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Review

Scientometric Analysis of Global Research on the Utilization of Geopolymer Composites in Construction Applications

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Abstract: This study conducts a scientometric review on the use of geopolymer mortar and composites in different construction applications. It aims to analyze the findings of past research and reveal the research constituents, development trends, and knowledge gaps. The Scopus database was employed to retrieve the relevant publications, while Bibliometrix was used to conduct the statistical analyses. Results revealed a steady and gradual increase in the number of publications after 2013, as the annual growth rate increased from 23.9% to 45.2% between the timeframes 2003–2013 and 2014–2022, respectively. The analysis highlighted that many authors collaborated on different construction applications of geopolymers regardless of geographic location. Meanwhile, *Construction and Building Materials*, China, and Universiti Malaysia Perlis were found to be the predominant journal, country, and institution, respectively. The scientometric analysis showed that the most frequently investigated applications for geopolymer mortars and composites were fire resistance, corrosion protection, and repair. Research gaps highlighted that other applications are not as well investigated despite the promising performance of the geopolymer composites, including 3D printing, heavy metals absorption, environmental protection, and underwater applications. Future research is required to assess the use of other alumina and silica-rich binders in geopolymers while also exploring their lifecycle assessment and economic impact.

Keywords: scientometric analysis; geopolymer; mortar; composites; construction applications

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1. Introduction

Conventional cement-based composites, such as concrete and mortar, are ranked as the most used construction materials in the world [1,2]. Concrete and mortar are mainly produced with ordinary Portland cement (OPC), coarse and fine aggregates, water, and additives. The widespread use of OPC by the construction industry is attributed to its impressive performance, affordability, availability, standardization, and compatibility with different types of materials and admixtures. Due to the increase in human population and the exponential increase in construction work, it is predicted that the OPC demand will reach 3.7–4.4 billion tons in 2050 [3]. In addition to the need for a large number of natural resources for the manufacture of OPC, it is estimated that this process emits around 6 to 9% of the total greenhouse gas emissions globally, which mainly result from the combustion of fossil fuels for the kiln, the heating limestone, and the consumption of electrical power [4]. Accordingly, the production of 1 ton of OPC emits 1 ton of CO_2 and consumes 1.5 tons of natural resources [5]. In addition, OPC is ranked as the third most energy-intensive material, after steel and aluminum, with a percentage of global energy consumption of 7% [5–7]. These environmental concerns created a need to find alternative materials to partially or fully replace it.

Geopolymers and alkali-activated materials are cement-free composites formulated by activating alumino-silicate materials, such as fly ash, metakaolin, and silica fume, and calcium-rich materials, such as blast furnace slag or ladle slag, respectively, with a sodium, potassium, or carbonate hydroxide-based alkaline solution. In 1978, Prof. Joseph Davidovits introduced geopolymer materials in construction [8]. During the geopolymerization reaction, the dissolution of silicate and aluminate compounds creates oligomers that condensate to form an amorphous and partially crystalline structure of polymers [9,10]. In the last two decades, the performance of geopolymers has been extensively studied [11–16]. Since then, these cement-free materials have shown superior mechanical performance and a higher ability to maintain their properties under harsh environments to cement-based materials, such as high temperatures, salt and acid attacks [17–21]. Furthermore, the use of geopolymer mortar in various construction applications has been examined, such as corrosion-resistant materials [22–24], fire protection materials [17,18,25], repairing, strengthening, and retrofitting old structures [26–32], grouting [33,34], bonding [27,35], coating [22,24], masonry materials [36], and for underwater placing [15,37].

The number of scientific publications has been exponentially increasing. As such, it is becoming nearly unfeasible to cover all studies within a specific topic. Nowadays, scholars are using different approaches for conducting quantitative and qualitative literature reviews. The scientometric study has been introduced as an essential tool that gives an objective, reliable, transparent, and systematic review that covers scientific activities and publications describing a specific topic [38]. Based on the data extracted from publications (authors, total publications and citations, affiliations, countries, etc.), a scientometric analysis can display a structure analysis for a large number of data, show trends of paper publications and keywords over time, detect the most productive authors, countries, affiliations, and journals, infer gaps or shifts within a specific topic, and analyze the connections of the extracted data plotted in the form of mapping and clustering networks [39–41]. The scientometric analysis was described by Boquera et al. [42] as "a way to elucidate the past, present, and future within the different areas of knowledge, reporting the main research interest and future trends". The deep analysis of keywords used by scholars to describe and summarize their research content is crucial to describe the current trending topics and their evolutions and to highlight gaps that can be covered in future work [39,41,43].

Lately, scientometric reviews have been used in different areas, such as cryptocurrency and stock markets [44], concrete as a thermal energy storage material [42], self-healing concrete [41], construction demolition waste management [45], biological water treatment [46], business and management [47], and sports [48], among others. Similarly, geopolymer and alkali-activated composites have been introduced in scientometric studies in recent years. Yang et al. [2] have found that the acceptance of geopolymer concrete by the industry is not achieved yet due to the lack of long-term performance testing. In addition, future work was suggested to examine the microstructure of the geopolymer matrix. Another study performed by Tian et al. [49] on fly ash-based geopolymers highlighted the high contribution and impact of China and Professor Davidovits as a prolific reference in the investigation and the development of fly ash-based geopolymer properties. According to Elmesalami and Celik [50], more studies should be carried out to evaluate the effect of steel polyethylene, glass basalt polypropylene, and natural microfibers on the properties of the engineered geopolymer composites. In addition, Ji and Pei [51] highlighted the efficiency of geopolymer composites in immobilizing heavy metals. Based on the literature, numerous articles have been published to investigate the use of geopolymers in different applications. Hence, there is a pressing need to determine the research trends and gaps for the use of geopolymers and alkali-activated materials in various construction applications.

Accordingly, this study is a scientometric review that provides a perception of the published scientific studies on the use of geopolymer mortars and composites in construction applications. The Scopus database was used to extract the relevant literature between 1996 and 2023 to identify the key contributors, research trends, evolution of topics, and knowledge gaps in the designated research area. This paper offers valuable information on the current research situation and future research directions on the use of geopolymers in various applications. It also provides decision-makers with the necessary information to make effective decisions on the subsequent development of this research field. This study was mainly prepared to achieve the following objectives:

1. Identify trends when analyzing studies published over the last 27 years on the use of geopolymer composites in different construction applications.
2. Highlight the recent developments in the field of using geopolymer composites in construction applications.
3. Determine trends and knowledge gaps and suggest future research ideas on the use of geopolymer composites in construction applications.

2. Background

Geopolymer mortar and composites have the potential to be used in different construction applications, owing to their superior mechanical, durability, and thermal resistance properties [13,52–54]. Additionally, many researchers reported the impressive ability of geopolymers to protect steel reinforcement against corrosion. Zhang et al. [22,23] reported excellent corrosion-resistant properties of geopolymer mortar made of slag and metakaolin with smaller open pores on average than those in OPC paste. Aguirre-Guerrero et al. [24] observed a decrease in the chloride diffusion, an increase in the electrical resistivity, and an enhancement in the corrosion protection of concrete samples coated with a metakaolin and fly ash-based geopolymer material compared to their non-coated counterparts. This decrease in permeability was due to the reduction in the porosity of the geopolymer caused by the dense structure of the geopolymerization reaction products, namely calcium aluminum silicate hydrate (C-A-S-H) and sodium aluminum silicate hydrate (N-A-S-H) gels. Similarly, under sulfate attack, a clay-fly ash geopolymer mortar possessed a superior ability to retain its strength, microstructure, and pH than a clay-cement-based mortar [55].

The structural stability of 3D-printed mortars depends on the bond strength between the layers. Panda et al. [56,57] studied the tensile bond mechanism and interfacial bond strength of a 3D-printed geopolymer mortar. The results showed that fly ash-geopolymer mortar could be used as a 3D printing material and achieve good bonding strength properties by considering printing parameters, such as time gap, printing speed, nozzle speed, and loading directions. Meanwhile, Husein et al. [13] concluded that geopolymer mortar possesses better repair characteristics than its cement-based counterpart, while high-calcium geopolymer mortars were superior to high-silicate equivalents in repair applications. Zhang et al. [22] linked the good bonding behavior between a geopolymer mortar and concrete substrate to the coexistence of calcium silicate hydrate gels in the cement and geopolymer matrix under strongly alkaline conditions. In another study, Phoongernkham et al. [58] examined the use of geopolymer mortars containing cement as a concrete repair material. Test results indicated that the geopolymer mortar with a high sodium hydroxide concentration and cement performed adequately under the shear bond prism test and bending test of the notched concrete beam. In addition, the interface zones of the concrete and the geopolymer mortar containing cement were homogeneous and dense within the contact zone due to the increase in reaction products. Accordingly, geopolymer mortars are recommended for 3D printing or repair due to the high bond stresses created at the mortar–mortar and mortar–concrete interfaces.

The use of geopolymer composites in retrofitting and strengthening old concrete structures, such as beams, columns, bricks, and joints, has also been studied. A review by Yan et al. [12] highlighted that the structural performance of the concrete, masonry, and timber structures reinforced with geopolymer composites was enhanced significantly in terms of ductility, toughness, deformation, and load-carrying capacity. Similarly, regardless of the type of fibers, fiber-reinforced metakaolin-slag geopolymer composites achieved excellent bond strength with soft mud clay bricks [30]. Menna et al. [29] have reported the effectiveness of the steel-reinforced geopolymer matrix in strengthening and increasing the ultimate bending moment capacity of a concrete beam. Meanwhile, Vasconcelos [59] produced a metakaolin geopolymer mortar suitable for use in concrete retrofitting applications. Therefore, it is obvious that the good bonding, mechanical, and durability characteristics of the geopolymer mortar make it a suitable replacement for conventional cementitious mortar for repair, strengthening, and retrofitting applications.

Fire resistance is another characteristic of geopolymers or alkali-activated materials that promotes their use in various construction applications. Lyon et al. [18] examined the fire response of a geopolymer matrix composite reinforced with carbon fiber. The results revealed that carbon-fiber-reinforced geopolymer composites did not ignite, burn, or release smoke. Furthermore, after a prolonged simulated fire exposure, the geopolymer composite maintained 67% of its original flexural strength. In another study [60], a fly ash-based geopolymer mortar was able to preserve its strength and weight under high-temperature exposure of 800 °C, owing to the formation of N-A-S-H gel during the activation of fly ash by an alkaline solution. Hager et al. [61] assessed the compressive strength variation of a fly ash-slag blended geopolymer mortar with different slag ratio replacements of 0, 10, 30, and 50% when exposed to high temperatures ranging from 200 to 1000 °C with a 200 °C increment rate. The findings showed that the addition of slag decreased the thermal resistance of mortar, as the compressive strength of unblended samples increased by 30 and 40% at 200 and 400 °C, respectively. Such a finding is due to the development of the geopolymerization reaction of unreacted fly ash. However, under the same conditions, the incorporation of slag resulted in a corresponding strength reduction of 5 and 25% compared to that of the unheated sample. The type of binder also played a vital role in improving the thermal resistance of geopolymer mortars. In fact, studies highlighted that precursors rich in CaO, such as slag, had a lower ability to maintain their characteristics after fire and heat exposure than others, such as fly ash [18,25,61]. Accordingly, geopolymer mortars produced with low CaO binders have higher fire resistance characteristics compared to their cementitious or high CaO counterparts. In addition, the compressive strength of a cellular geopolymer produced with class F fly ash and a foam agent used as a thermal insulation material was increased up to 250% after a thermal exposure of 600 °C [62]. In another study on the microstructure change of fly ash-based geopolymer material under high temperatures, it was noted that the alkaline-activated matrix became denser and the strength increased owing to the high solubility of aluminosilicate components that result in the synthesizing of vitreous phases and the formation of new nanosized crystals [63].

Furthermore, geopolymer composites possess an impressive ability to immobilize and treat heavy metals and radioactive wastes. Komnitas and Zaharaki [11] reported that geopolymers could transform semi-solid waste into an adhesive material and immobilize hazardous waste containing arsenic, lead, and mercury by storing them within its three-dimensional matrix. In other research work, Khater and Ghareib [64] produced a slag-based geopolymer mortar to immobilize heavy metals, such as barium sulfate, lead slag, lead phosphate, and electric arc furnace slag. Furthermore, the same product was efficiently used as a shielding material for gamma rays [65]. Paving blocks prepared with blends of fly ash and 40 to 80% of hazardous waste were characterized as eco-friendly materials due to the negligible leaching of toxic and heavy metals, such as lead, arsenic, zinc, chromium, and cadmium [66].

As a conclusion, the impressive mechanical and durability performances of geopolymer composites provide evidence of their high potential to be used in different construction applications. Based on previously discussed studies, they possess a high ability to retain their strength under harsh environments, such as fire, acids, and salt, while being used as a protective layer for reinforcement against corrosion. In addition, the high bond strength between geopolymer materials and previously cast cement-based elements or with freshly casted geopolymer materials results in the production of a cement-free material suitable to be used in different repair, retrofitting, and 3D printing applications. Nevertheless, with a large number of scientific studies on the valorization of geopolymer composites in different construction applications, a scientometric analysis is needed to analyze and find the research trends and gaps.

3. Methodology

The main function of scientometric analysis is to identify the influence and significance of a set of articles in a defined field of research. Nevertheless, it is vital to properly search for and select the papers to be studied. For this purpose, systematic search and selection criteria were first outlined with a focus on the words and phrases that appear in the title, abstract, and authors' keywords. The Scopus database was utilized to determine the publications that assessed the different applications involving geopolymer mortar and composites. It is considered one of the essential databases that includes most of the scientific and engineering manuscripts and has a broad scientometric scope [2]. Accordingly, a well-defined search query was applied using different keywords for the topic under study. It was divided into three parts to obtain accurate results relevant to the analyzed topic. The first part included the synonyms used by authors describing a geopolymer material. The second part highlighted the type of geopolymer material under study (i.e., mortar), while the word 'composite' was added to include mortar produced with fibers or additives. Finally, the third part represented the geopolymer mortar applications under investigation. The search query on Scopus was tailored to include all possible combinations of the material under assessment and its subsequent construction applications. As such, it was as follows: (TITLE-ABS-KEY ("Geopolymer" OR "Alkali-activated") AND TITLE-ABS-KEY ("Mortar" OR "Composite") AND TITLE-ABS-KEY ("Wastewater" OR " bond" OR "roof" OR "retrofit" OR "masonry" OR "Waste water" OR "Retrofitting" OR "Rehabilitation" OR "Bonding" OR "Roofing" OR "Adhesive" OR "Strengthening" OR "Plastering" OR "Repair" OR "Fire" OR "Roofing" OR "Corrosion" OR "Coating" OR "Adhesion" OR "Screed" OR "Protection" OR "Marine" OR "Underwater")).

The search yielded 1440 records (i.e., publications). While the vast majority of the records were in English (1392 records), 40 were in Chinese, and the remaining records were in other languages. Nevertheless, only the records in English were selected. This was to ensure that the grouping and sorting of different parameters under study were possible. Following the preliminary selection of records, those having undefined authors were excluded. Such a measure omitted the records associated with conference titles, where the search engine identified the record as relevant based on matches included in the conference abstract. The resulting 1254 documents were screened to assess their significance to the scope of research of this paper. In fact, the abstracts of these documents were examined for the use of materials other than geopolymer mortar (concrete, paste, etc.), the absence of the type of application, and duplication. Such documents were excluded from the analysis. As a result, the number of documents selected for this study was 789. The details of the process are illustrated in Figure 1.

The selected documents, extracted in BibTex format, required a suitable software tool for analysis. Several software packages are available for this purpose, such as "CiteSpace", "VOSviewer", "CitNetExplorer", and "Bibliometrix". Among these software tools, Bibliometrix R-package was selected for its ability to achieve the objective intended by the paper, i.e., simultaneously investigating and mapping bibliographic data related to geopolymer mortar construction applications. This package has a large range of flexibility and customizability, is an open-source, free bibliometric tool, and supports importing bibliographic data from Scopus. Developed by Massimo Aria and Corrado Cuccurullo, Bibliometrix presents itself as an "open-source tool for quantitative research in scientometrics and bibliometrics that includes all the main bibliometric methods of analysis" [67]. While it is written in R language by developers, it contains a built-in application, which allows users with limited to no coding experience to analyze, plot, and extract data easily. The workflow recommended by the developers [68], detailed in Figure 2, consists of 3 main stages: data collection, data analysis, and data visualization.

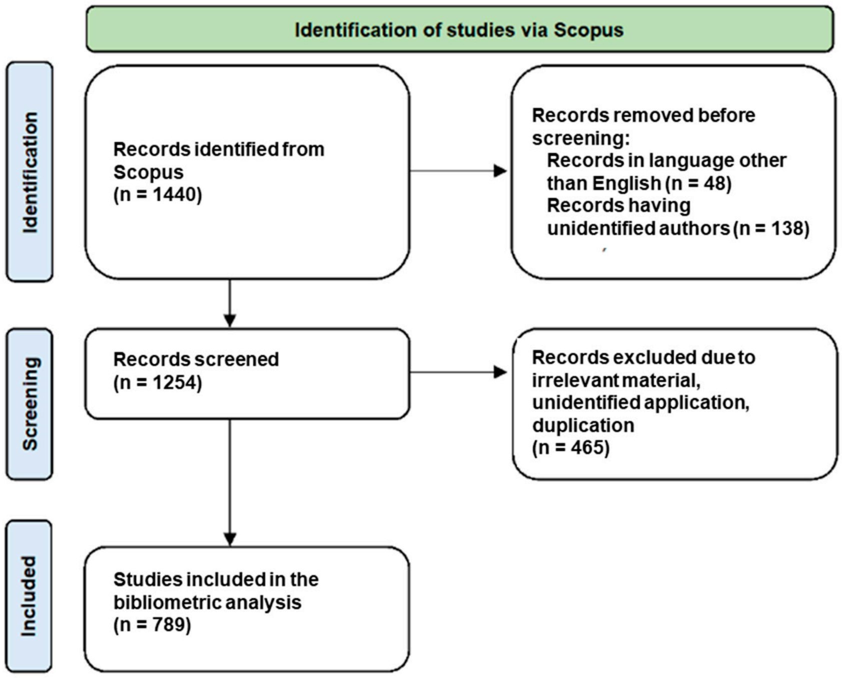


Figure 1. Search and selection of documents.

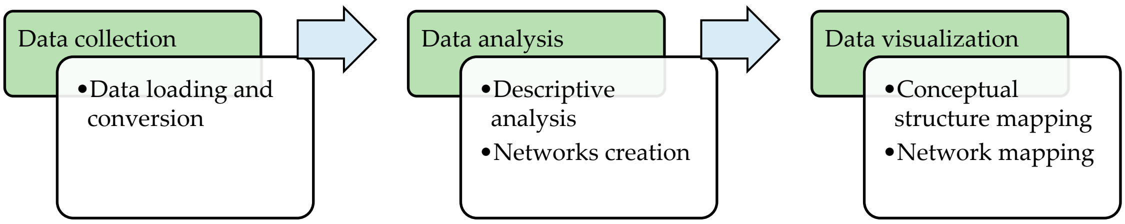


Figure 2. Workflow in Bibliometrix, adapted from [68].

The aforementioned workflow was followed in this study. The results were reported in the following arrangement: (1) general statistics, (2) keywords, (3) sources, (4) countries and institutions, (5) authors, and (6) publications. While the first included a descriptive analysis of the bibliographic data setting, the latter sections present an in-depth analysis and visualization of the different elements under study. The last section discussed the main findings and identified the research gaps.

In-depth keyword analysis was carried out by identifying keywords and their frequency to determine the timeline for trending, emerging, and missing keywords related to the different geopolymer applications. In addition, Biliometrix 3.1.4 software was employed to generate a cluster map based on the total number of authors' keywords. This tool can also group similar publications into research themes [41]. Following other works [69], the clusters were verified by identifying the major research findings. Furthermore, word clouds were generated across the duration under investigation to observe research trends and to identify research gaps.

Sources were ranked based on the total publications (TP), local citation (LC), h-index, and impact factor (IF). For countries and continents, the percentage of published papers, total citations (TC), and average article citations (AAC) were used as indices for ranking. In addition, a collaboration map between all countries was generated. Institutions were ranked based on TP. The ranking of authors was based on TP, total publications per year (TP/year), LC, AAC, and h-index. TP represented the contribution of authors, journals, countries, or institutions to the area of research, whereas the citation indices, i.e., TC, LC, and AAC, indicated the quality and importance of the studies published [69]. Meanwhile, TP/year was found to be a more reliable parameter to evaluate the consistency of contributions to the research area.

The top 10 publications were identified based on TC, TC/year, and LC. A co-citation cluster between different authors was carried out to identify the most relevant authors serving in the development and improvement of the performance of geopolymer composites in different construction applications. This analysis facilitates the recognition of the essential research studies, interconnections between authors, and fundamental research trends.

4. Scientometric Analysis

4.1. General Stastistics

General information about the documents used in this study is presented in Table 1. The scope of the study ranges between 1996 and 2023 and covers 789 documents from 273 sources. The average number of citations per document, standing at 18.34, is an overt indicator of the significance of the research field. In addition, 31,765 references were cited in these documents, demonstrating not only a rich literature relevant to the topic but also a possibility of co-citations within interdisciplinary fields. The collaboration index is measured by dividing the total number of authors of multi-authored documents by the number of multi-authored documents. With a value of 2.87, it seems to be moderate and resembles values reported in past studies [41,70–72].

Table 1. General information on the bibliographic data frame.

General Information	
Timespan	1996–2023
Sources (Journals, Books, etc.)	273
Documents	789
Average years from publication	3.97
Average citations per document	18.34
Average citations per year per doc	3.47
References	31765
Authors	
Authors	2072
Author appearances	3050
Authors of multi-authored documents	2042
Authors collaboration	
Single-authored documents	31
Documents per author	0.348
Authors per document	2.87
Co-authors per documents	4.22
Collaboration index	2.96

A classification of the collected documents by type is illustrated in Figure 3. The vast majority of the documents (558) are journal articles, followed by conference papers (174), review articles (38), book chapters (15), and books (4). The large number of review articles suggests that this research field has been extensively investigated to the point where sufficient data are available to be accrued into multiple literature review articles.

Moreover, the development of the number of publications with time is illustrated in Figure 4. It is obvious that an increasing number of papers have been published each year, particularly since 2015. The number of publications reached 779 in 2022, with an expected growth in numbers in 2023. To better understand the pattern pertaining to the number of publications per year, the timespan was divided into three timeframes, where the annual growth rate (AGR) of each was computed. For timeframes 1996–2002, 2003–2013, and 2014–2022, the AGR was 0, 23.9, and 45.2%, respectively. The timeframes were divided based on a the rate of increase in the cumulative number of publications. The latest AGR is a clear indicator of the rapid emergence of research in this field, which is anticipated to continue and expand in the coming years. This is owed to the impressive properties of geopolymer mortars and composites, making them suitable for various construction applications. A similar pattern was observed by Yang et al. [2], which shows the growth of research work related to "geopolymer concrete". Such an increase in the AGR highlights the ever-increasing need to produce alternative eco-friendly materials to cement-based counterparts for use in the construction industry.

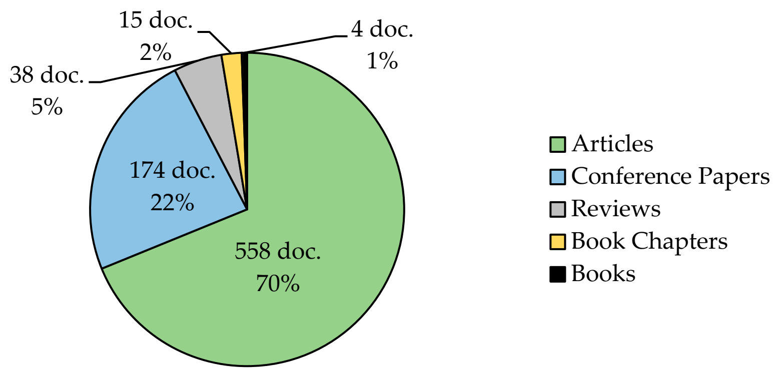


Figure 3. Classification of documents by type.

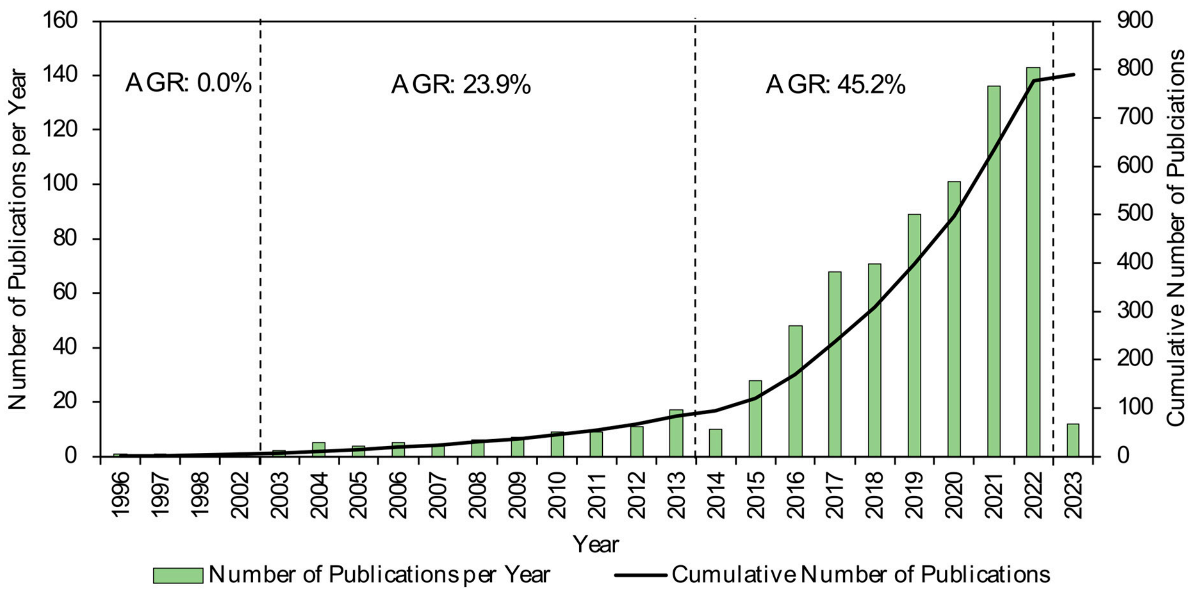


Figure 4. Number of publications with time.

4.2. Research Trends

4.2.1. Keyword Analysis

Figure 5 illustrates the evolution of investigating different types of applications of geopolymer mortars and composites between 2000 and 2022. Fire protection, corrosion resistance, coating, repair, and masonry were the top five applications with a cumulative number of publications of 79, 51, 45, 37, and 37 in 2022, respectively. Generally, the trend of this graph is similar to that of the total publications (Figure 4), where most applications have been investigated since 2013, except fire protection and corrosion resistance, which have been studies since 2003 and 2004, respectively.

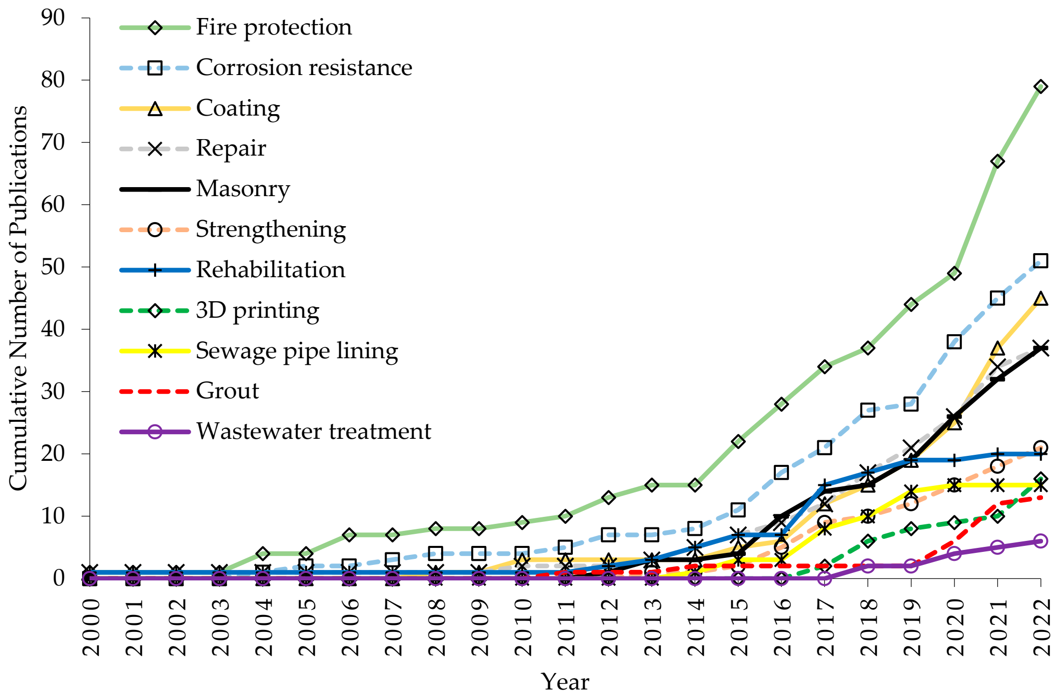


Figure 5. Number of publications related to the top applications over time.

The early investigation of using geopolymer composites for fire protection can be related to their impressive ability to maintain their weight and strength under high-temperature exposure [25]. In addition, the paper published in 1997 by Lyon et al. [18] was used as a benchmark to advance the comprehension of geopolymers prepared with different precursors under high-temperature exposure. Similarly, the ability of geopolymer mortars and composites to protect steel reinforcement against corrosion has been assessed extensively. With a decrease in the matrix permeability caused by the formation of the dense N-A-S-H and C-A-S-H gels, lower amounts of chloride or carbon dioxide accessed the steel reinforcement [23,73].

Furthermore, over the last few years, several articles investigated the use of geopolymer composites in repair, strengthening, and rehabilitation applications, owing to their excellent bonding behavior [5,6,23,54,56]. Meanwhile, it was difficult to differentiate the use of geopolymers in masonry blocks and plastering applications. Thus, the term masonry in Figure 5 refers to both applications. Similar to repair, strengthening, and rehabilitation, geopolymer materials were only assessed in masonry production from 2013. Using geopolymer mortars is particularly beneficial for masonry applications to accelerate construction operations and eliminate water curing that is generally required for the strength gain of cement-based masonry materials [36,74,75].

New applications for geopolymer mortars have been explored in the last 5 years, including sewage lining, wastewater treatment, 3D printing, and grouting. The performance of geopolymer mortars in a sewage environment has been assessed in past studies [76–79]. A fly ash geopolymer mortar could be a sustainable alternative for a sulfate-resistant Portland cement-based mortar, owing to its superior ability to maintain its mass and greater depth of neutralization under a sewage environment [76,77]. In other work, Bogdan et al. suggested a geopolymer material for wastewater treatment applications. Results showed that geopolymer mortars limited the growth of microorganisms on the surfaces of concrete samples to a better extent than their plain Portland cement and calcium aluminate cement-based counterparts [80]. Lately, there has been an increasing interest in developing the thixotropic, mechanical, and bonding properties of fly ash and slag geopolymer mortars reinforced with different types of reinforcement for 3D printing applications [56,57,81–83]. Research findings noted that 3D printing parameters and material strength development mostly affected the interlayer bond strength [56,57]. Meanwhile, the addition of slag to a fly ash-based geopolymer 3D printed mortar required a faster printing time to counter the fast setting of slag-based geopolymers and to ensure proper bonding between the 3D-printed layers [81]. Furthermore, reinforcing 3D geopolymer composites with steel cables achieved 290% higher flexural strength than their plain counterparts [83]. For the production of geopolymer mortar as a grouting material, Gullu et al. [84] produced a fly ash-based geopolymer mortar with feasible rheological properties compared to a native cement grouting material.

Research gaps could be highlighted through the analysis of the trend of applications identified in Figure 5. Geopolymer mortars and composites have displayed impressive performances when used as fire and corrosion protection materials, coating and masonry materials, or for repair, strengthening, and rehabilitation applications. Yet, their adoption in such construction applications requires further assessment in terms of serviceability. Thus, future research entails focusing on examining the lifecycle and economic impact of geopolymer mortar and composites in such applications. Other construction applications for geopolymer mortars are yet to receive adequate attention, such as tunnel and pipe lining or underwater placing. Also, despite their aptitude to adsorb and immobilize heavy metals, as highlighted in [11], limited studies have been carried out in this research field. Similarly, more work is needed in the recently explored applications, including 3D printing, wastewater treatment, sewage and tunnel lining, and as grouting materials. Such a demand for more research is to provide critical scientific evidence that could promote the adoption of geopolymer composites by relevant industries.

4.2.2. Keyword Co-Occurrence

Bibliometrix was used to produce the authors' keyword co-occurrence network. A threshold value of fifty nodes and minimum edges equal to two were set to include the keywords most repeatedly used. Figure 6 shows the cluster map of the authors' keywords. The box size represents the keyword occurrence by the authors in their research works, while the thickness of the connecting lines signifies the intensity of the interconnection between the nodes. The word "geopolymer" is noted to be the most commonly used keyword. In turn, "fly ash", "metakaolin", "silica fume", and "slag" are the primary aluminosilicate precursors employed in producing geopolymer composites. In addition, keywords such as "elevated temperature", "high temperature", "fire resistance", and "thermal conductivity" show that geopolymer composites were mostly assessed for fire and high-temperature resistance applications.

Furthermore, the co-occurrence network shown in Figure 6 was divided into four clusters. The red cluster is related to the main precursors used in the production of geopolymer composites while focusing on the main properties that have been tested. The green cluster represents the correlation between durability testing, especially thermal and high-temperature resistance, and each of mechanical properties and microstructure analysis. While the purple cluster highlights the applications related to bonding, strengthening, and protection of old and damaged structural elements, and the blue cluster is related to corrosion. The red cluster was represented by one primary keyword, "geopolymer". Conversely, the other clusters were characterized by a group of keywords. The red cluster mainly highlighted the precursors used in the production of geopolymer mortars and the main properties that have been evaluated, such as compressive strength, water absorption, and flexural strength. However, terms related to the fresh mortar properties, such as flow, setting time, plastic viscosity, and yield stress, were not found in the network. This indicates that more work should be carried out to assess the fresh properties of geopolymer materials. Moreover, for the green cluster, the main keywords were microstructure, durability, and mechanical properties, providing evidence to the need to conduct microstructure analysis when mechanical and durability testing were performed in the research work. Other keywords have also been found to be interconnected. For instance, the keyword porosity was connected to mechanical properties. This may be due to the direct relationship between the porosity, i.e., volume of pores in the mortar matrix, and the mechanical properties of geopolymer composites [26,85]. In the meantime, the purple cluster highlighted the keywords geopolymers, metakaolin, masonry, cultural heritage, coating, and strengthening. This cluster seemed to be focused on the use of geopolymers in specific construction applications. Lastly, the blue cluster was characterized by different keywords, including corrosion, chloride, and carbonation. Therefore, it is inferred that the blue cluster is primarily associated with the use of geopolymer composites as a protective layer for steel against corrosion. In fact, chloride ingress and carbonation are the two main reasons for corrosion initiation and rust creation [24,73,86,87].

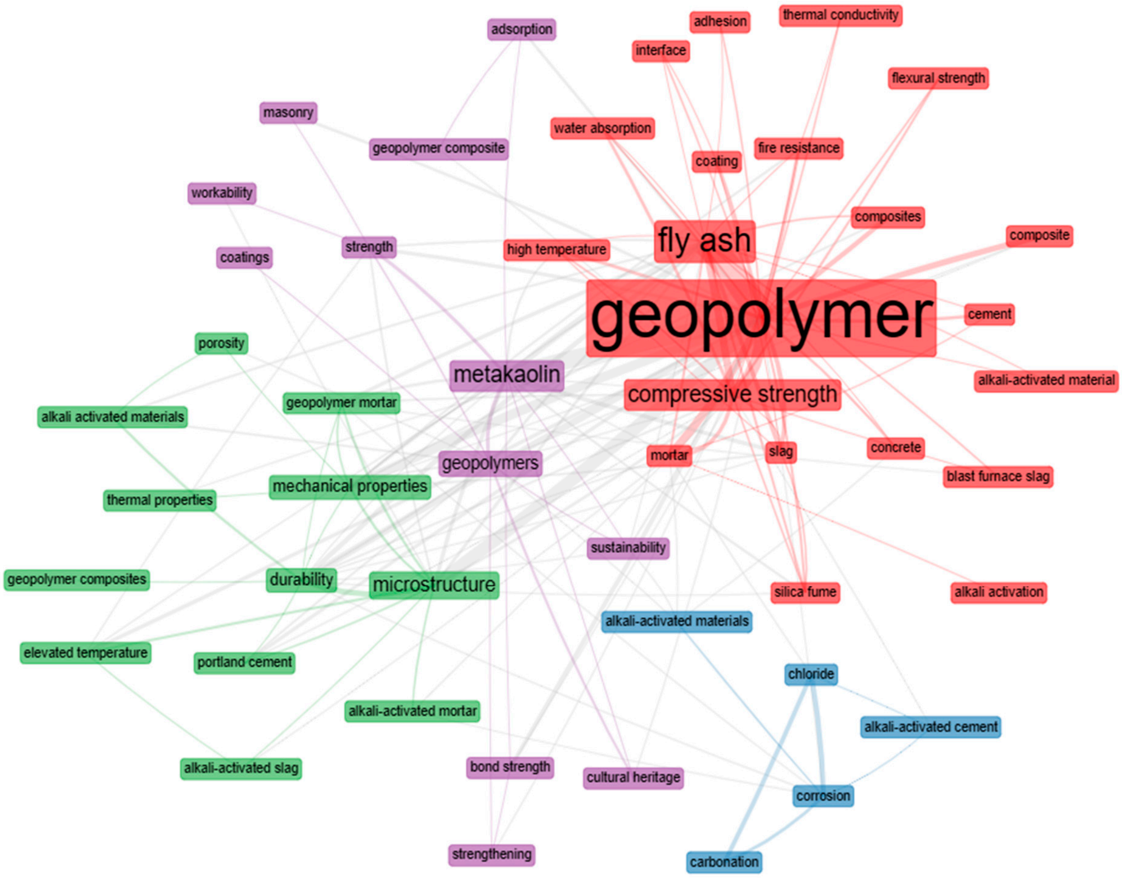
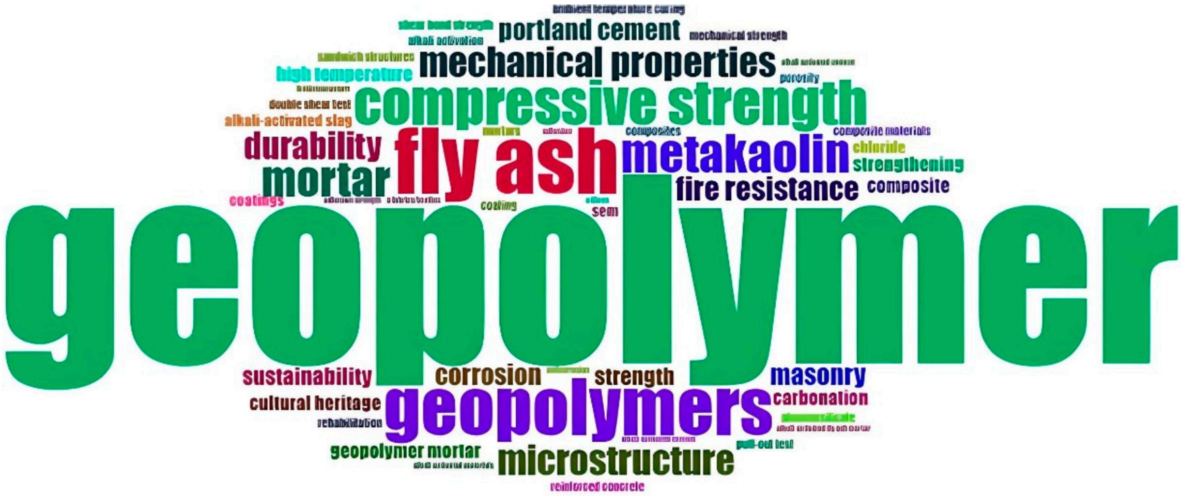


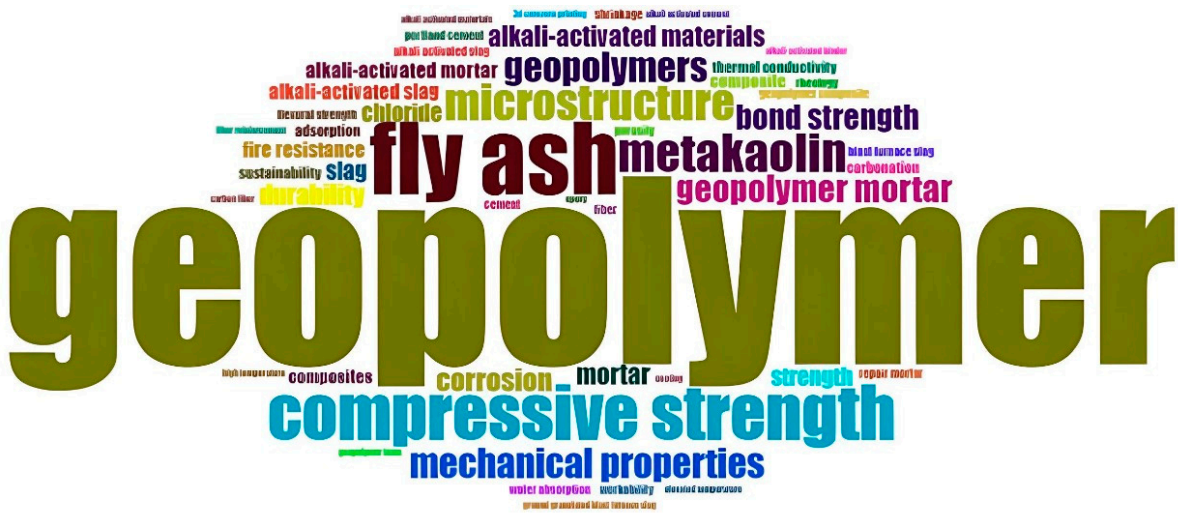
Figure 6. Co-occurrence network for the author's keywords.

4.2.3. Word Cloud

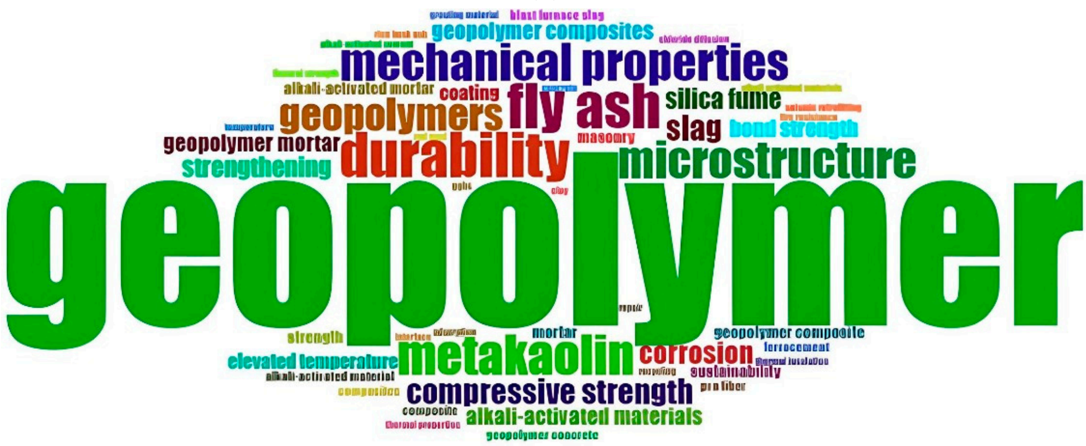
A word cloud is another tool to highlight research interests and trend developments. Figure 7 presents word clouds illustrating the most used author keywords within three time intervals: 1996–2017, 2018–2020, and 2021–2023, corresponding to 237, 261, and 291 articles, respectively. The time intervals were divided in a way to obtain a similar number of publications in each to facilitate the comparison. As anticipated, "geopolymer" was the most occurring keyword in all time slots, with a total occurrence of 244. Meanwhile, other terms, such as alkali-activated material, alkali-activated fly ash, and alkali-activated mortar were not as frequently used. As for the precursor binders, fly ash and metakaolin were mostly employed in past research. Yet, slag (also referred to as blast furnace slag and GGBS) became more prominently utilized after 2018. This could be due to the superior performance of blended geopolymer mortars made with fly ash and slag compared to counterparts comprising one of the two binders. Other materials, such as red mud and silica fume, also became more apparent in the latest time interval, indicating the exploration of new alternative materials in the past few years. Nevertheless, while geopolymer mortar is cement-free, cement was a commonly used keyword between 2018 and 2023. This is probably owed to the comparison of geopolymer mortar with cement-based mortar in terms of performance and microstructure. Indeed, the evidence emerging in the last five years on the superiority of geopolymers has been promoting its adoption by the construction industry.



(**a**)



(**b**)



(**c**)

Figure 7. Word cloud of most frequent author's keywords between (**a**) 1996–2017 (237 articles), (**b**) 2018–2020 (261 articles), and (**c**) 2021–2023 (291 articles).

The word clouds also highlight several material properties. For example, a focus on the compressive strength and mechanical properties of the geopolymer mortar was evident, while less attention to durability and microstructure was observed. Though no significant differences were noted in the second time period, more properties were addressed, including bond strength, shrinkage, and water absorption. Bond strength is significant to several applications of geopolymer mortar, such as repair and strengthening. As these two applications became more prominent in this time period, their corresponding characterization tests were more frequently employed. In the last time period, greater attention was paid to durability and microstructure than compressive strength and mechanical properties. This indicates a more profound knowledge of the material under study, with a need to develop a better understanding of its durability performance and microstructure.

Based on the word cloud analysis, several research gaps can be depicted. Despite the introduction of new aluminosilicate binding materials in the production of geopolymer composites, fly ash has remained the most used precursor. However, owing to the depletion in its quantities over the past years, researchers are required to search for other industrial materials that possess similar chemical compositions to fly ash to serve as a suitable replacement. Another reason to find other alternatives to fly ash is that the level of toxicity varies between one region and another, where Russian fly ash showed less toxicity level with a pH near neutral compared to fly ash exported from other countries [88]. In addition, the complete or partial replacement of natural fine aggregates with recycled counterparts in producing geopolymer mortars has not received adequate attention [89]. Also, it seems that, other than workability, the fresh properties and rheology of geopolymers have not been investigated thoroughly.

4.3. Sources

Figure 8 illustrates the cumulative number of publications with time, sorted by the top 10 sources. It is evident that *Construction and Building Materials* (*Constr. Build. Mater.*) had the highest number of published papers, with more than 100. The high number of papers published in this journal indicates that the topic is highly significant to the field of novel building materials. Other notable journals on the list of the top 10 sources include *Composites Part B: Engineering* (*Compos. B. Eng.*), *Journal of Cleaner Production* (*J. Clean. Prod.*), and *Cement and Concrete Composites* (*Cem. Concr. Comp.*). It is also worth noting that the top 10 sources include a conference series, namely the *IOP conference series: materials science and engineering* (*IOP Conf. Ser. Mater. Sci. Eng.*).

Analyzing the top sources by only considering the number of publications, i.e., total publications (TP), can be misleading. The significance of these sources could be further measured by their total local citations (LC), impact factor (IF), and h-index. The impact factor of a journal is measured by finding the average citation of its articles per year. The h-index represents h number of research work produced by journals or authors that have each been cited a minimum of h times [90]. The analysis of the impact of the sources in the context of these four parameters is illustrated in Table 2. It is noteworthy that the TP, LC, and h-index of the sources are obtained exclusively for the publications relevant to this study. At the same time, the IF is the journal's actual values based on the year 2021. For example, while the h-index of "*Construction and Building Materials*" is 198, for the publications relevant to this study, it is 33, i.e., 33 publications—among the total 772 studied in this paper—have at least 33 citations.

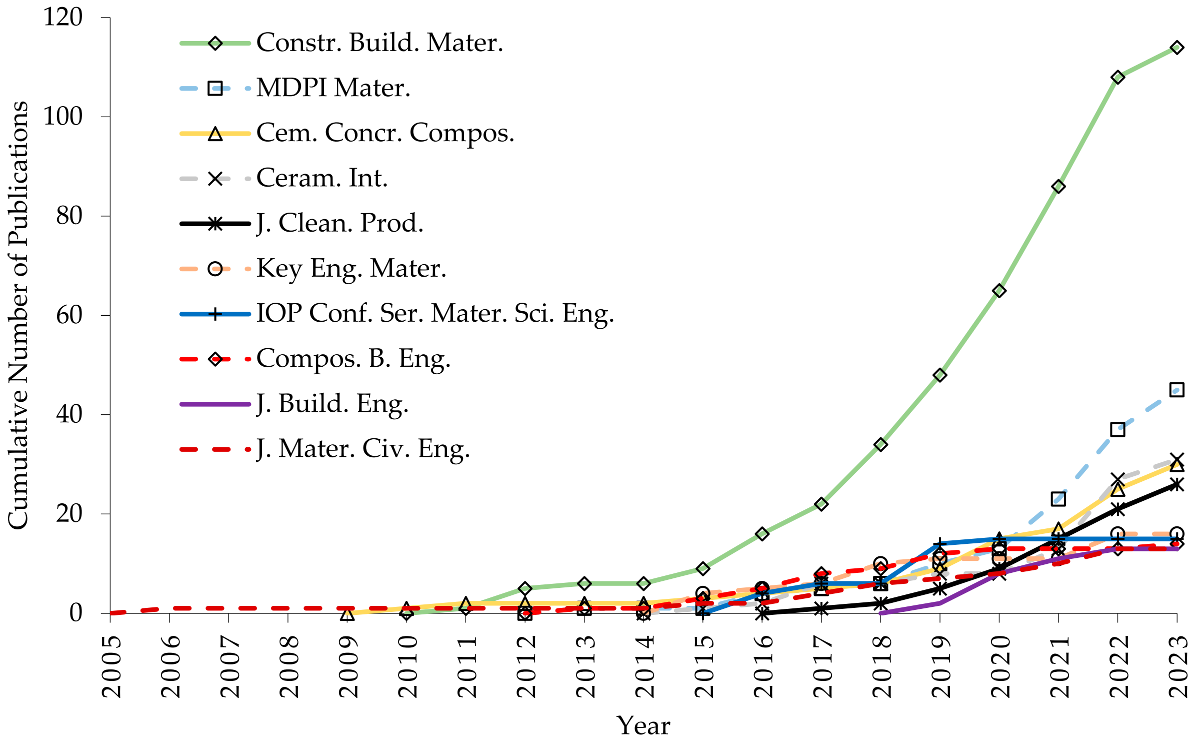


Figure 8. Number of publications in the top 10 sources over time.

Table 2. TP, TC, IF, and h-index of the top 10 sources by TP.

Sources	TP	LC	h-Index	IF
Constr. Build. Mater.	114	2676	33	7.69
MDPI Mater.	45	431	10	3.75
Cem. Concr. Compos.	30	583	13	9.93
Ceram. Int.	29	287	9	5.53
J. Clean. Prod.	26	653	11	11.07
Key Eng. Mater.	16	66	5	0.49
IOP Conf. Ser. Mater. Sci. Eng.	15	95	5	0.48
Compos. B. Eng.	13	1161	13	11.32
J. Mater. Civ. Eng.	13	239	7	3.53
J. Build. Eng.	13	163	8	7.09

Furthermore, Table 2 shows that, despite the higher IF of *Compos. B. Eng.*, *J. Clean. Prod.* and *Cem. Concr. Comp.* compared to *Constr. Build. Mater.*, the latter is superior in terms of the sources in TP, LC, and h-index with values of 114, 2676, and 33, respectively. This is related to the scope of this journal, which focuses on research in the areas of construction materials and repair [58]. Based on the total publications of the journals highlighted in Table 2, *Constr. Build. Mater.*, followed by *Materials* (*MDPI Mater.*), *Cem. Concr. Comp.*, *Ceramic International* (*Ceram. Int.*), and *J. Clean. Prod.* were the top five journals in publishing research (TP) on the valorization of geopolymer mortar and composites in construction applications. However, when comparing the journals in terms of LC and the h-index, *Compos. B. Eng.* had the second highest LC and h-index of 1161 citations and 13, respectively. The two most locally cited papers from the journal of *Compos. B. Eng.* are an experimental study related to the strengthening of reinforced concrete beams by metakaolin based-geopolymer composites produced with carbon fibers [29], and a review paper on the feasibility of using geopolymer mortar as an alternative environmentally friendly construction material to traditional cement mortar [91]. Such details provide scholars conducting research on the same topic further insight into the sources to maximize their impact.

4.4. Countries and Institutions

Figure 9 shows the contribution of countries and continents to the publications based on the geographic location of the first author's institution. A total of 61 countries contributed to the research topic under investigation herein, as shown in Figure 9a. It is evident that China has the highest number of publications, representing 17% of the total publications, followed by the USA, Italy, India, and Malaysia. These five countries were responsible for nearly 46% of the total publications. It seems that the excessive cement production of these countries and its associated environmental consequences were the primary motive behind investigating alternatives to cement [92–94]. In fact, China alone was responsible for producing around 2500 million tons of cement in 2021, while the USA and India were among the top five cement producers worldwide [95]. On the other hand, the demand for sustainable streams for local wastes in Italy and Malaysia was possibly the main reason behind their high scientific output on geopolymers [96,97].

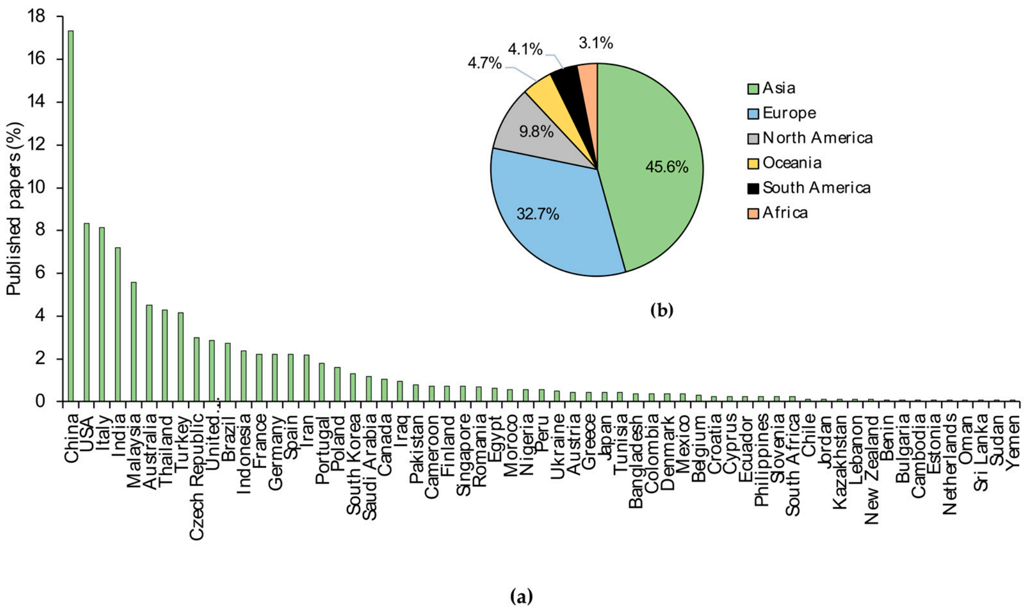


Figure 9. Percentage of published papers by (**a**) country and (**b**) continent.

Categorizing the productive countries by continent (Figure 9b) reflects a high contribution by mainly two continents, Asia at 45.6% and Europe at 32.7%. Subsequent to these two continents, North America, Oceania, South America, and Africa had contributions of 9.8, 4.7, 4.1, and 3.1%, respectively. The share of countries in the number of publications reflects the importance of the topic in each country and its relationship with its major economic and environmental issues. While this notion should drive toward further research in the field, this may not be possible without proper development and awareness in higher education institutions and research centers.

The top ten countries in terms of total number of citations are illustrated in Figure 10. China ranks first in the total number of citations, with over 2000 citations. As the same country also ranks first in the total number of published works, this shows that the number of citations in China may be predominantly affected by its number of publications, i.e., authors from China are more inclined to cite papers published in China. However, this was not the case in other countries. For example, while India ranks 4th in the total number of publications, it is not in the top ten countries in terms of the number of citations. Unlike China, it seems that authors from such countries are not as keen to cite fellow authors from the same country.

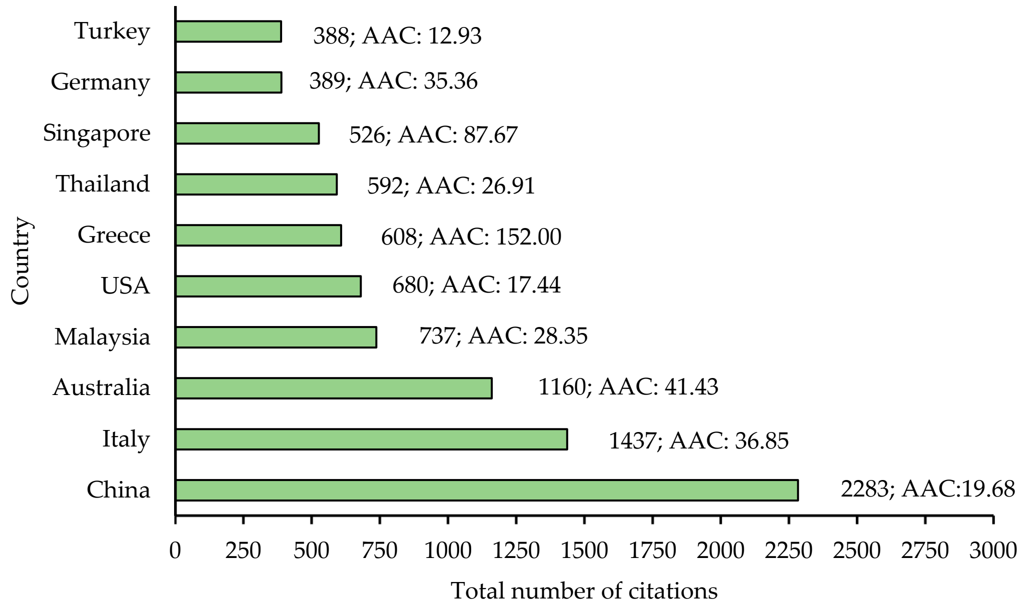


Figure 10. Total number of citations by country (AAC is the average article citation).

The average article citations (AAC) of each country are also presented in Figure 10. This index provides further insight into the impact of the publications. The highest AAC is that of Greece (152.0) with a total of 608 citations. This is owed to its low number of total publications (4) and the high number of citations (607) of a popular review paper entitled "Geopolymerisation: A review and prospects for the minerals industry" [11]. In fact, this paper describes the geopolymerization reaction, the ability of geopolymers to immobilize and adsorb toxic waste elements, and the efficient utilization of geopolymers in different construction applications.

Using Bibliometrix, a representation of the connections and intellectual interactions among the countries is shown in Figure 11. The red lines connecting any two countries represent a collaboration in publishing. More lines sourced in a particular country indicate a higher level of international collaboration. Apart from China, three other countries, namely Australia, USA, and Malaysia, have noteworthy collaborations with countries worldwide. This can be explained by their high number of publications and citations, as shown in Figures 9 and 10. On the other hand, a high collaboration rate was found between countries of the European Union. Meanwhile, countries with a low number of publications, such as Chile, Lebanon, Denmark, and South Africa, have shown very limited collaboration. It can be thus concluded that the number of publications and citations per country is proportional to its extent of collaboration with other countries and vice versa.

Moreover, a total of 834 institutions have contributed to the production of scientific studies related to the topic under investigation. Figure 12 presents the total number of articles published by the top 10 institutions and their geographic locations. It is evident that the highest contributing institution is Universiti Malaysia Perlis, with a total of 25 publications. Although Malaysia had less than 6% of the total number of publications globally, it was one of the most active countries in terms of collaboration. Khon Kaen University and University of Minho came in second place with a total of 18 publications each. Yet, it is worth noting that although China had the highest number of publications, it only had two institutions in the list of the top 10. This indicates that a wide range of institutions was responsible for the high publication rate, accentuating the relevance of this research field to the country itself and the ability to conduct such research by many universities. Such a research drive is owed to the massive production and utilization of cement in China. This is also linked to the availability of industrial by-products, such as fly ash and slag, for utilization as precursors in geopolymers [98].

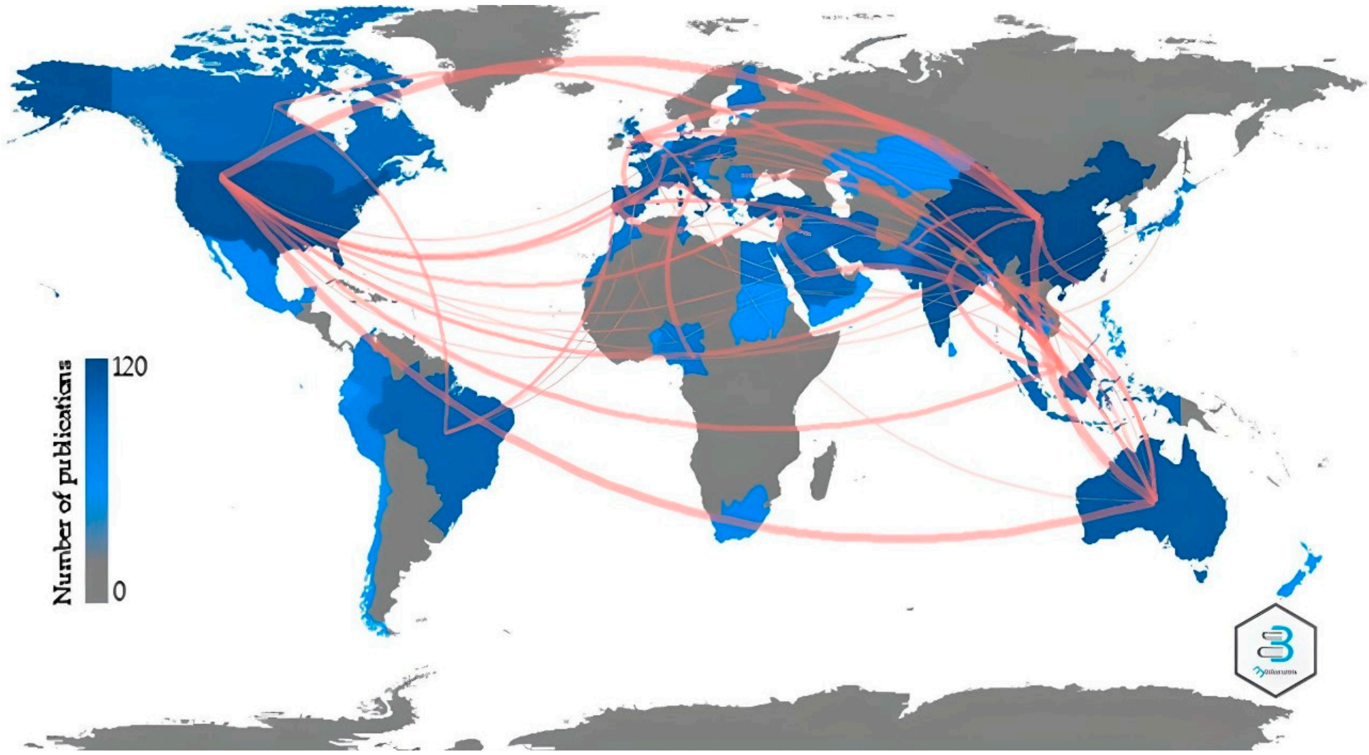


Figure 11. Countries collaboration map.

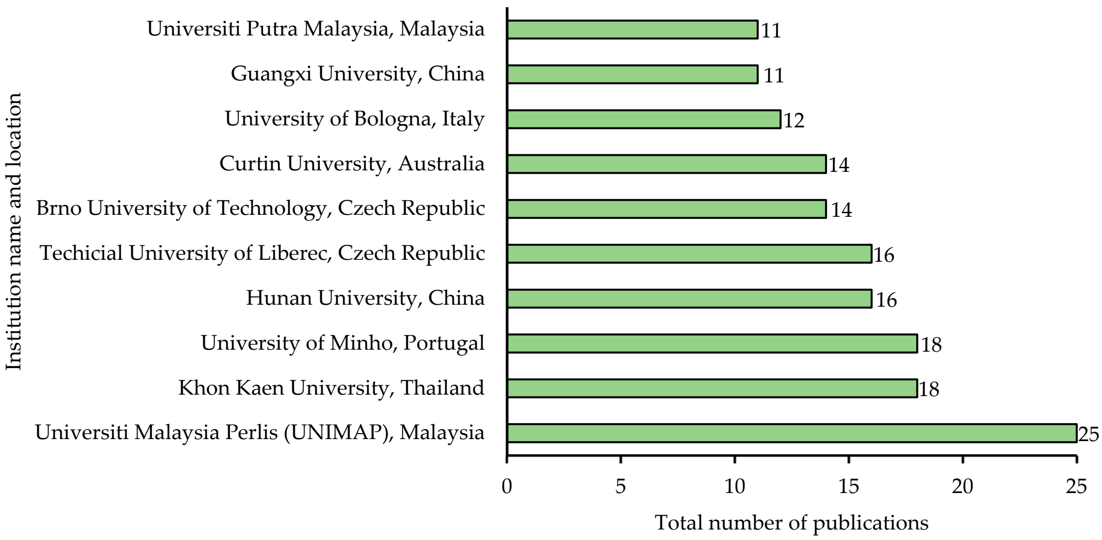


Figure 12. Top 10 institutions by number of publications.

4.5. Authors

The top 10 authors relevant to the investigated research topic by the total number of publications (TP) are shown in Table 3. Prinya Chindaprasirt was the most published author, with 18 publications and 623 citations. The author carried out studies on the effect of NaOH activation on fly ash-based geopolymers and the durability characteristics of cement pipes covered by fly ash-based mortar [99–101]. Owing to his high number of publications, Prinya Chindaprasirt promoted his institution Khon Kaen University as one of the top 10 institutions in terms of the TP. Yet, this was not the case with other authors. Some institutions, such as Universiti Malaysia Perlis, had more than one team investigating this research field, where their top author, Mohd Mustafa Al Bakri Abdullah, had only 10 publications out of the institution's TP of 25.

Table 3. TP, TC, h-index, TP/year, and AAC of top 10 authors by TP.

Authors	TP	LC	h-Index	TP/Year	AAC
Prinya Chindaprasirt	18	623	12	1.63	34.61
Maria Chiara Bignozzi	11	433	8	1.10	39.36
Mohd Mustafa Al Bakri Abdullah	10	76	5	1.42	7.60
Gregor Gluth	10	46	4	1.67	4.60
Fernando Pacheco-Torgal	10	174	7	0.83	17.40
Yanshuai Wang	10	132	7	2.00	13.20
Maria Criado	9	217	6	0.75	24.11
Alessandra Mobili	9	290	7	1.13	32.22
Francesca Tittareli	9	290	7	1.13	32.22
Lianyang Zhang	9	81	4	1.50	9.00

The number of publications does not provide a comprehensive overview of the impact of these authors on the research field. Thus, their impact is analyzed through their TP, LC, h-index, TP/year, and AAC, as shown in Table 3. Prinya Chindaprasirt had the highest h-index, which could be anticipated considering his high number of publications and citations. However, for the TP/year, Yanshuai Wang had the highest value, owing to his more recent history in the field, where his first publication on geopolymer materials was in 2017 [102]. As for the AAC, Maria Chiara Bignozzi had the highest value of 39.36. Research works of the author include investigations on the fire and thermal resistance of foamed geopolymers [103] and the corrosion behavior of steel covered by fly ash-based geopolymer mortar cured in different room temperatures [104]. In general, both the quality and quantity of publications were decisive in authors' rankings. Studies on specialized topics, early notions, and fundamental concepts attracted additional citations.

Figure 13 represents the collaboration network between others. It was generated by the collaboration network tool of Bibliometrix with a benchmark of 50 nodes and a minimum of one edge between different authors. In addition, 11 isolated nodes were removed, making the total of shown nodes 39. Similar to Figure 6, the size of the text represents the TP of a specific author, while the links identify the number of collaborations between different authors. The network is divided into 10 color-coded clusters. Two (blue and red) were linked with at least one collaboration to authors of different groups. Meanwhile, authors from China, represented in the grey color, had excellent collaborations among different authors, evident by the connectivity of the 14 nodes.

The main focus of the Italian team (red cluster) from the Università Politecnica Delle Marche and the National Research Council (ISAC-CNR) was on the corrosion behavior of steel protection with fly ash and metakaolin based-geopolymer mortar [105–108]. They concluded that the higher alkalinity of the geopolymer matrix was the reason for the superior protection characteristics of alkali-activated composites compared to the cementitious counterpart. In addition, other studies authored by the same group assured superior mechanical and sustainable characteristics of geopolymer mortar compared to cement mortar for fire protection applications [109] or as bricks coating material [110–112]. Furthermore, the primary aim of the second Italian team from the University of Naples, represented by the blue cluster, was to develop geopolymer composites for strengthening purposes [29,113], geopolymer-epoxy composites [114,115], and geopolymer bricks [116]. Finally, the Czech Aerospace Research Centre team (orange cluster) published conference papers on the performance of geopolymer composites exposed to fire and high temperatures for use as sandwich materials in aerospace construction [117–119]. Generally, this network shows a good collaboration between different authors from the same country, which aligns well with the collaboration index noted in Table 1. Nevertheless, limited collaboration is visible between authors from different countries.

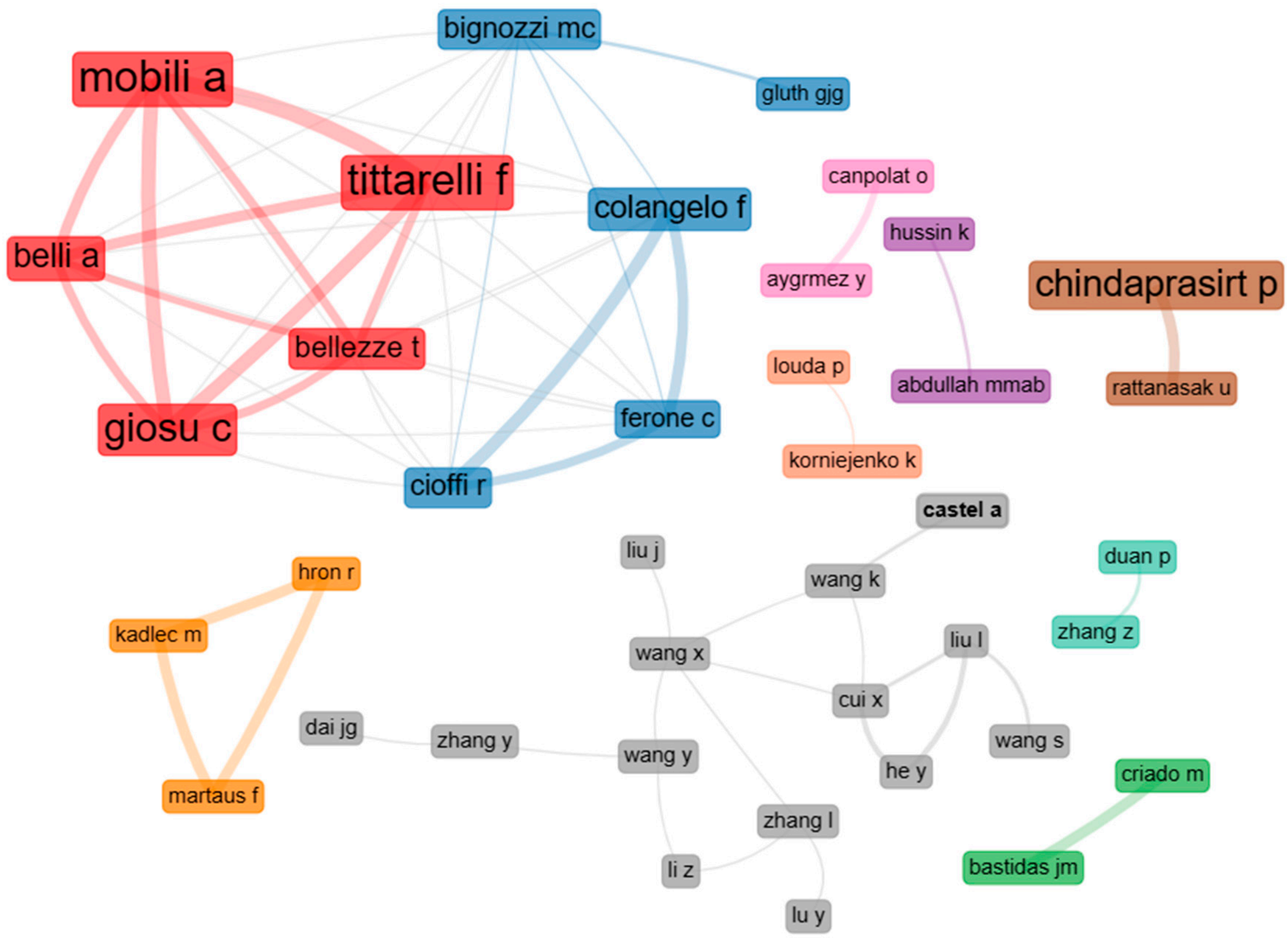


Figure 13. Collaboration network between authors (red cluster = corrosion behavior of steel protection with fly ash and metakaolin based-geopolymer mortar; blue cluster = develop geopolymer composites for strengthening and bricks; orange cluster = performance of geopolymer composites exposed to fire and high temperatures; and grey cluster = performance of geopolymers in aggressive environment).

5. Publications

Information related to the total and local citations of the articles under study was extracted from Bibliometrix. The total citation (TC) refers to the total number of citations of a paper, while the local citation (LC) is related to the number of citations of an article by another within the selected article group. The top 10 publications ranked based on the TC are shown in Table 4. The TC of these publications ranged between 134 and 648. It should be noted that 3 of the top 10 journal articles were review articles, with the most cited article being a review article published by Komnitas and Zaharaki [4]. In fact, it is because of this review article that Greece received the highest AAC value of 152. Generally, review articles are heavily cited due to their extensive analysis and their primary role in identifying research gaps and highlighting future recommendations. In addition to the adsorption of heavy metals, the subject areas of the top 10 publications were the use of geopolymers in various applications, including fire resistance, strengthening, 3D printing, repair, and marine coating.

Furthermore, the TC per year is a valuable index that can show the relevancy and the innovation of the idea of any paper. The review article titled "A review of recent research on the use of cellulosic fibers, their fiber fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering" ranked third based on the TC and had the highest TC per year with a value of 50.0 [12]. In this paper, the authors discussed the performance of different matrices reinforced with various types of fibers and fabric for strengthening and repair of old structures. The second highest TC/year was for an article titled "Measurement of tensile bond strength of 3D printed geopolymer mortar", which combines two trending topics, namely geopolymers and 3D printing. The high citation per year of such a paper is indicative of further investigation on using geopolymer materials in 3D printing.

Table 4. Top 10 articles ranked based on the total and local citations.

Rank	Paper Title	TC	Year	TC/Year	LC
1	Geopolymerisation: A review and prospects for the minerals industry [11]	648	2007	40.5	14
2	Effect of elevated temperatures on geopolymer paste, mortar, and concrete [17]	593	2010	45.6	22
3	A review of recent research on the use of cellulosic fibers, their fiber fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering [12]	350	2016	50.0	8
4	Fire-resistant aluminosilicate composites [18]	301	1997	11.6	14
5	Additive manufacturing of geopolymer for sustainable built environment [57]	251	2017	41.8	11
6	Measurement of tensile bond strength of 3D printed geopolymer mortar [56]	245	2018	49.0	7
7	Geopolymer mortars as sustainable repair material: A comprehensive review [13]	208	2017	34.7	25
8	Potential application of geopolymers as protection coatings for marine concrete: I. Basic properties [22]	168	2010	12.9	16
9	High calcium fly ash geopolymer mortar containing Portland cement for use as repair material [58]	155	2015	19.4	32
10	Potential application of geopolymers as protection coatings for marine concrete: II. Microstructure and anticorrosion mechanism [23]	134	2010	10.3	13

Local citation (LC) is another index that can show the effect of a paper on others included in the scope of the research. Generally, articles related to high-temperature resistance and repair are the most locally cited papers. A significant difference can be noticed by comparing the number of local and total citations of the top 10 articles. This provides evidence as to why none of the top 10 authors listed in Table 3, based on total productions and local citations, have authored any of the top 10 publications in Table 4, which are ranked based on total citations.

6. Research Trends and Future Prospects

Previous sections highlighted the most important research topics that have explored the use of geopolymer mortars and composites for different construction applications, including fire protection, corrosion resistance, coating, repair, masonry plaster or blocks, strengthening, rehabilitation, 3D printing, grouting, and wastewater treatment. Table 5 summarizes the current knowledge and future research opportunities in these research areas.

Table 5. Current knowledge and future prospects.

Research Topic	Current Knowledge	Future Prospects
Fire protection	• The fire resistance behavior of geopolymer mortar prepared with different types of alumina silica-rich binder including fly ash [120–122], metakaolin [123], slag [124], fly ash and metakaolin [123], fly ash and slag [125], fly ash, slag and calcined clay [25], and fly ash, zeolite and mullite [126]. • Behavior comparison between cement and geopolymer-based mortars exposed to fire and high temperatures [109,123,127]. • Reinforced [128] and non-reinforced [109,122] lightweight geopolymer mortars for fire protection applications have been developed. • The effect of auto glass waste [129] and recycled concrete aggregates [130] as fine aggregates on the thermal and fire resistance of geopolymer mortar. • The effect of alkaline activator ratio [131], Si to Al ratio [132], additives such as aluminum powder and calcined clay [133], nanomaterials such as nano titanium dioxide [60,134], and fibers such as polypropylene [135] fibers on the fire resistance of geopolymer composites. • The effect of fire and heat exposure on the tensile and bond strength of geopolymer mortar with a concrete structure [127], the bond performance of fiber-reinforced polymer bar with geopolymer mortar [136], the microstructure of geopolymer mortar [60,125], and the shear capacity of concrete beams strengthened with different layers of textile-reinforced geopolymer mortar [137]. • Impact of load-induced damage on the high-temperature resistance of geopolymer mortar [125]. • Fire resistance performance of fly ash-based geopolymer mortar for the protection of steel wire mesh layer embedded in ferrocement panels [120]. • The prediction of the post-fire behavior of geopolymer mortar using different models developed by gene expression programming [130].	• Assess the fire resistance, corrosion resistance, repair efficiency, strengthening ability, and 3D-printing capabilities of geopolymer material prepared with new alumina silica-rich binders such as volcanic ash, carbide slag, and perlite. • Evaluate the long-term performance of geopolymer masonry, coating, grouting, repair, 3D-printing, and strengthening material by observing its behavior under real-life environmental exposure. • Assess the structural behavior of damaged and corroded concrete beams and columns repaired and strengthened with geopolymer composites. • Conduct environmental impact, life, and cost cycle assessment for geopolymer mortar and composites produced as a repair, corrosion, fire, and heat protection material and for strengthening and 3D-printing applications. • Introduce more models that can predict the fire resistance and repair efficiency of geopolymer mortars. • Study the effect of different types of fibers on the performance improvement of geopolymer masonry, coating, and strengthening materials. • Examine the effect of different sustainable fine aggregates on the corrosion resistance and strengthening behavior of geopolymer composites. • Investigate the effect of different nano and micro materials such as nanoclay, nanosilica, carbon nanotube, microsilica, graphene, and graphite oxide on the fire resistance, adhesion, repair, strengthening, and coating behavior of geopolymer materials. • Use optimization methods to develop the best geopolymer mortar or composite mix design for corrosion and fire protection, strengthening, and 3D-printing applications. • Extend research work related to the rehabilitation of joints between different concrete structures.

Table 5. *Cont.*

Research Topic	Current Knowledge	Future Prospects
Corrosion resistance	• The corrosion behavior of geopolymer mortar prepared with different types of alumina silica-rich binders such as fly ash [24,138], metakaolin [24,139], slag [79], metakaolin and slag [140], zeolite [113], metakaolin and slag [141], red mud and slag [142], fly ash and slag [143], and fly ash and palm oil fuel ash [144]. • Corrosion behavior comparison of steel bars embedded in cement and geopolymer-based mortars [106,108]. • The effect of different alkaline activators such as sodium silicate, sodium hydroxide, potassium silicate, and potassium hydroxide on corrosion performance of geopolymer ferrocement panels [138]. • The effect of alkaline solution molarity on crack propagation and corrosion behavior of geopolymer mortar covering steel mesh for marine environments [145]. The effect of calcium and alkalinity on the chloride diffusivity of geopolymer mortar [146]. • Carbonation resistance [147] and chloride migration resistance of geopolymer mortars [143,145]. • Effect of steel [143], glass [148], polyvinyl alcohol [149], basalt [143], and cotton stalk [150] fibers on the sulfate corrosion resistance of geopolymer mortars. • Microstructure analysis and studies on the interfacial bonding between geopolymer composites and marine concrete [151] and between geopolymer mortar and embedded steel reinforcement [152].	• Develop geopolymer sprayed material for sewer pipes rehabilitation accessible in different countries around the world. • Produce lightweight 3D printed mortar and composites as insulation and waterproof materials. • Incorporation of different types of sand in geopolymer grout production is needed in order to reduce the binder and alkali-activated solution volume. • Produce more scientific work related to the wastewater treatment ability of geopolymer mortar and composites as they possess a high potential to remove waste microorganisms and heavy metals.
Coating	• The coating efficiency of hybrid geopolymer cement mortar produced with fly ash, metakaolin, and slag [153]. • Performance evaluation of fly ash and slag-based geopolymer mortar coating under harsh and chemical environments [154]. • The efficiency of silica fume-based geopolymer composites [155] and modified silica fume-based geopolymer composites with nano zinc oxide [156] as a flame retarding coating. • The suitability and shrinkage behavior of metakaolin-based geopolymer composites [151], silica fume, and slag-based geopolymer composites [157], and metakaolin and slag polypropylene fibers reinforced geopolymer mortar [22,23] for marine concrete protective coating. The development of slag-based geopolymer mortar as barrier coating protection for concrete substrates [158]. • The mechanical, durability, cost-effectiveness, and environmental impact of fly ash-based geopolymer mortar coating buried steel pipes [159].	

Table 5. *Cont.*

Research Topic	Current Knowledge	Future Prospects
	• The fire resistance characteristics, moisture absorption, mix design optimization, and microstructure analysis of rice husk ad silicone rubber-based geopolymer coating composites [160]. • Performance comparison between Portland and alkali-activated geopolymer mortars produced with rice husk ash and metakaolin as a coating material for lightweight panels [161]. • A review of the self-cleaning coating characteristics of geopolymer-based composites [162]. • Use the Taguchi optimization method to produce a feasible geopolymer fire-resistance coating material [163]. • Optimize adhesion strength and study the microstructure of the interfacial bonding surface between rice husk ash-based geopolymer coating and concrete substrate [164]. • Use of the response surface methodology to optimize the mix design and curing temperature and enhance the flexural properties of rice hush ash-based geopolymer composites coating material [165].	
Repair	• Geopolymer mortar and composite repair materials prepared with different types of alumina silica-rich binders such as: fly ash [166], metakaolin [167], slag [168], metakaolin and slag [169], fly ash and slag [170], fly ash, and rice husk ash [171], and fly ash, slag and metakaolin [153]. • The efficiency of geopolymer mortar and composites in repairing a damaged wall [166], pavements [172,173], reinforced concrete beams [174], and heritage buildings [175] or as waterproof repair materials [176]. • Repair characteristics comparison between cement and geopolymer composites [173,177]. • Adhesion and bonding behavior between geopolymer and cement composites [27,167,178]. • The effect of high temperature [177] and different harsh environments [179], such as: acid attack, rapid efflorescence exposure, wet-dry cycles, freeze-thaw cycles, and heat-cool cycles, on the bonding characteristics of geopolymer repair material. • The role of different fibers such as polypropylene [172], glass [170], basalt [180], rubbers [181] and polyvinyl alcohol [182] fibers, textiles made of carbon [180], and glass [183], and nano materials such as nano-silica [184] in the development of geopolymer repair composites.	

Table 5. *Cont.*

Research Topic	Current Knowledge	Future Prospects
	• Effect of curing regime [182], the water-binder ratio [185], sodium hydroxide molarity [185], sand content [186], and efflorescence [179] on geopolymer repair materials. • Visual and microstructure analysis of geopolymer repair materials exposed to aggressive environments [179]. • Predicting the mechanical and durability properties of geopolymer repair material by an artificial neural network [171].	
Masonry	• Geopolymer mortar and composites materials prepared with different types of alumina silica-rich binders such as: fly ash [187], metakaolin [74], fly ash and slag [188], slag and red mud [189], oil shale ash and Jordanian natural pozzolan [190], fly ash and dry paper sludge [191], high calcium wood ash and pulverized fuel ash [192], fly ash and municipal solid waste incineration fly ash [193], lime-pozzolana cement and fly ash [194], lime pozzolana cement and slag [194], silica fume and fly ash [195], and carbide lime and bottom ash [196], for masonry applications. • Durability performance [197] and microstructure analysis for geopolymer masonry materials [190,198,199]. • Comparative study between geopolymer and cement-based composites for masonry applications [198]. • Effect of curing regime [192], sodium silicate content [192], sodium silicate to sodium hydroxide ratio [193], liquid to solid ratio [193], and sodium hydroxide molarity [197] on the performance of geopolymer masonry blocks. • The role of jute fibers in the development of geopolymer masonry materials [200]. • Effect of sustainable aggregates such as recycled fine aggregates on the properties of geopolymer masonry materials [74,195]. • Production of lightweight blocks [200,201] and bi-layered colored masonry bricks [202].	
Strengthening	• Strengthening of cement concrete with fabric-reinforced geopolymer mortar jackets prepared with fly ash and slag geopolymer mortar, polyvinyl alcohol fibers, and basalt fabric tested under monotonic and cycling compressive load [203]. • Strengthening of cement concrete structures with steel fibers reinforced fly ash geopolymer matrix prepared with different sodium hydroxide molarities [204]. • Flexural characteristics of concrete slabs strengthened with fly ash and metakaolin geopolymer reinforced with carbon textile [205].	

Table 5. *Cont.*

Research Topic	Current Knowledge	Future Prospects
	• Influence of different jacketing configurations such as the bottom, two-sided, and three-sided jackets, and thickness of fibers reinforced geopolymer composites [206]. • Strengthening of concrete columns with different layers of carbon fibers [207]. • Strengthening of masonry prisms with fly ash geopolymer composites reinforced with polypropylene fibers and prepared with sodium hydroxide [208]. • Strengthening of masonry structure with metakaolin geopolymer mortar reinforced with basalt, steel, glass, and carbon meshes [30]. • Testing and modeling of shear behavior of strengthened concrete deep beams reinforced with carbon fabric matrix embedded in fly ash and slag geopolymer mortar [209]. • Shear strengthening of a prestressed concrete beam with slag geopolymer mortar reinforced with carbon fiber-reinforced polymer laminates [210]. • Effect of carbon textile reinforced geopolymer mortar layers on shear strengthening of reinforced concrete beams under normal conditions and under fire exposure [211]. • Assessment of textile fibers to mortar bond characteristics [212,213], direct shear and bending characteristics of steel and glass fibers reinforced inorganic matrix composite [214], the flexural characteristics of geopolymer mortar produced with different thicknesses and reinforced with carbon mesh and basalt fibers [180], and flexural behavior of hybrid polyvinyl alcohol fibers and glass textile reinforced fly ash and slag-based geopolymer mortars [183]. • Comparative study between cement and geopolymer fiber reinforced composites for strengthening purposes [205,210,215,216].	
Rehabilitation and sewage pipes lining	• Assessment of a beam-column joint rehabilitated with steel fibers reinforced fly ash and slag-based geopolymer mortar under monotonic and cyclic loading [217,218]. • Efficiency of geopolymer mortar for rehabilitating water and wastewater pipes [219]. • Evaluation comparison between fly ash and metakaolin geopolymer and cementitious-based mortar for rehabilitation of buried infrastructure [220]. • Effect of binder-to-sand ratio on the compressive, bonding, and microstructure characteristics of fly ash geopolymer mortar prepared for rehabilitation applications [221].	

Table 5. *Cont.*

Research Topic	Current Knowledge	Future Prospects
	• Comparison between fly ash and slag-based geopolymer mortars prepared with different fly ash to slag ratios, with ordinary cement and magnesium potassium phosphate cement mortar for rapid rehabilitation construction application [222]. • Study of the structural, mechanical, and morphological characteristics of porcelain stoneware-based geopolymer mortar to rehabilitate historical monuments [223]. • Effect of geopolymer mix design parameters such as the alkaline solution to fly ash ratio, curing temperature, and sodium silicate to sodium hydroxide and types of binders on the rehabilitation efficiency of geopolymer composites for buried pipes [224]. • Performance, cost, and environmental analysis of rehabilitating a large-diameter sewage pipe with unreinforced and fiber-reinforced sprayed geopolymer mortar in Texas [225,226]. • Mechanical testing and service life analysis of geopolymer mortar pipe lining technology for rehabilitating sewer and stormwater pipes [227]. • Assess the efficiency of geopolymer mortar for sewer system by focusing on initial site condition, long-term performance, finite element analysis, and construction challenges [228].	
3D printing	• Review of the fresh, mechanical, and printing time interval of 3D printed plain and fiber-reinforced mortar [225,226]. • Effect of steel cable reinforcement in enhancing the flexure properties of a 3D printed fly ash, slag, and micro silica-based geopolymer mortars [80,227]. • Effect of short carbon and glass fibers on the printing properties of geopolymer [229]. • Effect of magnesium aluminum silicate [230], rest time [230], and halloysite nanotube [231] on the rheological characteristics of 3D printing fly ash-based geopolymer mortar. • Effect of nano graphite platelets and nanoclay in strengthening of fly ash, slag and micro silica based geopolymer 3D printed mortars [79,232]. • Development of 3D printed geopolymer mortars prepared with different construction and demolition waste materials such as, hollow brick, roof tile, red clay brick, and glass, and activated with combinations of different alkaline solutions such as sodium hydroxide, calcium hydroxide, and sodium silicate [233,234]. • Life cycle assessment and multi-criteria decision-making based on the performance of cement and geopolymer 3D printing mortars [235].	

Table 5. *Cont.*

Research Topic	Current Knowledge	Future Prospects
	• Bond strength of fly ash 3D printed mortar [56]. • Performance of 3D printed foamed fly ash geopolymer mortar [236]. • Performance comparison between different cement and geopolymer 3D printing mortars in marine environments [237].	
Grouting	• Shrinkage characteristics improvement of slag-based geopolymer mortar for joint grouting of concrete structures [238]. • Reinforced slag and metakaolin-based geopolymer mortar grout to strengthen masonry blocks [30]. • Mechanical and microstructure analysis of red mud and fly ash mortar as a grouting material [239]. • Bond performance of multi-ply steel reinforced in geopolymer mortar grout composites [240]. • Effect of alkaline activator molarity concentration and liquid-to-binder ratio on the performance of fly ash and slag-based geopolymer mortar for shield tunneling grouting [241]. • Effect of glass, polypropylene, and basalt fibers on the fly ash, red mud, and slag-based geopolymer grout [242]. • Assessment of rock bolt grouting efficiency by cement mortar, geopolymer mortar, and geopolymer paste produced with fly ash and metakaolin and potassium-based alkaline solution [243].	
Wastewater treatment	• Phosphate removal efficiency of fly ash and calcined paper moll sludge geopolymer [244]. • Thermal treatment and utilization of aluminum waste in fly ash geopolymer mortar [245]. • Wastewater treatment using an alkali-activated oil shale cement mortar [246]. • Comparative study of dye removal efficiency by metakaolin and fly ash geopolymer [247]. • Comparative study between geopolymer and copper doper geopolymer mortars in limiting microorganisms growth in concrete exposed to wastewater [80].	

The majority of research on the suitability and compatibility of geopolymer mortar and composites for use in construction applications gave little attention to the lifecycle assessment and environmental and economic impact of the material under study. However, lately, some studies highlighted the environmental impact of geopolymers and their main components. The production of industrial materials, such as fly ash used in the production of geopolymer material, showed a lower rate of toxicity when compared to the production of OPC [248,249]. The use of optimization techniques for producing geopolymer materials has not been extensively studied yet. Such methods can help scientists reduce the experimental work while maximizing performance of a geopolymer composite for a specific application. Furthermore, geopolymer paste has shown a great potential for use as grouting material and in wastewater treatment. Yet, the sustainability of this material could be further improved by including fine aggregates in the mix as a means of reducing the binder and alkaline solution contents.

7. Conclusions

Geopolymer mortar and composites have been extensively examined in the past few years. The mechanical and durability characteristics of the geopolymer composites have been found to be superior to cement-based counterparts. Indeed, the former has shown a superlative ability to maintain its weight and strength and to protect steel reinforcement under harsh conditions, such as fire, sulfate, and acid attacks. As such, geopolymer mortar and composites can be used efficiently employed in different construction applications, such as fire and corrosion protection, repair, strengthening, and rehabilitation of old structures. In this work, a scientometric analysis was performed on 789 papers written by 2072 authors and published in 273 sources between 1996 and 2023. Journal articles and conference papers formed around 70 and 22% of the total number of scientific publications. At the same time, 38 review articles were published. The following conclusions can be drawn from this study:

- The cumulative production rate showed an increase in annual growth rate (AGR) from 23.9% to 45.2% between the timeframes 2003–2013 and 2014–2022, highlighting the rapid emergence of research in this field.
- The journal *Construction and Building Materials* contributed the most to the research area, having the largest number of published articles in this field.
- China and the USA had the highest number of publications and exhibited the highest rates of international collaboration.
- Based on the authors' analysis, Prinya Chindaprasirt, Maria Chiara Bignozzi, and Mohd Mustafa Al Bakri Abdullah from Khon Kaen University, University of Bologna, and Universiti Malaysia Perlis, respectively, were ranked the top three authors based on the total publications. However, Yanshuai Wang, Gregor Gluth, and Prinya Chindaprasirt were the most active authors in recent years based on the total publications per year.
- The publications analysis showed that geopolymer mortar and composite had been assessed in different applications, including heavy metal adsorption, fire resistance, strengthening, 3D printing, repair, and marine coating.
- Based on the keyword analysis, fire and corrosion protection were the most studied applications since 2003, while articles on coating, repair, masonry strengthening, and rehabilitation appeared in 2013.
- In the last five years, more publications have emerged on the usage of geopolymer mortars for 3D printing, grouting, sewage lining, and wastewater treatment.
- Bonding characteristics, durability testing, and microstructure analysis were extensively studied in the literature.

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