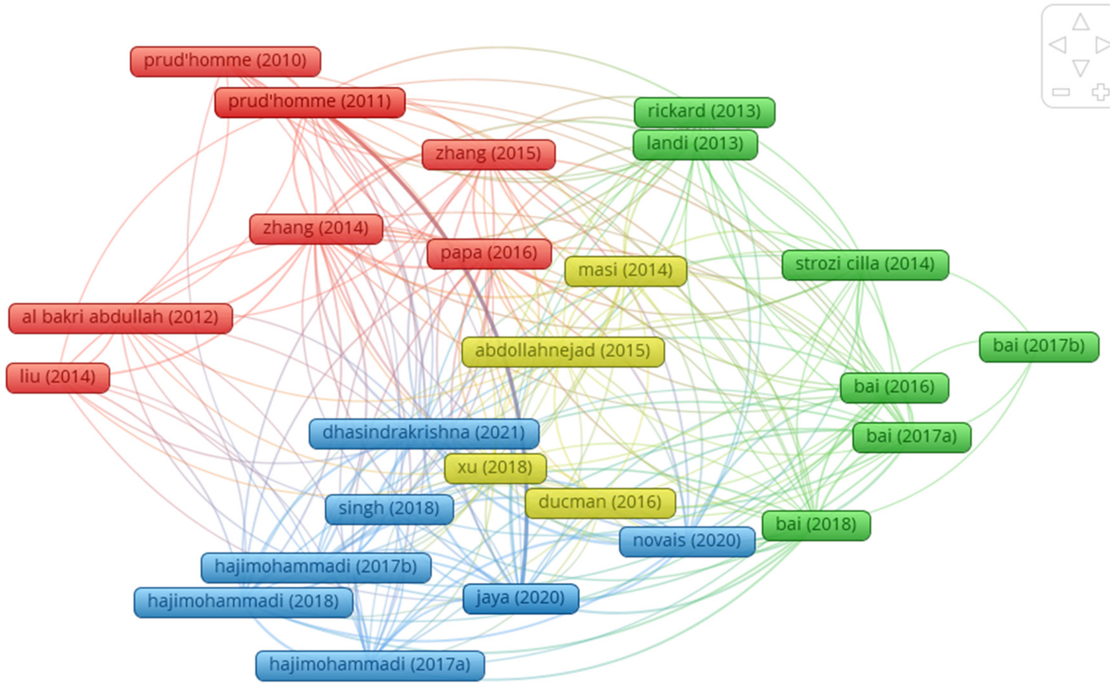
3.6 Science mapping of countries

Certain countries have submitted a larger quantity of articles to the journal than others, and they intend to maintain this pattern. The purpose of the scientific graph is to provide readers with data that is pertinent to the FGP research. Twenty-five countries satisfied the prerequisite of having a minimum of five articles. The list of nations with at least five publications on FGP research is presented in Table 5. The top three countries were China with 83, Italy with 47, and Australia with 39 publications. Australia (2,767 citations), Italy (2,132 citations), and China (1,987 citations) were found to be the three nations with the most number of citations. Figure 9 displays the scientific illustration as well as the density of the regions associated with citations. The magnitude of a nation's impact on a subject is determined by the extent of its frame size in Figure 9(a), which is based on the quantity of articles published on the subject. For instance, China's large node reflects its leading role in FGP research, driven by its extensive industrial by-products and significant funding for sustainable construction technologies [40,41]. Similarly, Italy's contributions are promoted by its expertise in materials science, particularly in thermal insulation and fireproof materials, aligning with its focus on energy efficiency [42]. Australia, with its strong academic-industry collaborations and commitment to carbon emission reduction, has demonstrated leadership in utilizing locally sourced industrial waste for geopolymer development [43,44].

The high publication counts and citation density observed in countries like China, Italy, and Australia underline the importance of international collaboration in FGP research. These leading nations act as global hubs of innovation, offering opportunities for partnerships that can enhance knowledge exchange and accelerate advancements. For example, collaborative efforts between countries with established FGP expertise and those with emerging research infrastructure can address region-specific challenges, such as the availability of raw materials or climatic considerations for FGP applications. Furthermore, international collaborations can help standardize geopolymer production techniques and testing protocols, facilitating the widespread adoption of these materials across diverse industries.

Table 4: List of the articles that have gained the most citations as of 2023

S/N	Document	Title	Citations
1	Zhang *et al.* [7]	Geopolymer foam concrete: An emerging material for sustainable construction	584
2	Zhang *et al.* [36]	Mechanical, thermal insulation, thermal resistance and acoustic absorption properties of geopolymer foam concrete	397
3	Liu *et al.* [37]	Evaluation of thermal conductivity, mechanical and transport properties of lightweight aggregate FGP concrete	320
4	Masi *et al.* [38]	A comparison between different foaming methods for the synthesis of light weight geopolymers	221
5	Al Bakri Abdullah *et al.* [39]	Fly ash-based geopolymer lightweight concrete using foaming agent	203



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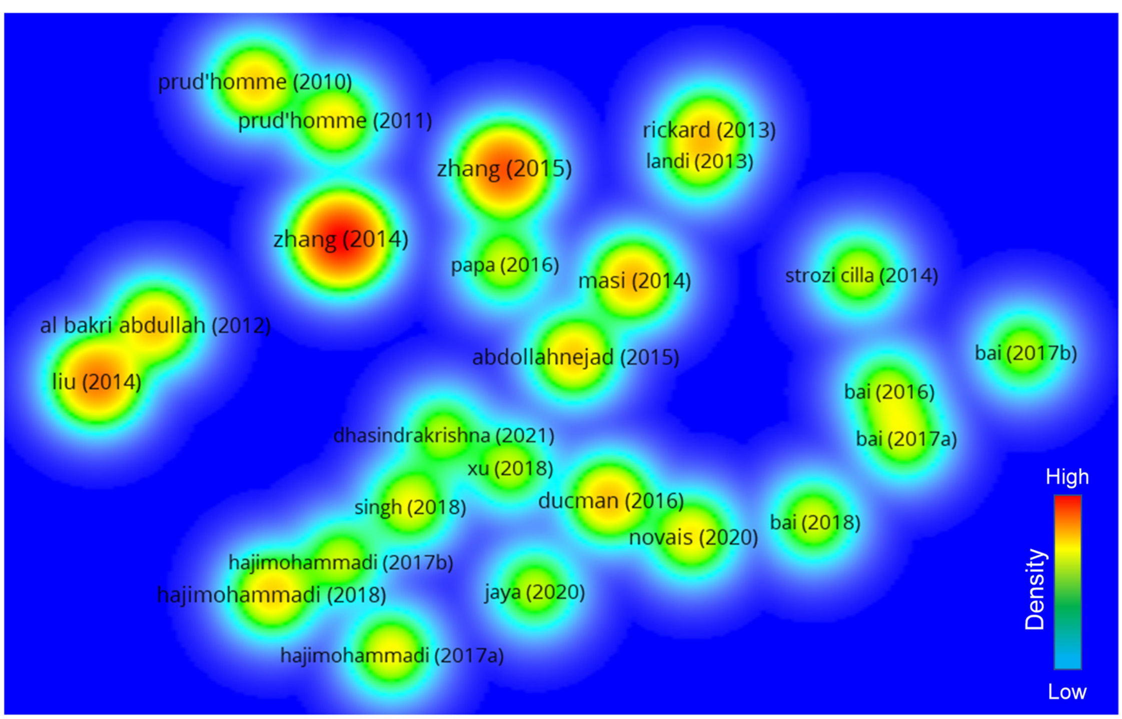

(b)

Figure 8: Mapping of documents: (a) network and (b) density.

The density map in Figure 9(b) reveals high-density regions corresponding to countries with active FGP research activities, providing young researchers insights into collaboration opportunities. By engaging with high-impact nations, researchers can access cutting-edge methods, participate in joint projects, and co-author influential publications. Such partnerships foster

Table 5: List of countries with a minimum number of five documents

S/N	Country	Documents	Citations
1	China	83	1,987
2	Italy	47	2,132
3	Australia	39	2,767
4	France	31	1,272
5	United States	28	1,264
6	Czech Republic	22	461
7	Poland	22	309
8	Malaysia	17	910
9	India	16	317
10	Brazil	14	428
11	Thailand	14	320
12	Portugal	11	549
13	Egypt	10	277
14	Turkey	10	46
15	Pakistan	9	133
16	Romania	8	231
17	Germany	8	156
18	Indonesia	8	86
19	Saudi Arabia	7	281
20	United Kingdom	6	1,124
21	Iraq	6	158
22	Spain	6	144
23	Hungary	5	54
24	Finland	5	51
25	Viet Nam	5	6

interdisciplinary approaches and drive innovation in advanced FGP composites, which are critical for addressing global sustainability challenges. These statistical data and graphical illustrations serve as a valuable resource for identifying leading nations and establishing scientific alliances. Collaborating with subject matter experts and institutions in these countries can significantly enhance researchers' contributions to the growing body of knowledge in FGP research and promote the global application of sustainable construction materials.

4 Discussion

This study used bibliometric data to perform a statistical analysis and scientific visualization of the FGP research. Prior manual evaluations exhibited shortcomings in their capability to accurately and comprehensively link discrete sections of the literature. Conventional literature reviews typically emphasize qualitative findings from a selection of studies. Although this approach is beneficial, it may be constrained in its capacity to deliver a thorough, quantitative assessment of research trends. In contrast, this study utilized scientometric analysis, which incorporates bibliometric analysis to portray the progression of research pertaining to FGP quantitatively. This method is innovative as it identifies critical keywords, prominent authors, leading journals, and active research through a systematic analysis of publication data. For instance, through the process of keyword mapping, this study elucidates research priorities, including an emphasis on thermal conductivity, mechanical properties, and environmental applications, while simultaneously identifying underexplored domains such as long-term durability. Furthermore, the co-citation and clustering analyses yield valuable insights into the collaborative networks and disciplinary emphasis within the field. By integrating these quantitative insights with a qualitative synthesis, this study provides a more holistic and data-informed perspective on the trajectory of the field and its future opportunities, thereby differentiating itself from conventional review methodologies.

This research conducted an analysis of the academic journals that published the greatest number of articles, the most frequently occurring keywords in published papers, the most cited academicians and documents, and the regions with the greatest interest in FGP studies. The findings of the keyword analysis indicate that a significant portion of the research focused on the utilization of FGP in materials intended for fire resistance and thermal insulation. Using FGP is also a feasible method to decrease the carbon emissions of the construction sector. In addition, an analysis was conducted on the literature data to categorize the most prolific and active authors and nations according to the number of published documents and citations. Emerging scholars can benefit from the quantitative assessment and scientific illustration of successful nations and authors as they forge collaborative alliances, establish scientific partnerships, and exchange innovative technological concepts. Scientists hailing from various countries who are motivated to investigate the implementation of FGP, researchers may engage in partnerships with domain authorities. This study conducted an analysis of the literature documents and a comprehensive survey of the most pertinent literature to ascertain and delineate the necessity for FGP, potential applications, limitations associated with the utilization of FGP, and likely resolutions to these limitations.

5 Foaming and stabilizing agents in FGP production

Numerous influencing factors, for instance, the composition and kind of foaming and stabilizing agents, the mix ratio design, and the type and content of raw materials, have been examined in relation to the regulation of pore

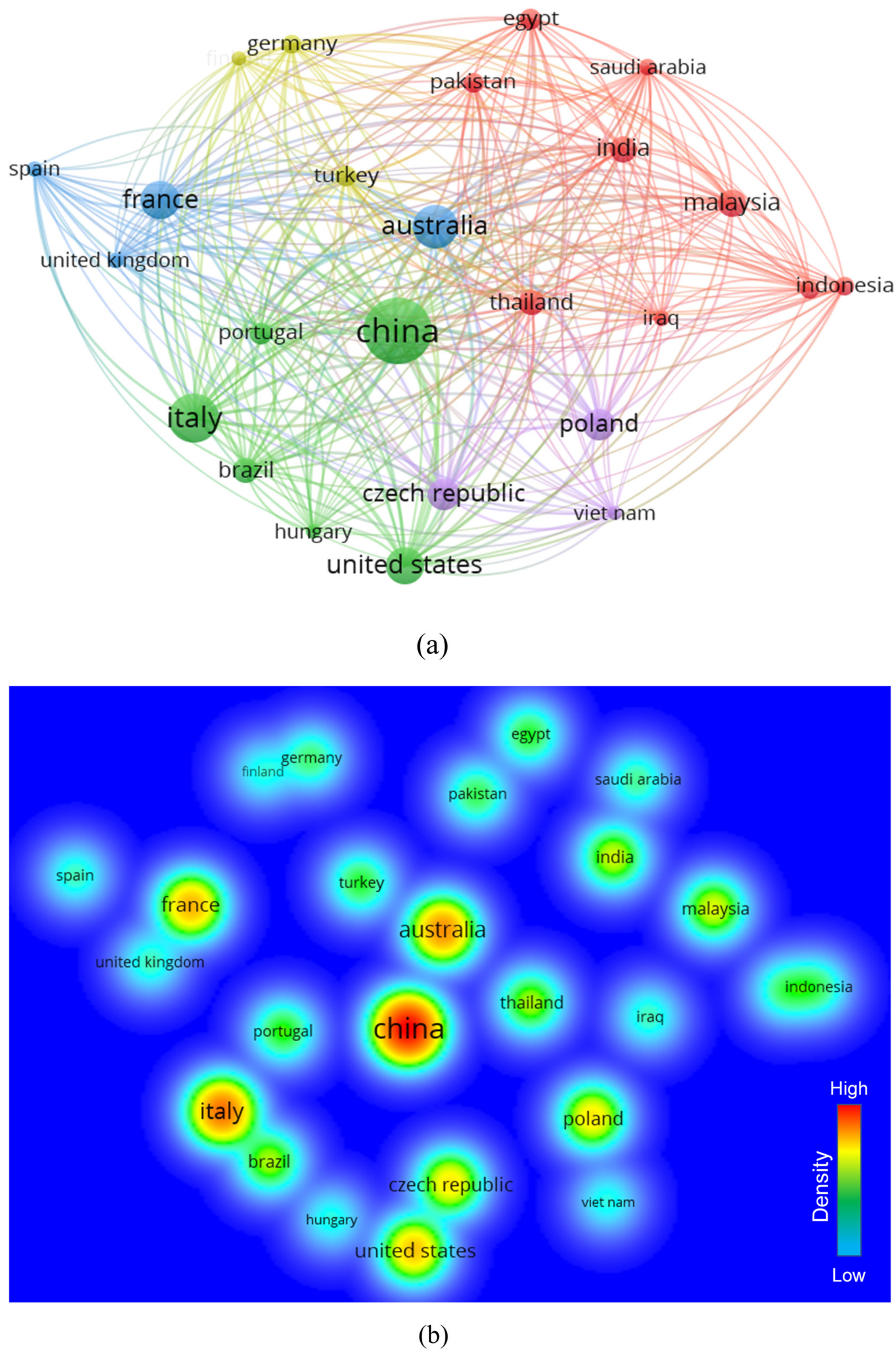

Figure 9: Mapping of countries: (a) network and (b) density.

structures in FGPs [45]. Foaming and stabilizing agents are notable components in this regard [46]. Hydrogen peroxide (H_2O_2) is the most frequently employed foaming agent; it produces foams by releasing O_2 in an alkaline environment [47]. Various organic extracts, including surfactants [48] and vegetable oils [49], have been utilized and investigated as foaming agents. Apart from its application as a foam stabilizer, calcium stearate demonstrates significant decreases in unrestrained and constrained drying shrinkage, along with the fissure features linked to dry shrinkage [50]. Stabilizing and foaming compounds are utilized in order to impart froth controllability to FGPs [51]. Hydrophobization of geopolymers has been considered one of the most efficacious techniques for preventing alkali loss. As a result, numerous hydrophobic modification agents, including silanes [52] and fatty acids [53], have been developed. In their study, Liu *et al.* [54] documented the utilization of polymeric hydrogenated siloxane-polymethyl-hydro siloxane (PMHS) to modify the surface hydrophobicity of geopolymers while acting as a waterproofing agent. Motivated by this observation and cognizant of the fact that PMHS would liberate H_2 in an alkaline environment, we implemented PMHS ingeniously as a frothing and aqueous-resistant agent in a single phase for the production of superhydrophobic FGPs in this investigation.

6 Possible applications of FGP

6.1 Thermal insulation: Technical properties and innovations

A substantial body of literature exists due to the significant technical advantages that geopolymer foams possess in comparison to conventional low thermal conductivity materials (*e.g.*, excellent resistance to heat, environmentally friendly synthesis, and fire resistance). A pioneering inquiry was conducted in 2010 by Prud'homme *et al.* [55]. As a foaming agent, silica fume was employed in the synthesis of geopolymer foams characterized by thermal conductivities ranging from 220 to 240 $mW{\cdot}m^{-1}{\cdot}K^{-1}$ and a density of 534 $kg{\cdot}m^{-3}$. Additionally, two investigations were conducted in the same year [56,57]. Vaou and Panias [56] documented significantly reduced thermal conductivities in perlite-based geopolymers, reaching as low as 30 $mW{\cdot}m^{-1}{\cdot}K^{-1}$ through the foaming of H_2O_2. In comparison, conventional insulation materials such as fiberglass and mineral wool typically have thermal conductivity values around 40 $mW{\cdot}m^{-1}{\cdot}K^{-1}$ [58]. This indicates that while FGPs offer beneficial thermal insulation properties, they may have higher thermal conductivity than traditional insulators like fiberglass and mineral wool.

Aluminum powder was utilized by Shu-Heng *et al.* [57] to create highly porous geopolymers based on phosphoric acid. Despite the fact that the samples' thermal conductivity was not revealed, they were manufactured with a compressive strength of 7 MPa and a porosity of 83%. Since then, there has been a significant surge in the number of studies devoted to porous geopolymers, with a particular emphasis on the development of formulations that provide thermal insulation. In addition to possessing an exceptionally limited ability to transfer heat, thermal insulating materials must also exhibit great resistance to vapor diffusion; failure to do so may permit water to permeate the materials, thereby significantly diminishing their insulating capabilities. Multiple authors have documented significant water uptake values: 26.2–41.1% [59], 31.9–56.3% [60], 30–50% [38], and 42.1–111.7% [61]. This limitation can be surmounted through the fabrication of bi-layered foams, which consist of a denser, bulkier layer that is highly porous and has a thin, dense surface layer that ensures high resistance to vapor diffusion. However, the bi-layered foam approach has complexity in production, requiring precise control over layering and interface bonding, which increases manufacturing demands. Additionally, the higher production costs and potential recyclability issues of multi-material layers may limit its scalability and adoption. The literature has previously showcased this solution [62,63], as evidenced by the images displayed in Figure 10.

6.2 Sound absorption: Acoustic characteristics and challenges

In addition, sound-absorbent materials are critical in mitigating the increasing degrees of noise pollution [64]. This is especially pertinent when contemplating construction materials, as sound absorbents improve the acoustic comfort of the interior for occupants and mitigate the health hazards (such as disruption of sleep) [65] linked to exposure to sound pollution. With few exceptions to date, exploration has been conducted into the acoustic properties of geopolymer foams [66,67]. However, these investigations yielded significant insights into the capability of geopolymer foams to function as sound barriers. Furthermore, they examined critical performance factors such as curing temperature [66], porosity and bulk density [36,66], and activating solution [66,68]. An upward trend in the sound absorption coefficient (α) was documented by Luna-

Galiano *et al.* [66] as the open porosity increased from 11.5 to 28.9% within the frequency range of 100–5,000 Hz. One peak appeared in the low-frequency region (approximately 500 Hz), while the other appeared at higher frequencies (approximately 2,500 Hz). Max α was approximately 0.25 or 2,500 Hz. Papa *et al.* [68] reported comparable results, wherein they also identified two absorption maxima, albeit within distinct frequency ranges: 3,000–5,000 and 500–3,000 Hz. The sound absorption in the frequency ranges of 1,000–1,500 Hz and 4,200–6,500 Hz varied between 0.45 and 0.9, contingent upon the exact variety of metakaolin and activating solution utilized. Stolz *et al.* documented an alternative pattern of acoustic absorption: they observed an exceptionally high α (approximately 0.85 in magnitude) in the low-frequency range (125–250 Hz), which dropped precipitously to approximately 0.15 in the 500–2,000 Hz range prior to regaining prominence at higher frequencies [67]. In comparison, flexible polyurethane foam can achieve α values of 0.95 at 500 Hz [69]. This comparison indicates that FGPs offer competitive sound absorption performance, particularly in specific frequency ranges, making them a viable alternative to conventional sound-absorbing materials.

Zhang *et al.* [36] examined the effect of the sample thickness and fraction of fly ash to slag as raw materials on the acoustic performance of geopolymer foams. The substitution of 30% of fly ash using powdered blast furnace slag led to little changes in the sound absorption properties. Nevertheless, the introduction of more closely spaced samples resulted in improved sound absorption at lower frequencies but had no impact at higher frequencies. Extremely high α values (0.7–1.0) were observed in the low-frequency range (40–150 Hz) for these specimens.

The impact of the bulk density of the foams on α was inspected by Hung *et al.* [70]. The results indicated that sound absorption was greater at lower densities across the frequency range of 100–4,000 Hz. With a very high α ranging from 0.5 (in the low-frequency region) to 0.9 (in the higher frequency region), the lightest specimen (0.4 $g \cdot cm^{-3}$) demonstrated the highest effectiveness of any geopolymer foam soundproofing. The aforementioned inquiries provide evidence for the feasibility of employing geopolymer foams as sound absorbers. However, additional research is necessary to validate prior findings and elucidate the significance of pertinent factors, including the type of pores (whether they are open or closed), their distribution in terms of size, and their tortuosity. Except for Hung et al. [70], in which α was greater than 0.4 across the entire frequency range of 100–4,000 Hz, the aforementioned studies all demonstrated sound absorption behavior that was merely intriguing at particular frequencies but comparatively subpar in other ranges.

The data indicate that FGPs exhibit varying α across different frequency ranges. For instance, studies have demonstrated high α values in the low-frequency range but relatively lower performance at mid-frequencies,

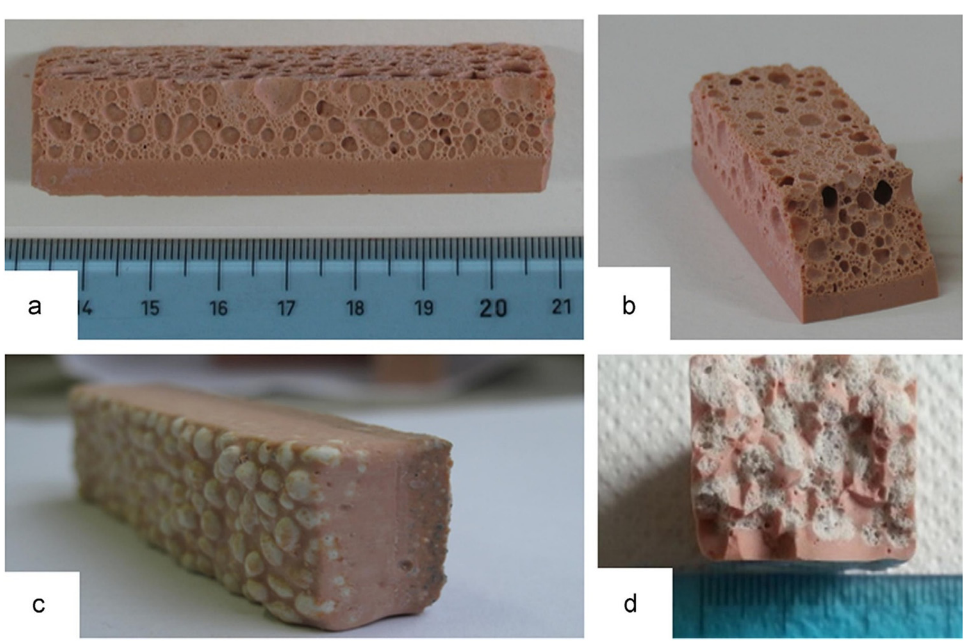

Figure 10: Digital pictures depicting bi-layered geopolymers, including (a and b) mortar, (c) paste, and (d) composite that incorporates glass spheres [62].

with subsequent improvements at higher frequencies. This frequency-dependent behavior suggests that FGPs can be tailored for specific real-world applications. In high-traffic urban areas, where low-frequency noise from vehicles predominates, FGPs' superior performance in the lower frequency range makes them ideal for sound barriers along roads and highways. Similarly, in industrial settings, where machinery often generates noise across a broader spectrum, FGPs could be adjusted to provide balanced absorption by modifying pore size, density, or material composition. For residential environments, where mid-to high-frequency noise (*e.g.*, voices and appliances) is prevalent, FGPs' tunability offers potential for acoustic panels or insulation that enhance indoor comfort. Further advancements in material engineering could optimize FGPs for specific frequency ranges. Adjustments such as controlling the porosity, adding fillers, or layering materials with varying densities could significantly enhance their acoustic performance. For example, increasing the proportion of open pores could improve absorption at higher frequencies, while denser compositions might enhance low-frequency damping. This flexibility underscores FGPs' versatility and points toward their potential development as a customized solution for diverse acoustic challenges.

6.3 Adsorbent: Applications and challenges

Exploring waste-based geopolymers as cost-effective and environmentally sustainable adsorbents could serve as a promising strategy to remediate industrial wastewater contamination and promote cleaner manufacturing processes. This is due to the fact that their synthesis can be conducted at room temperature with relatively low energy input, residues serving as solid precursors, and a minimal amount of activating solution being utilized. These conditions significantly limit the release of greenhouse gases. In addition, the strong binding of pollutants to the geopolymer matrix facilitates their use in alternative applications (*e.g.*, as a filler or aggregate in the manufacturing of new construction materials) after exhaustion is possible and uncomplicated. These are significant advantages over the standard adsorbent activated carbon, whose recovery after use is difficult and has extremely high production costs [71]. The potential of this possibility as a viable substitute for activated carbons has been acknowledged for some time [72,73] due to the capacity of geopolymers to undergo cation exchange with the solution [74]. Recent scholarly articles [75–77] cover the subject; nevertheless, none of them made a distinction between bulk-type and pulverized geopolymer adsorbents; this deficiency will be rectified in the following section.

According to Al-Zboon *et al.* [78], the lead uptake from coal fly ash-based geopolymer powders was 81 $mg\cdot g^{-1}$. Cheng *et al.* [79] described an even greater lead uptake of 100 $mg\cdot g^{-1}$ from metakaolin-based powders. An illustration of the application of the same concept to the extraction of dyes from effluent is the geopolymer block developed by Liu *et al.* [80], which is both floatable and permeable. However, prior to adsorption, the geopolymers were pulverized and filtered using a 100-mesh screen. Notwithstanding the noteworthy outcomes of methylene blue removal at a rate of 50.7 $mg\cdot g^{-1}$, the pulverized geopolymers remain unsuitable for direct application in packed beds and are not readily retrievable. Lately, the scientific community has shown a keen interest in the potential utilization of monolithic bodies (such as membranes) as opposed to powders. This approach offers the advantage of safety and simplicity when compared to the utilization of nano or micro-scale powders, as it enables the direct utilization of materials in packed beds without the need for support materials.

In lieu of a post-separation step, Ge *et al.* [81] employed a cylindrical membrane made of metakaolin-based geopolymer to extract Ni^{2+} from a synthetic effluent. Novais *et al.* [61] employed cylindrical discs as a means of lead extraction from wastewater. Notwithstanding the relatively low lead uptake exhibited by the monolithic geopolymers (ranging from 0.95 to 6.34 $mg\cdot g^{-1}$) when compared to pulverized geopolymers [78,79], this study was among the initial to explore the utilization of monolithic adsorbents, namely those in bulk form rather than powder form. A further geopolymer adsorbent of the bulk variety was documented [82]. The maximal adsorption capacity of the zeolites supported on geopolymers was 37.9 $mg\cdot g^{-1}$. Salehi and Kani reported the existence of a cylindrical mesoporous adsorbent [83] for the purpose of removing dyes. The adsorbent possessed an average pore diameter of 20 nm and a specific surface area (SSA) of 56.6 $m^2\cdot g^{-1}$. Maximum adsorption capacities for malachite green oxalate and basic violet were 46.6 and 46.4 $mg\cdot g^{-1}$, respectively. Bai *et al.* [84] utilized monolithic FGPs to extract copper and ammonium, achieving 87% copper elimination and 95% ammonium elimination, corresponding to uptakes of 0.54 and 0.57 $mg\cdot g^{-1}$, respectively. Tang *et al.* [85] have documented an additional method of stimulation: the implementation of metakaolin geopolymer spheres characterized by a substantial SSA (approximately 54 $m^2\cdot g^{-1}$) and a total porosity of 60% (refer to Figure 11). The maximal absorption values for Cu^{2+}, Pb^{2+}, and Ca^{2+} ions bound to the spheres were determined to be 35, 46, and 24 $mg\cdot g^{-1}$, respectively.

6.4 Catalytic applications

The potential utilization of geopolymers in catalytic processes has been hypothesized for quite some time [86]. Geopolymers are viable catalysts because of the high permeability of their chemical durability, high SSA, and mechanical strength [87]. Nevertheless, the potential of these substances as catalyst supports has been the subject of very few investigations thus far [86,88] and even fewer as catalysts [89–91]. However, investigations on the use of geopolymer have been carried out for various catalytic applications, including effluent treatment [92–94], syngas production [95], and biodiesel manufacturing [90,96]. The current review is more particular, focused on the utilization of geopolymer foams in their bulk form rather than in particle form (for pertinent literature, see previous studies [87,97]). As far as our understanding, a single study [98] has examined the application of bulk-type geopolymer in the synthesis of biodiesel. An additive manufacturing process was utilized to shape a geopolymer mixture into a lattice structure (refer to Figure 12). Subsequently, this novel material underwent testing to determine the characteristics that make it suitable for the heterogeneous transesterification of soybean oil with methanol. When 3 weight percent of the structured catalyst was utilized to transesterify soybean oil for 4 h, 43.5 weight percent of biodiesel was produced. The results presented are exceedingly encouraging and provide evidence for the practicality of making use of geopolymers of the bulk kind as catalysts in relevant industrial applications.

7 Challenges and potential solutions

7.1 Adaptability in the construction sector

In current decades, geopolymers have garnered attention as a possibly more environmentally sustainable alternative to Portland cement due to their lower carbon footprint and ability to incorporate industrial by-products. Their adaptability stems from the customization potential in terms of porosity, adsorption, and leaching properties, which broadens their utility beyond traditional construction materials. These materials are finding innovative applications in renewable energy generation, such as biogas systems, where their thermal stability and resistance to chemical degradation play a crucial role. Moreover,

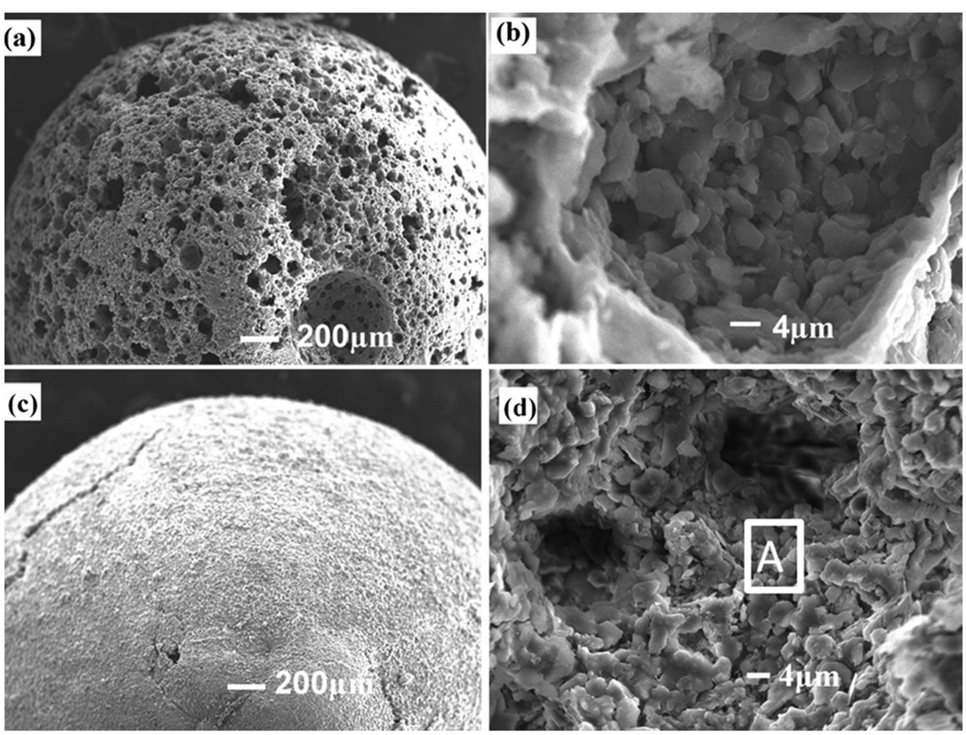

Figure 11: SEM images depicting the surface characteristics of porous geopolymer spheres are as follows: (a) the spheres' exterior surface and (b) the pore microstructure; (c) the spheres' exterior surface prior to the addition of K12; and (d) the pore microstructure subsequent to the adsorption process on Cu(II) [85].

geopolymers are being explored for environmental remediation, particularly in wastewater treatment, where their ability to adsorb contaminants like heavy metals and dyes has shown promise. Their use in energy-efficient construction is particularly noteworthy, as they serve as thermal insulation materials that significantly reduce energy consumption in buildings. The adaptability of geopolymers facilitates progress in sustainable technologies. Additional research and development may enhance their physical and chemical properties for targeted applications. Their versatility guarantees that geopolymers serve not merely as alternatives to conventional materials but as a transformative remedy for urgent worldwide issues in sustainability and energy efficiency. However, interdisciplinary challenges persist in fully realizing their potential. The lack of standardized testing protocols across engineering, materials science, and environmental science disciplines hinders broader adoption. Future studies should focus on developing unified frameworks for evaluating mechanical, thermal, and environmental performance to bridge these gaps and support seamless integration into diverse applications. Exploring advanced computational models and hybrid composites can further accelerate their practical implementation in the construction sector.

7.2 Advancing material properties and processing techniques

Geopolymers have exhibited considerable promise as materials with minimal thermal conductivity. However, additional pertinent characteristics of construction materials, including their capacity to absorb and release moisture and acoustic resistance, have received comparatively less attention thus far and warrant further research. Further research is warranted to ascertain the optimal processing techniques (*e.g.*, replica method and direct frothing) and synthesis conditions necessary to meet the demands of these applications. Further investigation into novel processing methodologies, such as 3D printing, is warranted in order to fabricate monoliths featuring intricate geometries that enable enhanced regulation of pore size distribution and, consequently, improved performance. Notwithstanding the intriguing prospects presented by 3D printing, there exist engineering obstacles pertaining to the temporal alteration of the viscosity of slurries through geopolymerization reactions [99]. These challenges must be surmounted. It is necessary to research various techniques for extending the curing times of slurry in order to guarantee an appropriate printing timeframe. Irrespective of the method of processing, it is critical to utilize precursors that are both readily available and locally sourced. Ideally, untapped waste streams that are unsuitable for Portland cement blends should be utilized. Furthermore, compositions should be meticulously planned to guarantee cost-competitiveness in production while assuming net-zero emissions. Subsequent investigations ought to rely heavily on life cycle analysis to substantiate the ecological advantages linked to the use of geopolymer foams in building settings.

7.3 Advanced adsorption applications

An additional promising application of geopolymer foams is in the realm of adsorption. The majority of research conducted thus far has been devoted to the extraction of heavy metals and cationic dyes from synthetic wastewater. Industrial effluents may also contain anionic species; nevertheless, no study has documented the extraction of these species *via* geopolymer foams (as opposed to powders), and the application of powdered geopolymers is even less frequent [100]. Further research should be conducted regarding this subject matter. Furthermore, further research should be conducted on emerging sources of contamination, including pharmaceuticals and crude oil.

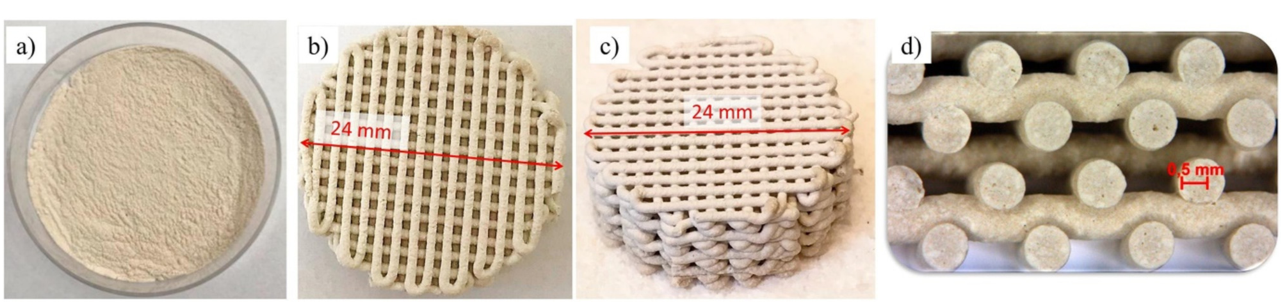

Figure 12: Photographs of the powdered sodium-based geopolymer (a) and the direct ink writing-fabricated graded lattice structure (b–d) [98].

Further research investigating the functionalization of the geopolymer surface and the fabrication of geopolymer composites (*e.g.*, incorporating activated carbons or zeolites) could potentially augment the efficacy of these novel adsorbents. The primary obstacle impeding the broader application of geopolymer adsorbents is the disparity between what has been studied in the lab, frequently simulated using unattainable scenarios (*e.g.*, synthetic wastewaters), and the intricacies of actual effluents [74,101]. It is expected that research concerning industrial effluents will be a popular subject in the near future.

7.4 Potential for pH buffering and catalytic applications

The investigation into the utilization of geopolymer foams as pH buffering materials is limited. However, the limited number of studies conducted thus far indicate their viability for this application with significant added value. To further demonstrate their potential, additional research should be conducted under more stringent conditions and for extended durations so as to more closely resemble their definite industrial application (*e.g.*, continuous anaerobic digestion systems). An investigation into the assessment of the catalytic characteristics exhibited by geopolymer foams is warranted as well. By doping the geopolymer foams with unique reactive species, their catalytic properties could be significantly enhanced.

7.5 Higher production cost

A notable limitation of FGPs in comparison to conventional construction materials such as bricks, concrete blocks, and expanded polystyrene is the comparatively higher production cost under specific conditions. The expense of alkali activators, including sodium silicate and sodium hydroxide, is a major factor in this cost, frequently constituting a substantial share of the overall material expenditure [102]. Moreover, the requirement for specialized apparatus and regulated manufacturing settings, like exact foaming operations or curing environments, significantly increases production expenses [103]. Transportation and storage expenses may escalate if raw materials such as fly ash or slag are not locally accessible, requiring long-distance transportation [7]. Moreover, the absence of economies of scale in numerous places, attributable to restricted adoption and production infrastructure, renders FGPs less cost-competitive compared to extensively manufactured conventional materials [7]. These considerations combined underscore the necessity for advances in production techniques and supply chain efficiency to improve the economic viability of FGPs.

7.6 Limitations in experimental standardization

Despite significant progress in FGP research, a major limitation lies in the lack of standardized testing protocols across studies. Variations in experimental conditions, such as raw material compositions, pore structure measurements, curing processes, and environmental testing, make comparing results and generalizing findings difficult. For instance, thermal conductivity values may vary widely depending on the porosity measurement method or the type of foaming agent used, while differences influence α in frequency ranges and material thicknesses. This lack of uniformity complicates efforts to establish benchmarks for FGP performance in thermal and acoustic applications. Additionally, discrepancies in experimental designs hinder the reproducibility of results, limiting the reliability of studies for industrial-scale applications. Addressing these challenges requires the development of standardized testing protocols. Such protocols should define consistent parameters for evaluating FGP properties, including thermal conductivity, sound absorption coefficients, and durability under controlled environmental conditions. For thermal applications, specify the temperature range, heat flux, and material thickness for thermal conductivity testing. Also, standardize frequency bands, porosity characterization, and sample sizes for acoustic applications for sound absorption tests. By implementing standardized methodologies, researchers can produce more reliable and comparable data, facilitating advancements in material design and enabling broader adoption of FGPs in construction and environmental applications.

8 Environmental aspects of FGPs

FGPs are a viable substitute for conventional construction materials, providing significant environmental advantages. In contrast to the manufacturing of ordinary Portland cement, which accounts for roughly 8% of global CO_2 emissions, the synthesis of geopolymers does not release CO_2 into the environment [104]. This substantial decrease in greenhouse gas emissions shows FGPs as a more sustainable alternative. Lifecycle assessments (LCAs) highlight the ecological benefits of FGPs. Research indicates that geopolymers possess a diminished environmental footprint relative to OPC concrete, attaining a broad spectrum of strengths while sustaining lesser ecological implications [105,106]. Moreover, the production of geopolymer foam concrete is linked to reduced energy requirements and less CO_2 emissions, enhancing its environmental advantages [103].

The use of industrial by-products, such as fly ash and metakaolin, in the manufacture of FGPs diverts waste from landfills and reduces the demand for natural raw materials, therefore preserving natural resources [107]. Nonetheless, obstacles persist, such as the ecological consequences of alkali activators employed in geopolymer synthesis and the inconsistency in the availability of appropriate industrial by-products [107]. It is essential to address these problems through ongoing research and development to fully harness the environmental potential of FGPs. In conclusion, FGPs provide a sustainable substitute for traditional construction materials, with LCAs demonstrating reduced carbon footprints and environmental effects. Their adoption might significantly reduce the construction sector's contribution to global CO_2 emissions.

9 Conclusions

This research used scientometric analytic methodology to assess the information presented in the literature on geopolymer foam FGP. A total of 361 records from Scopus were examined using the VOSviewer software. The primary findings of the research are as follows:

- The assessment of annual publications in the field of FGP research revealed uneven advancement up to the year 2021. However, in the last 2 years (2022 and 2023), a significant increase in the number of articles was seen. The review indicated that the focus of researchers had been redirected towards FGP research due to its progress during the previous 7 years.
- An assessment of publishing sources (journals/conferences) that include contents on FGP research revealed that "Construction and Building Materials," "Ceramics International," and "Materials" are the top journals that are determined based on the number of papers they published with 46, 27, and 22 documents, respectively.
- The examination of keywords on the FGP study revealed that inorganic polymers, geopolymers, geopolymer, compressive strength, and thermal conductivity are the most frequently used keywords. According to a keyword analysis, FGP has been investigated the most. Based on the findings of the keyword analysis, much of the research on FGP has focused on its utilization in thermal insulation and fire-resistant materials. Additionally, employing FGP is a feasible strategy for mitigating the carbon emissions associated with the building industry.
- Based on their contribution to the FGP investigations, the prominent nations were evaluated, and it was observed that 14 nations had published a minimum of 10 articles by the year 2023. China, Italy, and Australia contributed 83, 47, and 39 articles, respectively.
- The potential applications of FGP include thermal insulation, sound absorption, adsorbents, and catalysts. However, in order to further showcase their capabilities, it is necessary to undertake more study under more rigorous settings and over longer periods of time in order to precisely emulate their real-world industrial use.
- Challenges with FGPs, such as higher production costs, lack of standardized testing protocols, and limitations in experimental scalability, highlight the need for advancements in manufacturing processes, supply chain optimization, and unified evaluation frameworks. Addressing these challenges through interdisciplinary research and targeted material adjustments will be crucial for advancing FGP adoption and unlocking their full potential to contribute to sustainability goals.

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References

[1] Balachandra, A. M., N. Abdol, A. Darsanasiri, K. Zhu, P. Soroushian, and H. E. Mason. Landfilled coal ash for carbon dioxide capture and its potential as a geopolymer binder for hazardous waste remediation. *Journal of Environmental Chemical Engineering*, Vol. 9, 2021, id. 105385.

[2] Díaz, E. E. S. and V. A. E. Barrios. Development and use of geopolymers for energy conversion: An overview. *Construction and Building Materials*, Vol. 315, 2022, id. 125774.

[3] Bi, S., M. Liu, J. Shen, X. M. Hu, and L. Zhang. Ultrahigh self-sensing performance of geopolymer nanocomposites via unique interface engineering. *ACS Applied Materials & Interfaces*, Vol. 9, 2017, pp. 12851–12858.

[4] Luukkonen, T., Z. Abdollahnejad, J. Yliniemi, P. Kinnunen, and M. Illikainen. One-part alkali-activated materials: A review. *Cement and Concrete Research*, Vol. 103, 2018, pp. 21–34.

[5] Singh, B., G. Ishwarya, M. Gupta, and S. K. Bhattacharyya. Geopolymer concrete: A review of some recent developments. *Construction and Building Materials*, Vol. 85, 2015, pp. 78–90.

[6] Bakharev, T. Resistance of geopolymer materials to acid attack. *Cement and concrete research*, Vol. 35, 2005, pp. 658–670.

[7] Zhang, Z., J. L. Provis, A. Reid, and H. Wang. Geopolymer foam concrete: An emerging material for sustainable construction. *Construction and Building Materials*, Vol. 56, 2014, pp. 113–127.

[8] Delair, S., É. Prud'homme, C. Peyratout, A. Smith, P. Michaud, L. Eloy, et al. Durability of inorganic foam in solution: The role of alkali elements in the geopolymer network. *Corrosion Science*, Vol. 59, 2012, pp. 213–221.

[9] Xu, F., G. Gu, W. Zhang, H. Wang, X. Huang, and J. Zhu. Pore structure analysis and properties evaluations of fly ash-based geopolymer foams by chemical foaming method. *Ceramics International*, Vol. 44, 2018, pp. 19989–19997.

[10] Narayanan, A. and P. Shanmugasundaram. An experimental investigation on flyash-based geopolymer mortar under different curing regime for thermal analysis. *Energy and Buildings*, Vol. 138, 2017, pp. 539–545.

[11] Huang, Y., L. Gong, L. Shi, W. Cao, Y. Pan, and X. Cheng. Experimental investigation on the influencing factors of preparing porous fly ash-based geopolymer for insulation material. *Energy and Buildings*, Vol. 168, 2018, pp. 9–18.

[12] Shao, N.-n, Y.-b Zhang, Z. Liu, D.-m Wang, and Z.-t Zhang. Fabrication of hollow microspheres filled fly ash based foam geopolymers with ultra-low thermal conductivity and relative high strength. *Construction and Building Materials*, Vol. 185, 2018, pp. 567–573.

[13] Rickard, W. D. A., L. Vickers, and A. Van Riessen. Performance of fibre reinforced, low density metakaolin geopolymers under simulated fire conditions. *Applied Clay Science*, Vol. 73, 2013, pp. 71–77.

[14] Seelam, P. K., H. Sreenivasan, S. Ojala, S. Pitkäaho, T. Laitinen, H. Niu, et al. Modified geopolymers as promising catalyst supports for abatement of dichloromethane. *Journal of Cleaner Production*, Vol. 280, 2021, id. 124584.

[15] Ge, Y., Y. Yuan, K. Wang, Y. He, and X. Cui. Preparation of geopolymer-based inorganic membrane for removing Ni^{2+} from wastewater. *Journal of Hazardous Materials*, Vol. 299, 2015, pp. 711–718.

[16] Zakka, W. P., N. H. A. S. Lim, and M. C. Khun. A scientometric review of geopolymer concrete. *Journal of Cleaner Production*, Vol. 280, 2021, id. 124353.

[17] Udomsap, A. D. and P. Hallinger. A bibliometric review of research on sustainable construction, 1994–2018. *Journal of Cleaner Production*, Vol. 254, 2020, id. 120073.

[18] Markoulli, M. P., C. I. Lee, E. Byington, and W. A. Felps. Mapping human resource management: Reviewing the field and charting future directions. *Human Resource Management Review*, Vol. 27, 2017, pp. 367–396.

[19] Amin, M. N., W. Ahmad, K. Khan, and M. M. Sayed. Mapping research knowledge on rice husk ash application in concrete: A scientometric review. *Materials*, Vol. 15, 2022, id. 3431.

[20] Aghaei Chadegani, A., H. Salehi, M. Yunus, H. Farhadi, M. Fooladi, M. Farhadi, et al. A comparison between two main academic literature collections: Web of Science and Scopus databases. *Asian Social Science*, Vol. 9, 2013, pp. 18–26.

[21] Afgan, S. and C. Bing. Scientometric review of international research trends on thermal energy storage cement based composites via integration of phase change materials from 1993 to 2020. *Construction and Building Materials*, Vol. 278, 2021, id. 122344.

[22] Hallinger, P. and J. Kovačević. A bibliometric review of research on educational administration: Science mapping the literature, 1960 to 2018. *Review of Educational Research*, Vol. 89, 2019, pp. 335–369.

[23] Ahmad, W., H. Alabduljabbar, and A. F. Deifalla. An overview of the research trends on fiber-reinforced shotcrete for construction applications. *Reviews on Advanced Materials Science*, Vol. 62, 2023, id. 20230144.

[24] He, C., S. Zhang, Y. Liang, W. Ahmad, F. Althoey, S. H. Alyami, et al. A scientometric review on mapping research knowledge for 3D printing concrete. *Materials*, Vol. 15, 2022, id. 4796.

[25] Khan, K., W. Ahmad, M. N. Amin, S. A. Khan, A. F. Deifalla, and M. Y. M. Younes. Research evolution on self-healing asphalt: A scientometric review for knowledge mapping. *Reviews on Advanced Materials Science*, Vol. 62, 2023, id. 20220331.

[26] Qin, D., Y. Hu, and X. Li. Waste glass utilization in cement-based materials for sustainable construction: A review. *Crystals*, Vol. 11, 2021, id. 710.

[27] Yang, D., J. Zhao, W. Ahmad, M. Nasir Amin, F. Aslam, K. Khan, et al. Potential use of waste eggshells in cement-based materials: A bibliographic analysis and review of the material properties. *Construction and Building Materials*, Vol. 344, 2022, id. 128143.

[28] Mei, J., G. Xu, W. Ahmad, K. Khan, M. N. Amin, F. Aslam, et al. Promoting sustainable materials using recycled rubber in concrete: A review. *Journal of Cleaner Production*, Vol. 373, 2022, id. 133927.

[29] Alkadhim, H. A., M. N. Amin, W. Ahmad, K. Khan, M. N. Al-Hashem, S. Houda, et al. Knowledge mapping of the literature on fiber-

reinforced geopolymers: A scientometric review. *Polymers*, Vol. 14, 2022, id. 5008.
[30] Zuo, J. and Z.-Y. Zhao. Green building research–current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, Vol. 30, 2014, pp. 271–281.
[31] Darko, A., C. Zhang, and A. P. Chan. Drivers for green building: A review of empirical studies. *Habitat International*, Vol. 60, 2017, pp. 34–49.
[32] Ahmad, W., M. Khan, and P. Smarzewski. Effect of short fiber reinforcements on fracture performance of cement-based materials: A systematic review approach. *Materials*, Vol. 14, 2021, id. 1745.
[33] Wuni, I. Y., G. Q. Shen, and R. Osei-Kyei. Scientometric review of global research trends on green buildings in construction journals from 1992 to 2018. *Energy and Buildings*, Vol. 190, 2019, pp. 69–85.
[34] Su, H.-N. and P.-C. Lee. Mapping knowledge structure by keyword co-occurrence: a first look at journal papers in Technology Foresight. *Scientometrics*, Vol. 85, 2010, pp. 65–79.
[35] Yu, F. and B. E. Hayes. Applying data analytics and visualization to assessing the research impact of the Cancer Cell Biology (CCB) Program at the University of North Carolina at Chapel Hill. *Journal of e Science Librarianship*, Vol. 7, 2018, id. 4.
[36] Zhang, Z., J. L. Provis, A. Reid, and H. Wang. Mechanical, thermal insulation, thermal resistance and acoustic absorption properties of geopolymer foam concrete. *Cement and Concrete Composites*, Vol. 62, 2015, pp. 97–105.
[37] Liu, M. Y. J., U. J. Alengaram, M. Z. Jumaat, and K. H. Mo. Evaluation of thermal conductivity, mechanical and transport properties of lightweight aggregate foamed geopolymer concrete. *Energy and Buildings*, Vol. 72, 2014, pp. 238–245.
[38] Masi, G., W. D. A. Rickard, L. Vickers, M. C. Bignozzi, and A. Van Riessen. A comparison between different foaming methods for the synthesis of light weight geopolymers. *Ceramics International*, Vol. 40, 2014, pp. 13891–13902.
[39] Al Bakri Abdullah, M. M., K. Hussin, M. Bnhussain, K. N. Ismail, Z. Yahya, and R. A. Razak. Fly ash-based geopolymer lightweight concrete using foaming agent. *International Journal of Molecular Sciences*, Vol. 13, 2012, pp. 7186–7198.
[40] Zhang, Z. H., H. J. Zhu, C. H. Zhou, and H. Wang. Geopolymer from kaolin in China: An overview. *Applied Clay Science*, Vol. 119, 2016, pp. 31–41.
[41] Feng, D., J. Wang, Y. Wang, X. Xiao, W. Hou, and S. Liang. Alkali-activated geopolymer materials prepared from coal gangue and municipal solid waste incineration byproducts. *Journal of Building Engineering*, Vol. 80, 2023, id. 108074.
[42] Currò, G., O. Fiandaca, and F. Minutoli. The fire vulnerability of insulating materials for residential building energy efficiency: From unawareness of early applications to desirable formulation of certification protocols. *In Proceedings of the Proceedings of the 11th International Conference of Ar.Tec. (Scientific Society of Architectural Engineering), Cham, 2025*, 2025, pp. 227–248.
[43] Gourley, J. T. Geopolymers in Australia. *Journal of the Australian Ceramic Society*, Vol. 50, 2014, pp. 102–110.
[44] Shamsaei, E., O. Bolt, F. Basquiroto de Souza, E. Benhelal, K. Sagoe-Crentsil, and J. Sanjayan. Pathways to commercialisation for brown coal fly ash-based geopolymer concrete in Australia. *Sustainability*, Vol. 13, 2021, id. 4350.
[45] Dhasindrakrishna, K., K. Pasupathy, S. Ramakrishnan, and J. Sanjayan. Progress, current thinking and challenges in geopolymer foam concrete technology. *Cement and Concrete Composites*, Vol. 116, 2021, id. 103886.
[46] Li, T., Z. Wang, T. Zhou, Y. He, and F. Huang. Preparation and properties of magnesium phosphate cement foam concrete with H_2O_2 as foaming agent. *Construction and Building Materials*, Vol. 205, 2019, pp. 566–573.
[47] Hajimohammadi, A., T. Ngo, P. Mendis, T. Nguyen, A. Kashani, and J. S. J. van Deventer. Pore characteristics in one-part mix geopolymers foamed by H2O2: The impact of mix design. *Materials & Design*, Vol. 130, 2017, pp. 381–391.
[48] Wattanasiriwech, D., K. Yomthong, and S. Wattanasiriwech. Characterisation and properties of class C-fly ash based geopolymer foams: Effects of foaming agent content, aggregates, and surfactant. *Construction and Building Materials*, Vol. 306, 2021, id. 124847.
[49] Bai, C., T. Ni, Q. Wang, H. Li, and P. Colombo. Porosity, mechanical and insulating properties of geopolymer foams using vegetable oil as the stabilizing agent. *Journal of the European Ceramic Society*, Vol. 38, 2018, pp. 799–805.
[50] Azarhomayun, F., M. Haji, M. Kioumarsi, and M. Shekarchi. Effect of calcium stearate and aluminum powder on free and restrained drying shrinkage, crack characteristic and mechanical properties of concrete. *Cement and Concrete Composites*, Vol. 125, 2022, id. 104276.
[51] Singh, N. B. Foamed geopolymer concrete. *Materials Today: Proceedings*, Vol. 5, 2018, pp. 15243–15252.
[52] Xue, X., Y.-L. Liu, J.-G. Dai, C.-S. Poon, W.-D. Zhang, and P. Zhang. Inhibiting efflorescence formation on fly ash–based geopolymer via silane surface modification. *Cement and Concrete Composites*, Vol. 94, 2018, pp. 43–52.
[53] Duan, P., C. Yan, W. Luo, and W. Zhou. A novel surface waterproof geopolymer derived from metakaolin by hydrophobic modification. *Materials Letters*, Vol. 164, 2016, pp. 172–175.
[54] Liu, Z. H., X. Q. Pang, K. T. Wang, X. S. Lv, and X. M. Cui. Superhydrophobic coatings prepared by the in situ growth of silicone nanofilaments on alkali-activated geopolymers surface. *ACS Applied Materials & Interfaces*, Vol. 11, 2019, pp. 22809–22816.
[55] Prud'homme, E., P. Michaud, E. Joussein, C. Peyratout, A. Smith, S. Arrii-Clacens, et al. Silica fume as porogent agent in geo-materials at low temperature. *Journal of the European Ceramic Society*, Vol. 30, 2010, pp. 1641–1648.
[56] Vaou, V. and D. Panias. Thermal insulating foamy geopolymers from perlite. *Minerals Engineering*, Vol. 23, 2010, pp. 1146–1151.
[57] Le-Ping, L., C. Xue-Min, Q. Shu-Heng, Y. Jun-Li, and Z. Lin. Preparation of phosphoric acid-based porous geopolymers. *Applied Clay Science*, Vol. 50, 2010, pp. 600–603.
[58] Klemczak, B., B. Kucharczyk-Brus, A. Sulimowska, and R. Radziewicz-Winnicki. Historical evolution and current developments in building thermal insulation materials – A review. *Energies*, Vol. 17, 2024, id. 5535.
[59] Ascensao, G., M. P. Seabra, J. B. Aguiar, and J. A. Labrincha. Red mud-based geopolymers with tailored alkali diffusion properties and pH buffering ability. *Journal of Cleaner Production*, Vol. 148, 2017, pp. 23–30.
[60] Bumanis, G., L. Vitola, D. Bajare, L. Dembovska, and I. Pundiene. Impact of reactive SiO2/Al2O3 ratio in precursor on durability of porous alkali activated materials. *Ceramics International*, Vol. 43, 2017, pp. 5471–5477.
[61] Novais, R. M., G. Ascensão, N. Ferreira, M. P. Seabra, and J. A. Labrincha. Influence of water and aluminium powder content on

the properties of waste-containing geopolymer foams. *Ceramics International*, Vol. 44, 2018, pp. 6242–6249.

[62] Palmero, P., A. Formia, P. Antonaci, S. Brini, and J.-M. Tulliani. Geopolymer technology for application-oriented dense and lightened materials. *Elaboration and characterization Ceramics International*, Vol. 41, 2015, pp. 12967–12979.

[63] Perná, I. and T. Hanzlíček. The solidification of aluminum production waste in geopolymer matrix. *Journal of Cleaner Production*, Vol. 84, 2014, pp. 657–662.

[64] Echeverria, C. A., F. Pahlevani, W. Handoko, C. Jiang, C. Doolan, and V. Sahajwalla. Engineered hybrid fibre reinforced composites for sound absorption building applications. *Resources, Conservation and Recycling*, Vol. 143, 2019, pp. 1–14.

[65] Cao, L., Q. Fu, Y. Si, B. Ding, and J. Yu. Porous materials for sound absorption. *Composites Communications*, Vol. 10, 2018, pp. 25–35.

[66] Luna-Galiano, Y., C. Leiva, C. Arenas, and C. Fernández-Pereira. Fly ash based geopolymeric foams using silica fume as pore generation agent. Physical, mechanical and acoustic properties. *Journal of Non-Crystalline Solids*, Vol. 500, 2018, pp. 196–204.

[67] Stolz, J., Y. Boluk, and V. Bindiganavile. Mechanical, thermal and acoustic properties of cellular alkali activated fly ash concrete. *Cement and Concrete Composites*, Vol. 94, 2018, pp. 24–32.

[68] Papa, E., V. Medri, D. Kpogbemabou, V. Morinière, J. Laumonier, A. Vaccari, et al. Porosity and insulating properties of silica-fume based foams. *Energy and Buildings*, Vol. 131, 2016, pp. 223–232.

[69] Mitrevska, M. J., V. Mickovski, T. Samardzioska, and G. Iannace. Experimental and numerical investigation of sound absorption characteristics of rebonded polyurethane foam. *Applied Sciences*, Vol. 12, 2022, id. 12936.

[70] Hung, T.-C., J.-S. Huang, Y.-W. Wang, and K.-Y. Lin. Inorganic polymeric foam as a sound absorbing and insulating material. *Construction and Building Materials*, Vol. 50, 2014, pp. 328–334.

[71] Rafatullah, M., O. Sulaiman, R. Hashim, and A. Ahmad. Adsorption of methylene blue on low-cost adsorbents: a review. *Journal of Hazardous Materials*, Vol. 177, 2010, pp. 70–80.

[72] Li, L., S. Wang, and Z. Zhu. Geopolymeric adsorbents from fly ash for dye removal from aqueous solution. *Journal of Colloid and Interface Science*, Vol. 300, 2006, pp. 52–59.

[73] Wang, S., L. Li, and Z. H. Zhu. Solid-state conversion of fly ash to effective adsorbents for Cu removal from wastewater. *Journal of Hazardous Materials*, Vol. 139, 2007, pp. 254–259.

[74] Luukkonen, T., H. Runtti, M. Niskanen, E.-T. Tolonen, M. Sarkkinen, K. Kemppainen, et al. Simultaneous removal of Ni (II), As(III), and Sb(III) from spiked mine effluent with metakaolin and blast-furnace-slag geopolymers. *Journal of Environmental Management*, Vol. 166, 2016, pp. 579–588.

[75] Rasaki, S. A., Z. Bingxue, R. Guarecuco, T. Thomas, and Y. Minghui. Geopolymer for use in heavy metals adsorption, and advanced oxidative processes: A critical review. *Journal of Cleaner Production*, Vol. 213, 2019, pp. 42–58.

[76] Ji, Z. and Y. Pei. Bibliographic and visualized analysis of geopolymer research and its application in heavy metal immobilization: A review. *Journal of Environmental Management*, Vol. 231, 2019, pp. 256–267.

[77] Siyal, A. A., M. R. Shamsuddin, M. I. Khan, N. E. Rabat, M. Zulfiqar, Z. Man, et al. A review on geopolymers as emerging materials for the adsorption of heavy metals and dyes. *Journal of Environmental Management*, Vol. 224, 2018, pp. 327–339.

[78] Al-Zboon, K., M. S. Al-Harahsheh, and F. B. Hani. Fly ash-based geopolymer for Pb removal from aqueous solution. *Journal of Hazardous Materials*, Vol. 188, 2011, pp. 414–421.

[79] Cheng, T. W., M. L. Lee, M. S. Ko, T. H. Ueng, and S. F. Yang. The heavy metal adsorption characteristics on metakaolin-based geopolymer. *Applied Clay Science*, Vol. 56, 2012, pp. 90–96.

[80] Liu, Y., C. Yan, Z. Zhang, Y. Gong, H. Wang, and X. Qiu. A facile method for preparation of floatable and permeable fly ash-based geopolymer block. *Materials Letters*, Vol. 185, 2016, pp. 370–373.

[81] Ge, Y., X. Cui, Y. Kong, Z. Li, Y. He, and Q. Zhou. Porous geopolymeric spheres for removal of Cu (II) from aqueous solution: synthesis and evaluation. *Journal of Hazardous Materials*, Vol. 283, 2015, pp. 244–251.

[82] Khalid, H. R., N. K. Lee, S. M. Park, N. Abbas, and H.-K. Lee. Synthesis of geopolymer-supported zeolites via robust one-step method and their adsorption potential. *Journal of Hazardous Materials*, Vol. 353, 2018, pp. 522–533.

[83] Salehi, A. and E. Najafi Kani. Green cylindrical mesoporous adsorbent based on alkali-activated phosphorous slag: synthesis, dye removal, and RSM modeling. *Adsorption*, Vol. 24, 2018, pp. 647–666.

[84] Bai, C., G. Franchin, H. Elsayed, A. Zaggia, L. Conte, H. Li, et al. High-porosity geopolymer foams with tailored porosity for thermal insulation and wastewater treatment. *Journal of Materials Research*, Vol. 32, 2017, pp. 3251–3259.

[85] Tang, Q., Y.-y Ge, K.-t Wang, Y. He, and X.-m Cui. Preparation and characterization of porous metakaolin-based inorganic polymer spheres as an adsorbent. *Materials & Design*, Vol. 88, 2015, pp. 1244–1249.

[86] Sazama, P., O. Bortnovsky, J. Dědeček, Z. Tvarůžková, and Z. Sobalík. Geopolymer based catalysts – New group of catalytic materials. *Catalysis Today*, Vol. 164, 2011, pp. 92–99.

[87] Luukkonen, T., A. Heponiemi, H. Runtti, J. Pesonen, J. Yliniemi, and U. Lassi. Application of alkali-activated materials for water and wastewater treatment: a review. *Reviews in Environmental Science and Bio/Technology*, Vol. 18, 2019, pp. 271–297.

[88] Falah, M., K. J. D. MacKenzie, R. Knibbe, S. J. Page, and J. V. Hanna. New composites of nanoparticle Cu (I) oxide and titania in a novel inorganic polymer (geopolymer) matrix for destruction of dyes and hazardous organic pollutants. *Journal of Hazardous Materials*, Vol. 318, 2016, pp. 772–782.

[89] Alzeer, M. I. M. and K. J. D. MacKenzie. Synthesis and Catalytic Properties of New Sustainable Aluminosilicate Heterogeneous Catalysts Derived from Fly Ash. *ACS Sustainable Chemistry & Engineering*, Vol. 6, 2018, pp. 5273–5282.

[90] Alzeer, M. I. M., K. J. D. MacKenzie, and R. A. Keyzers. Porous aluminosilicate inorganic polymers (geopolymers): a new class of environmentally benign heterogeneous solid acid catalysts. *Applied Catalysis A: General*, Vol. 524, 2016, pp. 173–181.

[91] Zhang, Y. and L. Liu. Fly ash-based geopolymer as a novel photocatalyst for degradation of dye from wastewater. *Particuology*, Vol. 11, 2013, pp. 353–358.

[92] Zhang, Y. J., P. Y. He, M. Y. Yang, and L. Kang. A new graphene bottom ash geopolymeric composite for photocatalytic H2 production and degradation of dyeing wastewater. *International Journal of Hydrogen Energy*, Vol. 42, 2017, pp. 20589–20598.

[93] Chen, L., K. Zheng, and Y. Liu. Geopolymer-supported photocatalytic TiO_2 film: Preparation and characterization. *Construction and Building Materials*, Vol. 151, 2017, pp. 63–70.

[94] Gasca-Tirado, J. R., A. Manzano-Ramírez, C. Villaseñor-Mora, M. S. Muñiz-Villarreal, A. A. Zaldivar-Cadena, J. C. Rubio-Ávalos, et al. Incorporation of photoactive TiO_2 in an aluminosilicate inorganic polymer by ion exchange. *Microporous and Mesoporous Materials*, Vol. 153, 2012, pp. 282–287.
[95] Candamano, S., P. Frontera, A. Macario, F. Crea, J. B. Nagy, and P. L. Antonucci. Preparation and characterization of active Ni-supported catalyst for syngas production. *Chemical Engineering Research and Design*, Vol. 96, 2015, pp. 78–86.
[96] Satmon, J., Z. Hu, and M. Q. Zhu. Synthesis of novel geopolymer supported nano bimetallic catalysts and its application for isopropanol dehydrogenation. *Key Engineering Materials*, Vol. 777, 2018, pp. 190–195.
[97] Asim, N., M. Alghoul, M. Mohammad, M. H. Amin, M. Akhtaruzzaman, N. Amin, et al. Emerging sustainable solutions for depollution: Geopolymers. *Construction and Building Materials*, Vol. 199, 2019, pp. 540–548.
[98] Innocentini, M. D. M., R. F. Botti, P. M. Bassi, C. F. P. R. Paschoalato, D. L. Flumignan, G. Franchin, et al. Lattice-shaped geopolymer catalyst for biodiesel synthesis fabricated by additive manufacturing. *Ceramics International*, Vol. 45, 2019, pp. 1443–1446.
[99] Franchin, G., P. Scanferla, L. Zeffiro, H. Elsayed, A. Baliello, G. Giacomello, et al. Direct ink writing of geopolymeric inks. *Journal of the European Ceramic Society*, Vol. 37, 2017, pp. 2481–2489.
[100] Siyal, A. A., M. R. Shamsuddin, N. E. Rabat, M. Zulfiqar, Z. Man, and A. Low. Fly ash based geopolymer for the adsorption of anionic surfactant from aqueous solution. *Journal of Cleaner Production*, Vol. 229, 2019, pp. 232–243.
[101] Kutuniva, J., J. Mäkinen, T. Kauppila, A. Karppinen, S. Hellsten, T. Luukkonen, et al. Geopolymers as active capping materials for in situ remediation of metal(loid)-contaminated lake sediments. *Journal of Environmental Chemical Engineering*, Vol. 7, 2019, id. 102852.
[102] Rajini, B., A. V. Rao, and C. Sashidhar. Cost analysis of geopolymer concrete over conventional concrete. *International Journal of Civil Engineering and Technology*, Vol. 11, 2020, pp. 23–30.
[103] Abdellatief, M., M. A. Elrahman, H. Alanazi, A. A. Abadel, and A. Tahwia. A state-of-the-art review on geopolymer foam concrete with solid waste materials: components, characteristics, and microstructure. *Innovative Infrastructure Solutions*, Vol. 8, 2023, id. 230.
[104] Sotelo-Piña, C., E. N. Aguilera-González, and A. Martínez-Luévanos. *Geopolymers: Past, present, and future of low carbon footprint eco-materials Handbook of Ecomaterials*, Vol. 4, 2019, pp. 2765–2785.
[105] Firdous, R., M. Nikravan, R. Mancke, M. Vöge, and D. Stephan. Assessment of environmental, economic and technical performance of geopolymer concrete: a case study. *Journal of Materials Science*, Vol. 57, 2022, pp. 18711–18725.
[106] Ricciotti, L., A. Occhicone, A. Petrillo, C. Ferone, R. Cioffi, and G. Roviello. Geopolymer-based hybrid foams: Lightweight materials from a sustainable production process. *Journal of Cleaner Production*, Vol. 250, 2020, id. 119588.
[107] Yang, H., L.Liu, W.Yang, H.Liu, W.Ahmad, A.Ahmad, et al. A comprehensive overview of geopolymer composites: A bibliometric analysis and literature review. *Case Studies in Construction Materials*, Vol. 16, 2022, id. e00830.