sustainability

Review

Sustainability of Green Building Materials: A Scientometric Review of Geopolymers from a Circular Economy Perspective

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Abstract: Ecosystems suffer from CO_2 emissions and pollution caused by waste materials, mainly agricultural and industrial, that are dumped in landfill sites. These materials contain aluminosilicates, which are key ingredients for producing geopolymer composite (GPC). While cement, the main component of ordinary Portland cement (OPC), is a highly energy-consuming and polluting material in terms of CO_2 emissions, water absorption, and land depletion, GPC is an emerging building material that can contribute to the sustainability of the construction industry. In this research, bibliometric data on GPCs were collected from Dimensions databases, and a scientometric analysis was performed using the innovative VOSviewer software (ver. 1.6.19). The scope was to examine the development of GPC for construction applications in the context of a circular economy and as an emerging green building material. Using specific query metrics and three keywords (geopolymer, circular economy, and green building materials), bibliometric records were analyzed to identify the articles, authors, and journals with the highest impact. This investigation can help scholars and policymakers in deepening their knowledge in this growing research area. From a societal perspective, this study stimulates geopolymer developments through policies aimed at promoting the circular economy, such as the adoption of green subsidies in research and development (R&D) and production.

Keywords: geopolymer; inorganic polymers; waste management; building materials; circular economy; CO_2 emissions; scientometric analysis; environmental and resource economics

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1. Introduction

Total primary energy consumption increased by 1% in 2022 [1], which has significant implications for both CO_2 emissions and energy prices [2].

In particular, the building sector is crucial because it contributes 34% of global energy usage and more than 30% of CO_2 emissions, in addition to land consumption and the depletion of raw materials [3].

From an energy point of view, a building can be seen as a system that includes sub-systems like heating, cooling, lighting, installations, envelopes, and materials. The reduction in their energy impact depends on a combination of efficient technology usage, energy supply mix alteration, and careful building envelope design. The design of a high-performance envelope (through the choice of envelope structure and materials) is especially significant, primarily due to the envelope expenses, and is one of the most efficient approaches to existing buildings [4–8].

In Europe, by 2050, a large proportion of the building stock will be leaky and inefficient, as the renovation rate is around 1% [9,10]. In contrast, in Asia and Africa, the building stock is expected to double by 2050 [11]. However, the global buildable area is projected to grow by 75% over the next thirty years, especially in emerging and developing countries [12]. This growth, together with necessary retrofits, contributes significantly to raw material depletion and waste generation. In fact, the utilization of materials worldwide is expected to increase by over two-fold by 2060, and approximately one third can be attributed to materials employed within the building and construction sector [13].

Therefore, developing new building materials is a relevant issue, since the energy cost of their extraction, treatment, and disposal affects the environmental impact of construction noticeably [14]. Indeed, considering environmental concerns, an increasing number of researchers are exploring the development of eco-friendly building materials, also known as green building materials (GBMs) [15,16]. It is important to note that evaluating the environmental impact of certain products (or practices, in general) can be a complex issue. Terms like 'bio', 'eco', 'green', and 'sustainable' are often used arbitrarily. Indeed, in daily life, they overlook certain aspects of the materials to emphasize only specific features related to environmental impact, such as natural origin, recycled materials, and non-toxicity. In more rigorous terms, the prefix 'bio-' is related to those materials derived from biological (natural) resources such as wood, bamboo, straw, wool, hemp, and raw earth. The prefix 'eco-' especially refers to their impact on the environment, by taking into consideration the production process, transport, and disposal, with an emphasis on recycled/recyclable materials. The adjective green, on the other hand, embraces a broader scope by implying a global approach to sustainable construction (from the raw material to its use within the factory) such as entire systems (solar panels, photovoltaic panels, green roofs), organic materials (recycled wood, FSC wood), and reconversion of waste from other production chains, the disposal of which could be potentially harmful to people or the environment.

The implementation of a life cycle assessment (LCA) is a useful method to evaluate the real environmental burden of a product (or a process) during its entire life (from cradle to grave). In particular, by searching the Dimensions database using the keywords 'green building materials' and 'life cycle assessment', it is possible to observe the number of scientific articles considering these topics. As shown in Figure 1, after 2014, there is a persistent growth trend in publications (the 2023 data are obviously partial); in addition, a linear estimation (OLS) was performed to predict trends in the period 2000–2050 (2000 is the start year for the analysis of the present study) and 2014–2050 (2014 is the first year reporting publications on GBM and LCA jointly). The current literature on LCA highlighted how the use of GBMs could reduce the carbon footprint of buildings compared to standard materials [17,18].

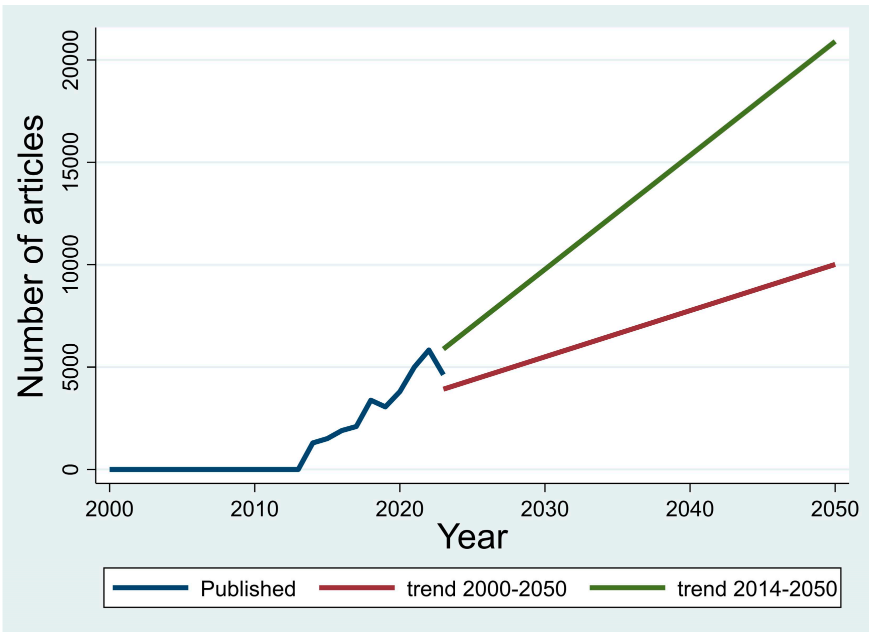

Figure 1. Publication trends by year for LCA and green building materials (our elaboration from the Dimensions data using Stata software ver. 17).

The extensive and growing literature on green buildings [19] inevitably must deal with environmental assessments of the possible materials that can be used [20]. In this area of research, geopolymers have started to attract increasing interest over the last twenty years.

The concept of geopolymers as a new material was initially introduced by Joseph Davidovits in 1972. According to a restricted definition, geopolymers are synthetic aluminum–silicate materials that are obtained from both a reactive powder of silicon and aluminum and an activating alkaline solution [21]. Geopolymer is a compound word that consists of geo and polymer, where 'geo' refers to industrial or geological materials that have a large amount of silica and alumina and 'polymer' means a chain of molecules formed from the repetition of units [22,23]. More widely, they include a wide range of inorganic, synthetic, or natural materials, with a polymeric structure very resistant to fire and high temperatures, making them suitable for use in various sectors and particularly in the construction industry for the consolidation of structures and infrastructures [24–27].

In a wide sense, other sectors in which geopolymers can be used are those involving thermal insulators, artificial decorative stones, cultural heritage restoration, the encapsulation of toxic and radioactive waste, fireproof buildings, insulating materials, ceramic tiles, heat shock-resistant refractories, casting materials, aircraft and automobiles, high-resin system technology, containment barriers for toxic substances and radioactive waste, and oral drug administration [28].

Their advantages include the reproducibility of the process; great resistance to compression, abrasion, acids, saline solutions, and high temperatures; no emission of toxic gases; minimum dimensional shrinkage; low thermal conductivity; adhesion to different materials (e.g., cement, steel, glass, ceramic); and excellent surface definition after molding [29–32].

From an environmental perspective, it is essential to highlight that the primary advantages of geopolymers are their low environmental impact and energy-efficient production process. This reflects the recommendations of numerous authors concerning sustainable development and mitigating climate change, in which they emphasize the importance of political interventions as an essential factor for achieving these goals [33–37]. The growth of the industrial sector increases risks associated with waste production and disposal. Thus, the use of raw materials to produce valuable products such as geopolymers has the double advantage of saving natural resources and fostering sustainability.

In fact, geopolymers can be produced from various natural materials and industrial by-products [38]. This is because most industrial waste contains materials (such as fly ash, bottom ash, and blast furnace slag) which have a sufficient quantity of reactive alumina and silica to be used as a base material for geopolymer production. Several industrial, agricultural, and human-made wastes can be used [24,26,27,30], such as metakaolin [39,40], ash [41–45], granulated blast furnace slag (GGBS), red mud, sludge [25,46–48], silica fume [49,50], crumb rubber [51], and construction demolition waste (CDW) [52]. This approach, which makes it possible to exploit resources that would otherwise be wasted, unused, or even harmful (to humans and the environment), has clearly led to the growth of interest in geopolymers from a circular economy perspective.

The circular economy can be defined as "an economic system based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production, distribution and consumption processes with the aim to accomplish sustainable development" [53]. In this sense, recycling is a pillar of sustainability economics, a branch of economics that focuses on the efficient use of resources, scarce by definition, and on the reduction in waste [54]. Therefore, the same reasoning can be extended to natural wastes, such as volcanic ash [55–60] and agricultural and aquacultural wastes [61,62]. The disposal of these wastes causes serious social and environmental problems, so their recycling can reduce these problems and help in the conservation of natural resources. Moreover, the circular economy has a positive impact on economic growth and on the labor market by reducing unemployment, poverty risk, and social exclusion, especially in lagging countries [63].

For these reasons, geopolymers are often compared to traditional OPC (the most widely used construction material in the world after water). In particular, the geopolymer production process requires less energy and is much less polluting than that of Portland cement [64–66]. Cement is produced from limestone or clay, which must be fired at temperatures of about 1500 °C [67], generating large quantities of carbon emissions [68,69]. On the other hand, the geopolymer production process requires, depending on the raw materials used, lower temperatures, between 25 °C and 120 °C, with a rapid consolidation time quantifiable in hours, and it can be implemented directly in situ, also eliminating transportation and environmental costs [64,70,71]. In this sense, geopolymer implementation can lead to sustainability in the construction sector, considering that the cement industry is among the largest emitters of CO_2 in the world [72,73].

Using geopolymer binders allows a reduction in carbon dioxide emissions equal to 80%, compared to traditional cement, since its raw materials (e.g., kaolin, metakaolin, FA, silica fume, GGBS, bagasse ash, crumb rubber, waste glass powder, volcanic ash, palm oil fuel ash, and rice husk ash) do not require any type of thermal pretreatment and can be directly incorporated into the production process [23]. However, the curing temperature remains an important parameter since it affects the mechanical performance of the final geopolymer [40,74–76].

The materials used in the creation of geopolymers can affect curing and performance, which ultimately determine their usefulness in construction [77,78]. Numerous studies have focused on assessing the strength and durability of geopolymers as supplementary cementitious material (SCM) [79–81]. In fact, geopolymer concrete, produced by the activation of aluminosilicate materials such as fly ash, exhibits a high initial strength, more resistant binding properties than current Portland cement, and a higher resistance to chemical attacks [32,50]. Conversely, Portland concrete structures, when exposed to aggressive environments, tend to deteriorate much faster than their expected duration would suggest [82]. Some studies have shown that Portland cements currently in use, if exposed to aggressive climatic conditions, deteriorate in about 50 years, therefore requiring periodic demolition and restructuring [83].

To summarize, the benefits of geopolymers as innovative green building materials are schematically described in Figure 2. In particular, it is important to note the versatility of the material, which makes it suitable for different types of use and functions within the construction industry, as well as its printability, which makes it suitable for additive manufacturing on an architectural scale.

Therefore, the interest in geopolymers as sustainable building materials has stimulated a large amount of scientific research. Following previous works by other researchers, the study presented in this paper is essential to guide scholars and policymakers in this fast-growing field. There are many aspects to be explored at this stage, from the formulation to the application of geopolymers and from their performance to their environmental impacts. In particular, this study offers a novel perspective related to the circular economy. The remainder of the paper is structured as follows. In Section 2, the materials and methods are described. The results are provided in Section 3. Section 4 presents the discussion, limitations, and avenues for further research, while Section 5 concludes by featuring the final conclusions and policy implications.

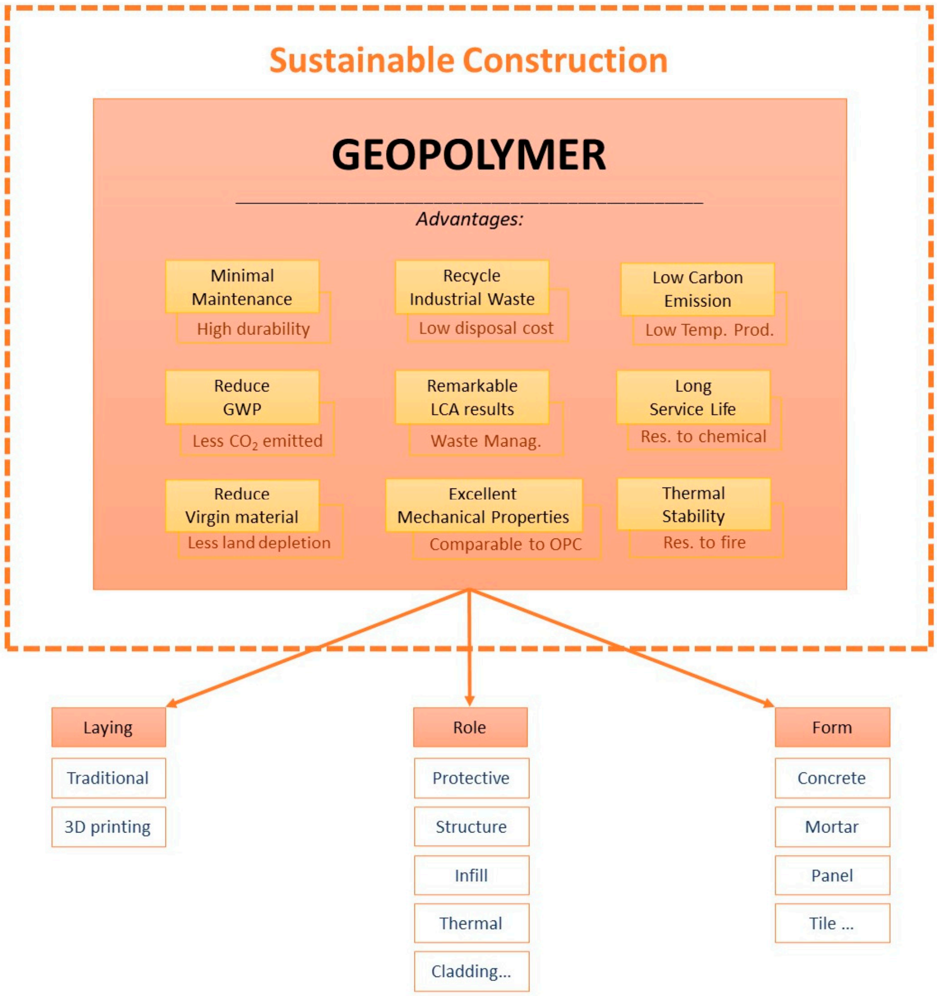

Figure 2. Benefits of geopolymers as green building materials and their applications.

2. Materials and Methods

The aim of this research was to perform a scientometric assessment of the bibliometric information on GPC as an eco-friendly construction material, qualitatively and quantitatively displaying scientific data and generating links and maps among the bibliometric records. With computer assistance, scientometric analysis is a method that reviews the literature in a rigorous and scientific way and that can determine the main research or authors in a topic or field, and how they are connected, by considering all the published scientific articles. In this way, it is useful for examining a large amount of scientific data and reveals trends in a specific field and emerging new research areas. Bibliometrics and scientometrics are new and closely related scientific fields that use statistical methods to measure and analyze large volumes of data related to scientific publications in a specific area. Bibliometrics is the numerical study of the bibliographic data for publications, which includes measures like the total number of publications, citation counts, mean normalized citation score (MNCS), h-index, and ratios of interdisciplinarity and specialization, being a rapid, straightforward, and effective way to evaluate research output and quality. Scientometrics is mainly focused on, but not limited to, measuring the impact of scholars, journals, papers, institutions, and citations. In addition, it employs science mapping to represent and visualize the relationships existing between the above-mentioned aspects [84].

Considering the difficulty of managing such an amount of data, in this research scientometric analysis allowed us to reveal and examine the bibliographic records about geopolymers, the circular economy, and green building materials. Moreover, with the use of the innovative VOSviewer software (ver. 1.6.19), it is possible to graphically show statistics and connections between journals and authors. In this sense, this software provides the essential features to create, visualize, and examine bibliometric networks [85]. With regard to the terminology used by the software, 'Item' refers to the object of interest, which can be a publication, a researcher, or a keyword, and so on, depending on the 'type of analysis'. Between any pair of items could exist a 'Link' which means a connection or a relationship that associates them. Each link has a positive numerical value that represents its 'Strength'; a higher value means a stronger link. Items are also grouped into non-overlapping 'Custers', which implies that an item may belong to only one cluster. Therefore, a 'Network' is a collection of items, together with the links between the items.

The software distinguishes four 'types' of analysis (co-authorship, citation, bibliographic coupling, and co-citation), where each type is characterized by the links sought. For every investigation, specific items can be used as 'units of analysis' (UOAs) to be selected: authors, organizations, countries, documents, and sources. Another important parameter that can be set is the counting method, which assigns a unit (full counting) or a fractional (fractional counting) weight (strength) to the link found between the UOAs.

For example, in the case of a co-authorship analysis using documents as items, assuming an article co-authored by n researchers, it is possible either to count the strength of the link between the n authors of that document as 1 (full counting) or to consider the value 1/n for each of the n co-authorship links (fractional counting). In this study, full counting was adopted as it affords stronger significance to collaborations, which is considered fundamental due to the interdisciplinary nature of the subject.

The current study presents different types of analysis, tabulated in Table 1, based on different maps created with VOSviewer (ver. 1.6.19). The filters applied to the data (called thresholds) will be discussed in more detail in their respective paragraphs in Section 3.

Table 1. Parameters applied in the scientometric analysis.

Analysis	Paragraph	Type of Data	Data Source	Links	Items	Thresholds
Journals	3.2	Bibliographic Data	CSV file	Citations	Sources	No. publications: 10 No. citations: 10
Keywords	3.3	Text Data	Txt file	Co-Occurrences	Terms	No. occurrences: 10 No. occurrences: 50
Authors	3.4	Bibliographic Data	CSV file	Co-Authorship	Authors	No. publications: 5 No. citations: 5
Localizations	3.5	Bibliographic Data	CSV file	Co-Authorship	Countries	No. publications: 30 No. citations: 30

A key aspect, therefore, is data acquisition. Bibliometric records can be retrieved from different sources. The main research databases currently employed by scholars (e.g., Scopus, Web of Science, ScienceDirect, Google Scholar, Dimensions, PubMed) differ slightly with respect to various aspects such as the type of publications, journals indexed, and research topics. Our scientometric analysis was conducted based on a bibliometric dataset retrieved from one of the most innovative and larger scientific databases, Dimensions, created in 2018 by Digital Science. This choice is justified by the intention to include as many elements as possible in the study. Moreover, the Dimensions database is particularly suitable for this research purpose, considering the transversality and interdisciplinarity of geopolymers in different research areas such as engineering, geology, chemistry, economics, and architecture.

The use of this database constitutes the first innovative aspect of this study. The numerous scientometric analyses in the literature rely on databases assembled from Scopus or, in a few cases, WoS, as shown in the few examples in Table 2.

The use of Scopus is justified by the authors as it is an established practice in other fields of research. Furthermore, statements such as 'Scopus has wider coverage and more contemporary publications' are often used by authors [84,86,90]. Such statements refer to studies from 2012–2013 (thus outdated) and the recent work of Meho et al., 2019 [92], which, however, only refers to and focuses on conference proceedings. Generally speaking, from 1924 to August 2023, the Scopus database covers 42,115 journals, 23,934 of which are active and in the English language. However, the Scopus and Dimensions databases, in relation to the same parameters, (keyword: geopolymer; resource: articles; years: up to 2022) yield 10,480 and 38,549 items, respectively. Therefore, Dimensions shows a coverage almost four times that of Scopus.

Table 2. Databases and tools for scientometric analysis in the literature.

Authors	Database	Map Tool	Topic	Timespan
Yang et al., 2022 [22]	Scopus	VOSviewer (1.6.17)	Geopolymer concrete	All years to present (–August 2021)
Matsimbe et al., 2022 [86]	Scopus	VOSviewer	Geopolymer concrete	2011–APR 2022
Zakka et al., 2021 [84]	Scopus	VOSviewer	Geopolymer concrete	All years to present (–March 2020)
Darko et al., 2019 [87]	Scopus	VOSviewer (1.6.8)	Green buildings	All years to present (–October 2018)
Ababio et al., 2022 [88]	Scopus and WoS	VOSviewer (1.6.17) Gelphi (0.9)	Circular economy Built environment	All years to present (–March 2022)
Xiao et al., 2019 [89]	WoS	CiteSpace	Green building economics	All years to present (–May 2019)
Asghar et al., 2023 [90]	Scopus	VOSviewer (1.6.18)	Geopolymer concrete	All years to present (–September 2022)
Zhao et al., 2019 [91]	WoS	CiteSpace	Green buildings	2000–2016

Furthermore, as pointed out by [91], Scopus is less efficient than WoS with regard to green buildings when the topic is not strictly observed from an engineering perspective. These considerations reinforce the choice of a database that is inclusive, universal, effective, and unprejudiced, such as the one used in this analysis.

To conduct this review, the three keywords in Table 3 (geopolymer, circular economy, and green building materials) were input into the Dimensions search engine and linked together with the logical operator 'AND'. To the best of the authors' knowledge, these research inputs represent another important difference from the scientometric analyses in the literature. No other studies to date have conducted such analyses considering the three different aspects simultaneously.

Table 3. Parameters applied in retrieving data from Dimensions database.

Parameters	Selections
Document	Article
Language	English
Source	Journal
Keywords	Geopolymer, circular economy, green building materials
Timespan	2000–2022

Yang et al. [22], Matsimbe et al. [86], Zakka et al. [84], and Asghar et al. [90] focused on geopolymers and, more specifically, mortars and concretes. Darko et al. [87] and Zhao [91] explored the vast topic of green buildings. In these studies, there are general economic considerations that emphasize the absence of in-depth research on social and economic sustainability issues. Similarly, studies that focus more on economic aspects, such as Ababio et al. [88] and Xiao et al. [89], deal with construction materials in general and never consider geopolymers.

Table 3 reports, in detail, the research parameters applied in retrieving data from the Dimensions database to better characterize the identified research gap.

As shown in Table 3, the 'document' type and 'source' were limited to 'article' and 'journal', respectively. The document type is limited to articles because, for science mapping objectives, papers in scientific journals have the highest credibility and trustworthiness as research sources and have been categorized as 'certified knowledge' [87].

This criterion is used in most other scientometric analyses; moreover, it is also possible to observe that most of the contributions on geopolymers come from articles in journals [84,90].

In line with previous research, non-English documents were excluded from our study. In addition, it was decided that we would carry out the analysis within the time frame from 2000 to 2022, excluding 2023 in order to avoid partial data.

To this end, Figure 3 schematically reports the procedures followed for the scientometric analysis. The elements not used in our analysis are identified in gray. Thus, among the selectable databases, WoS, Scopus, and OpenAlex are visualized in gray, but only Dimensions is highlighted in green because it is the one chosen and used for the analysis. The same logic is applied to the choice of format and filters for the next step, and so on.

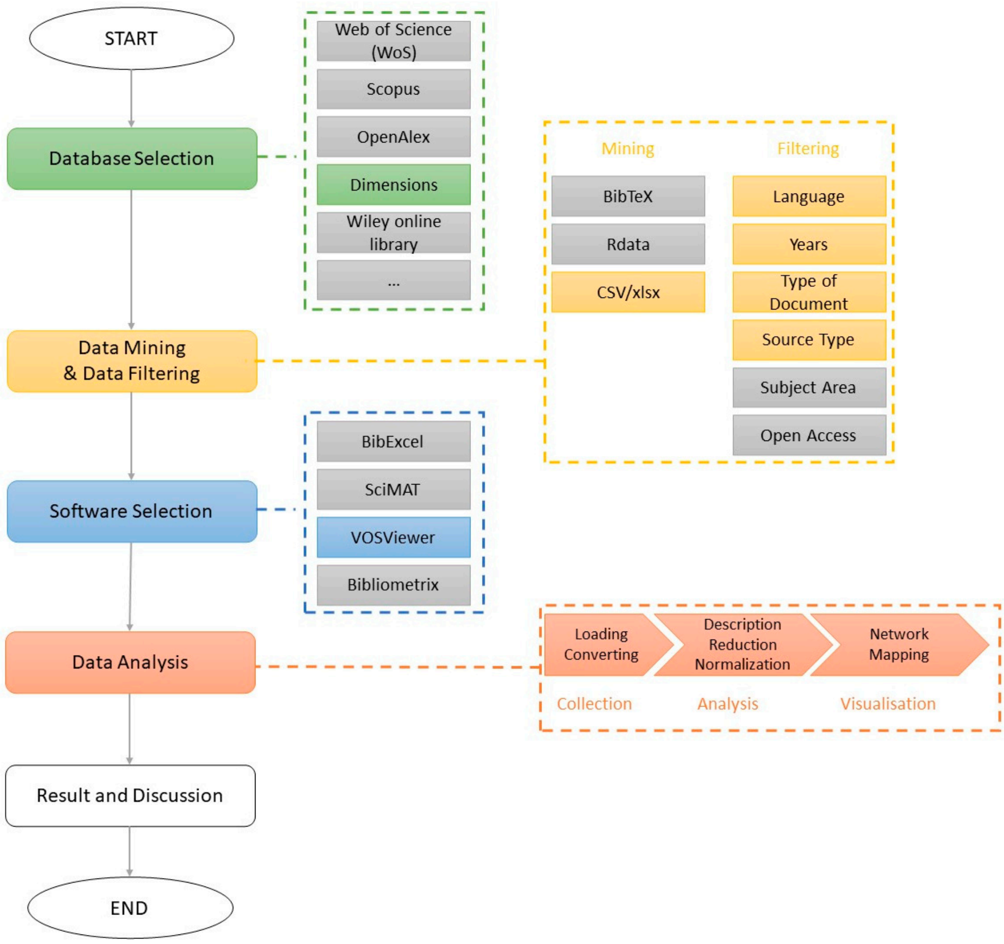

Figure 3. Steps of scientometric analysis in sequential order.

3. Results

In this section, the main results of the study are presented with the help of tables and figures. The scope of this section is to provide and visualize a scientometric analysis of the existing literature on geopolymers, the circular economy, and green building materials. The investigation examines the following aspects: the yearly distribution and growth trends of publications; the top journals in which the articles have been published; keyword co-occurrence, showing the most frequent and relevant terms used in the articles; the top authors who have contributed the most to the field; the articles that received the greatest number of citations; and the countries in which the largest amount of geopolymer research has been conducted.

3.1. Publication Trends and Growth by Year

By systematically examining the number and topics of published works in a specific research field over a period of time, it is possible to obtain a reliable measure of how the field has evolved, its current issues, its emerging trends, and its new challenges. This analysis not only provides a retrospective view of the field's development but also serves as a powerful tool for understanding its current state and helping researchers anticipate the likely directions and topics that will shape its future.

As can be seen from Figure 4, publication trends by year for our three selected keywords show an upward trend, but geopolymers and the circular economy are still less investigated than the vast subject of green building materials.

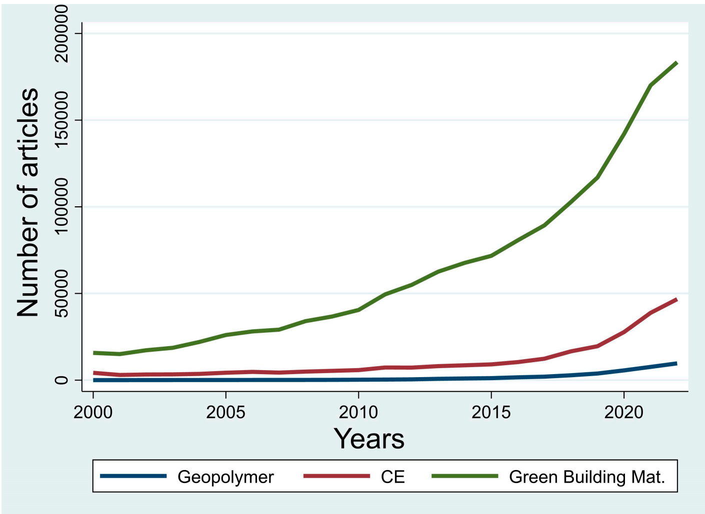

Figure 4. Publication trends by year for geopolymer, circular economy, and green building materials (2000–2022) (our elaboration from Dimensions' data using Stata software ver. 17).

To examine the trends in publication more thoroughly, we present the pairwise publication trends in Figure 5. From this figure, it can be observed that the research on the relationships between geopolymers and the circular economy has scarcely been investigated, while the research on green building materials and the circular economy shows the most growth. Another relevant aspect is that, at the year of beginning of the analysis, there were 0, 2, and 1561 items at the intersections of Geopolymer and CE, Geopolymer and GBM, and GBM and CE, respectively. Therefore, the only pairwise publication trend with some degree of interest in 2000 was the one between green building materials and the circular economy (GBM and CE). The average scientific production in this latter pair remained mostly constant until 2014, although in some cases it showed peaks above and below the annual average value of around 1075 papers/year. Similarly, until 2014, the other two pairs showed a constant trend, but with significantly lower average values (2 papers/year for Geopolymer and CE and 41 papers/year for Geopolymer and GBM).

Finally, in Figure 6, the intersection between the three selected keywords can be seen, which is the scope of the present study. It can be observed that there were no studies simultaneously concerned with geopolymers, the circular economy, and green building materials until 2007. Similarly to the above, the trend can be divided into three periods: an emerging period (2008–2014), a pickup pace period (2015–2018), and an exponentially growing period (2019–2022) that lasts until the present date. In fact, the number of articles published in 2022 was 624, which corresponds to approximately 47% of the total number of publications between 2000 and 2022 (1330).

The findings of the current study are similar to those made by other researchers who have studied geopolymers. In Matsimbe et al. [86], the emerging period is 2001–2008, the pickup pace period is 2009–2015, and the fast growth period is 2016–2021. In Asghar et al. [90] the intervals are 1989–2006, 2007–2014, and 2015–2022, respectively, while in Zakko et al. [84]

the period of the highest growth is 2014 to 2019. To some extent, our results recall the growing trend of LCA studies observed since 2014, in Figure 1, showing increasing attention toward environmental issues, which may represent, at least in part, the reasons behind our findings. According to a thorough analysis of these results, the growing interest in the topic analyzed can be attributed to several factors, including the funding for new materials (as precursors or alkaline activators) and formulations as well as the experiments related to performance optimization, the advances in waste management strategies, the ability to tap into various industrial by-products, and the attention paid to environmental issues and climate change. The last of these factors is also conveyed by international political initiatives such as the Sustainable Development Goals and the Paris Agreement.

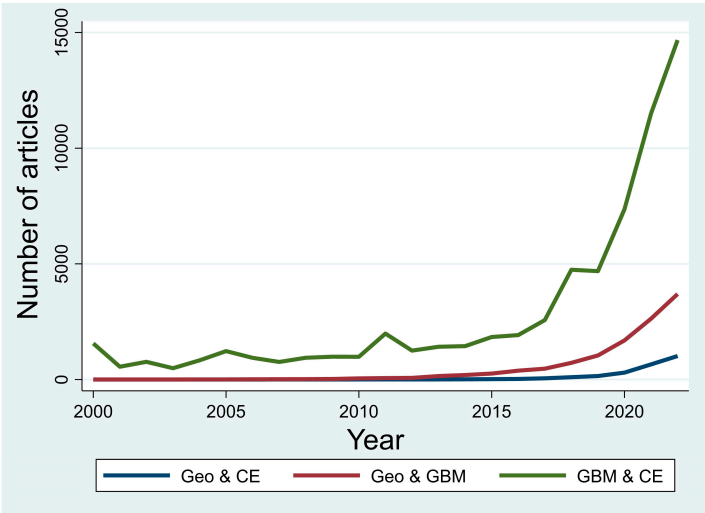

Figure 5. Pairwise publication trends by year (2000–2022) (our elaboration from Dimensions' data using Stata software ver. 17).

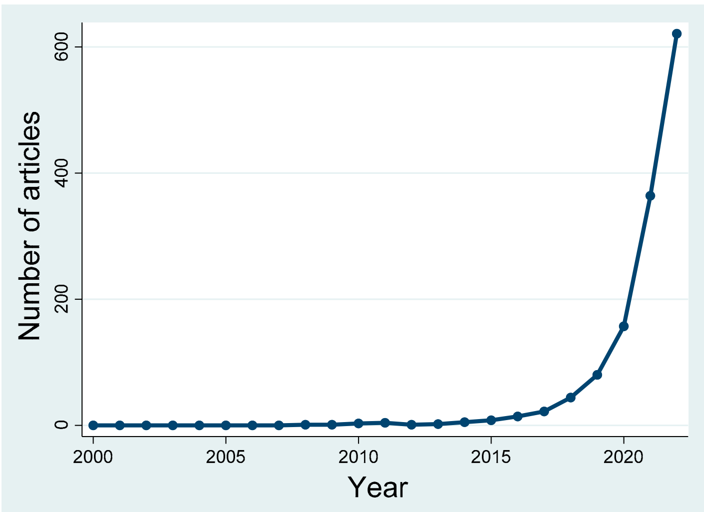

Figure 6. Publication trends by year for the intersection of the selected keywords (geopolymer, circular economy, and green building materials from 2000–2022) (our elaboration from Dimensions' data using Stata software ver. 17).

3.2. Main Journals

The assessment of the advancement and novelty achieved in a certain field or domain can be aided by creating a map representing the sources of publications that are relevant to that specific research area. The map in Figure 7 was created based on the bibliographic data (CSV files) obtained from Dimensions by applying the filter shown in Table 3. It is a 'citations analysis' with 'sources' as UOAs. In this way, the figure displays the network between the publication sources, with at least 10 publications on the research area and 10 citations analyzed reporting our keywords (geopolymer, circular economy, and green building materials). These two parameters (publications and citations) were set to 10 to obtain meaningful results. In this way, they filtered 321 sources into 22 items, which represent just over 5% of the starting set. The 22 elements were classified into five different clusters, shown in Table 4.

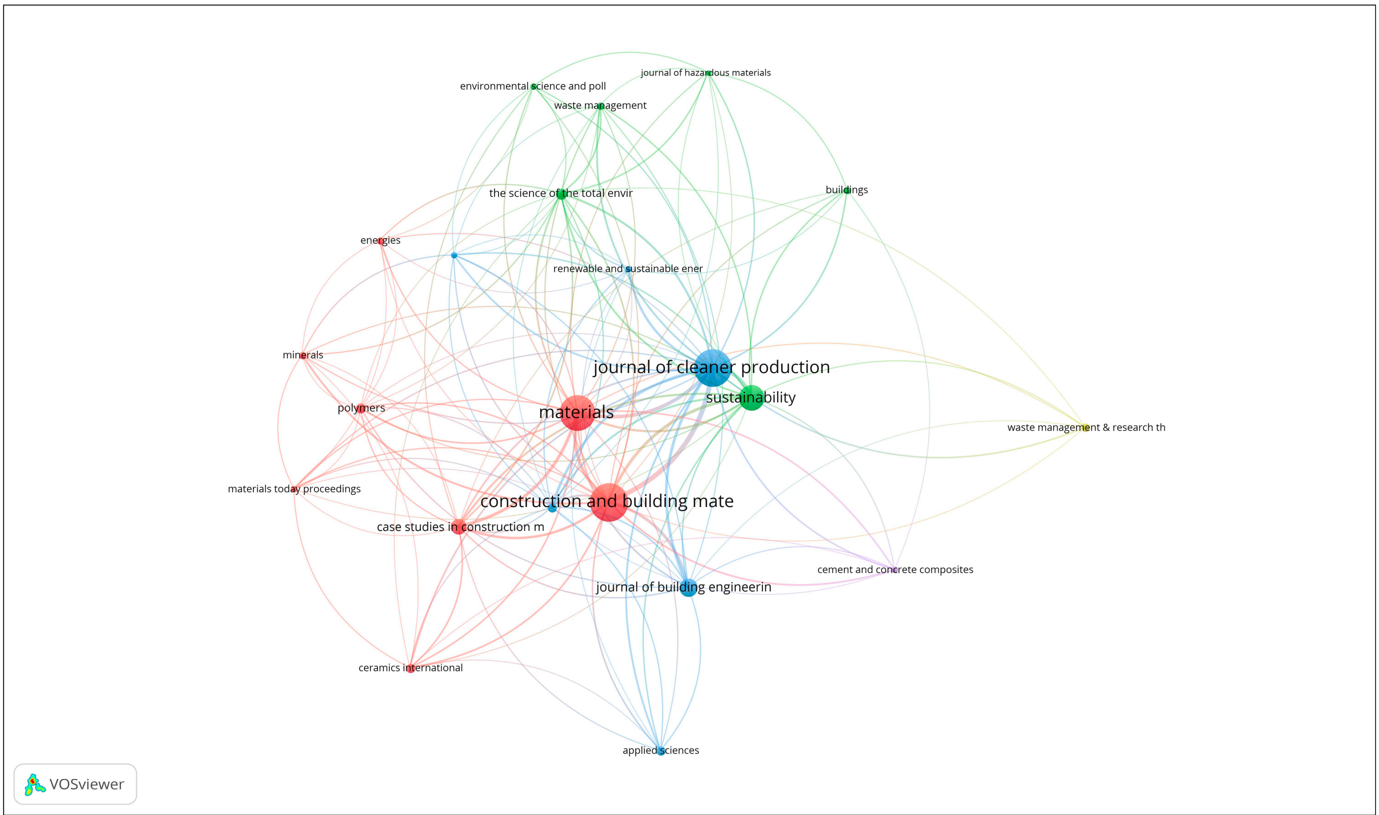

Figure 7. Network of main publication sources.

The map in Figure 7 shows the network of the 22 sources, which consists of 135 links with a total weight of 611 (evaluated via the full counting method). It is worth noting that this approach to analyzing the sources is different from that in previous research. In line with the present study, Ababio et al. [88] developed a 'citation analysis' with 'source' as the UOA but set the parameter to 8, while Asghar et al. [90] conducted a 'bibliographic coupling' with 'source' as the UOA and a parameter of 35. The primary difference between them lies in the type of link sought and the strength given to it. The secondary difference lies in the setting of parameter values. The current study, as in Ababio et al. [88], involved a citation analysis in order to emphasize the links between the sources created by scholars. The choice of the parameter values of 10, as mentioned, was guided by the size and relatively 'new' nature of the starting set, for which a value such as 35 would have restricted the results to only six journals (less than 2% of the total).

In addition, as shown in Table 5, the top five journals are *Construction and Building Materials*, the *Journal of Cleaner Production*, *Materials*, *Sustainability*, and the *Journal of Building Engineering*. This type of analysis is particularly useful for scholars since it is crucial to select reputable and reliable publication sources. By making the best choice it is possible to ensure their research's accessibility and trustworthiness for the target audience. An interesting aspect to note is that in the bibliometric analyses considered in Table 2, *Construction and Building Material*, the *Journal of Cleaner Production*, and *Materials* are included among the most important sources as in the present paper.

Table 4. Classification of main sources into clusters.

Cluster 1 (Red)	Cluster 2 (Green)	Cluster 3 (Blue)	Cluster 4 (Yellow)	Cluster 5 (Purple)
Case Studies in Construction Materials	Buildings	Applied Sciences	Waste Management & Research: The Journal for a Sustainable Circular Economy	Cement and Concrete Composites
Ceramics International	Environmental Science and Pollution Research	Journal of Building Engineering		
Construction and Building Materials	Journal of Hazardous Materials	Journal of Cleaner Production		
Energies	Sustainability	Journal of Environmental Management		
Materials	The Science of the Total Environment	Renewable and Sustainable Energy Reviews		
Materials Today Proceedings	Waste Management	Resources Conservation and Recycling		
Minerals				
Polymers				

Table 5. Top journals with at least 10 documents (2000–2022).

Journals	No. Publications	No. Citations	Impact Factor	Cite Score
Construction and Building Materials	123	3434	7.4	12.4
Journal of Cleaner Production	118	5686	11.1	18.5
Materials	109	1674	3.4	5.2
Sustainability	72	1138	3.9	5.8
Journal of Building Engineering	45	1014	6.4	8.3

3.3. Keyword Co-Occurrence

Analyzing keywords is a useful technique for determining the main research areas of a paper. In this case, the map was based on text data within the bibliographic database file obtained from Dimensions. The aim was to extract the keywords that reflect the essence of the research domain and summarize the most important aspects of the specific research field, helping scholars to identify its scope and boundaries. In the current study, the keyword search was conducted using only the 'title' field. A total of 3491 terms were extracted from the dataset. Of these, 72 keywords met the criterion of a 'minimum number of occurrences' of 10, but only 71 were properly linked. The top five keywords extracted were Review (226 times), Material (188), Concrete (141), Waste (128), and Production (89). Thus, in Figure 8, the network shows 71 items divided in the four clusters of Table 6.

Considering our investigated research area, Geopolymer appears 47 times (the data are underestimated because other similar words such as geopolymers, geopolymer composite, and geopolymer concrete appear too), Circular Economy appears 48 times, and the phrase Green Building Materials does not appear, but Building Material appears 24 times and Construction Material appears 28 times.

Analyzing the results, it can be observed that waste, and more specifically fly ash and slag, is the most frequently investigated precursor for geopolymers. Regarding the characterization of properties, it is noted that mechanical properties are the most researched, and in particular compressive strength is the most frequently investigated. The other even less considered recurring features investigated are environmental impact, LCA, and microstructural studies. Finally, it is interesting to note that references to additive manufacturing appear in addition to traditional 'concrete' and 'mortar'. Similarly, the scope of use is not limited to 'building materials' but is also considered in the area of arts and cultural heritage.

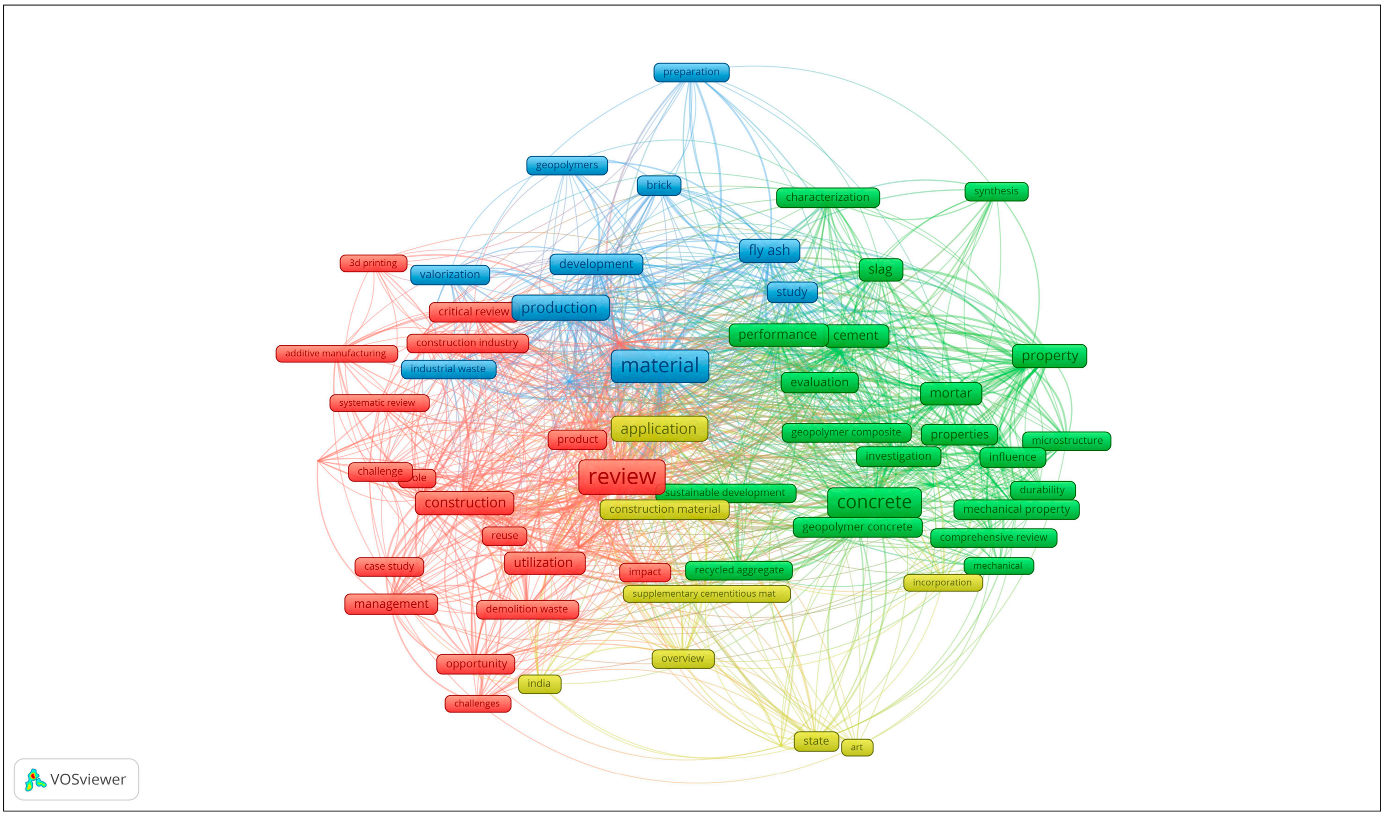

Figure 8. Network visualization of the co-occurrence of keywords.

Table 6. Co-occurrence analysis (clusters and items).

Cluster 1 (Red)		**Cluster 2 (Green)**		**Cluster 3 (Blue)**		**Cluster 4 (Yellow)**	
Keyword	**No. Occ.**	**Keyword**	**No. Occ.**	**Keyword**	**No. Occ.**	**Keyword**	**No. Occ.**
3D Printing	10	Cement	54	Brick	25	Application	84
Additive Manufacturing	12	Characterization	30	Building Material	24	Art	11
Assessment	49	Comprehensive Review	22	Design	26	Art Review	13
Case Study	18	Compressive Strength	21	Development	44	Construction Material	28
Challenge	22	Concrete	141	Fly Ash	71	Incorporation	12
Challenges	12	Durability	13	Geopolymers	14	India	13
Circular Economy	48	Effect	59	Industrial Waste	19	Overview	19
Construction	73	Evaluation	41	Life Cycle Assessment	34	State	27
Construction Industry	22	Geopolymer	47	Material	188	Supplementary Cementitious Material	11
Critical Review	31	Geopolymer Composite	17	Preparation	16		
Demolition Waste	22	Geopolymer Concrete	23	Production	89		
Environmental Impact	18	Influence	24	Study	46		
Impact	18	Investigation	24	Valorization	25		
Management	37	Mechanical	11				
Municipal Solid Waste	11	Mechanical Property	32				
Opportunity	24	Microstructure	18				
Product	31	Mortar	58				
Reuse	20	Performance	60				
Review	226	Properties	39				
Role	13	Property	63				
Sustainability	31	Recycled Aggregate	21				
Systematic Review	12	Slag	52				
Use	46	Sustainable Development	18				
Utilization	51	Synthesis	16				

These findings can certainly assist researchers in identifying relevant papers for their research topics by enabling them to conduct their research more effectively and efficiently.

Subsample of Material Keywords

As a further step to the analysis, our research has been extended to keyword occurrences in the title and abstract with at least 50 appearances. The choice to fix the 'minimum number of occurrences' at 50 comes from the larger size of the dataset, in order to obtain a more meaningful set. In fact, among 27,683, only 190 keywords were selected and are presented in Figure 9. In the density visualization, reddish colors were used to indicate greater influence, and blueish colors to indicate lesser influence. The most recurring keywords are material, waste, property, concrete, study.

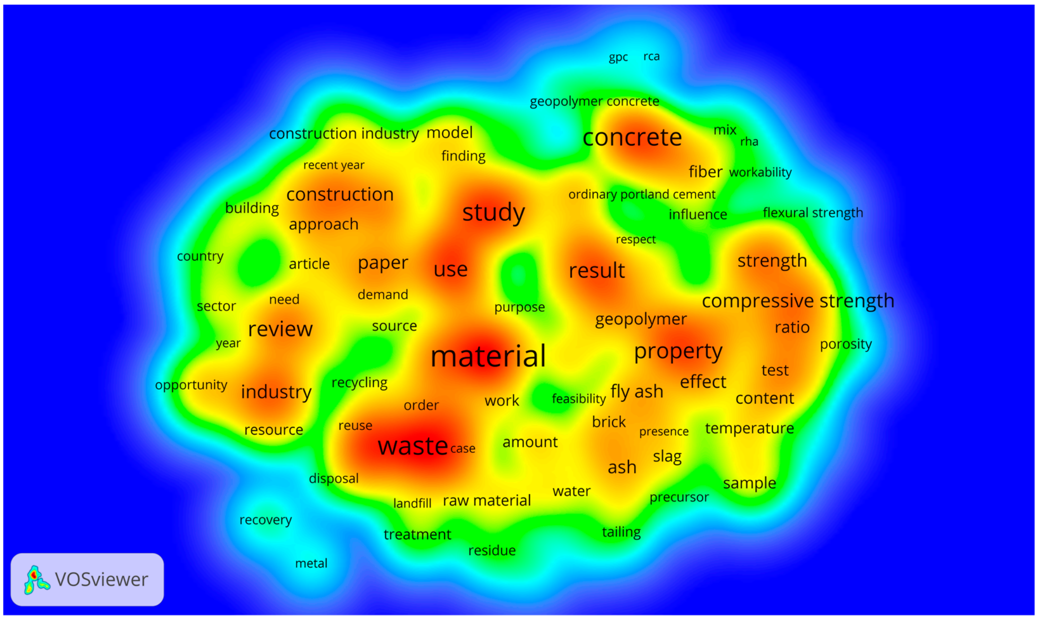

Figure 9. Density visualization of the co-occurrence of keywords.

The first 30 keywords resulting from the scientometric analysis are listed in Table 7, along with their relative number of occurrences. As shown, they mainly relate to materials, technical properties, and industrial applications.

Table 7. Top 30 most occurring keywords in the literature ('title' and 'abstract' fields).

S/N	Keyword	Occurrences	S/N	Keyword	Occurrences
1	Material	1545	16	Construction	505
2	Waste	1156	17	Performance	497
3	Concrete	1035	18	Research	492
4	Study	1011	19	Industry	491
5	Property	785	20	Paper	472
6	Result	741	21	Effect	455
7	Review	717	22	Strength	448
8	Use	706	23	Aggregate	444
9	Application	657	24	Fly Ash	444
10	Production	611	25	Method	444
11	Product	590	26	Ash	427
12	Process	576	27	Composite	423
13	Analysis	571	28	Technology	412
14	Compressive Strength	543	29	Development	383
15	Cement	513	30	Mortar	376

Compared to what can be seen from the analysis in the previous section, the highly experimental nature of the study area can be observed more clearly by analyzing the 'abstract' field. As evidence of this, words such as 'result', 'test', 'investigation', 'experimental result', 'analysis', 'sample', and 'specimen' occur 2275 times (5% of the total occurrences).

In addition, it is also possible to distinguish different fields of investigation, such as physical–mechanical, microstructural investigations, feasibility, process, and mix design (Table 8).

Table 8. Keyword occurences listed by topic.

Pos.	Keyword	Occurrences
	Physical–Mechanical	
14	Compressive Strength	543
22	Strength	448
40	Mechanical Property	304
44	Structure	282
49	Mpa	272
69	Resistance	225
83	Density	185
90	Durability	175
104	Porosity	147
113	Water Absorption	134
120	Flexural Strength	127
121	Microstructure	125
177	Durability Property	62
	Microstructural Investigations	
149	XRD	93
157	SEM	84
171	X-ray Diffraction	70
	Feasibility	
68	Cost	225
148	Workability	93
164	Feasibility	75
	Process	
12	Process	576
54	Time	260
56	Temperature	256
153	Formation	87
170	Manufacture	70
172	Preparation	69
	Mix Design	
31	Addition	353
33	Ratio	341
34	Content	340
86	Composition	180
91	Mix	175
139	Incorporation	102

From Table 8, it is possible to see that the largest share of occurrences concerns mechanical–structural characterization, with a total of 8% of occurrences. Two additional areas are process and mix design (with 3% each). Therefore, 20% of the keywords are related to experimental activities and analyses. These findings reflect the results obtained in the 'title' field, with mechanical properties being the most researched area, and especially compressive strength. However, very few keywords were found indicating research on the thermal–hygrometric performance of geopolymers.

The most frequently used keywords related to materials are presented in Table 9.

Table 9 does not include terms such as geopolymer, GPC, concrete, cement, Portland cement, OPC, solution, binder, mixture, building material, cementitious material, AAM, or SCM. Because of this, it emerges that the most recurring material is related to waste. The items 'waste' (and all the variants that can be associated with it) and 'ashes' together cover more than 50% of the occurrences, strengthening the circular economy perspective of the research. Unexpectedly, metakaolin reaches only 1%, and volcanic ash does not appear, although it can be included under the different keywords 'sand', 'natural resources', and 'natural aggregate'. The material-related keywords can help researchers explore the topic of geopolymers in construction applications as a virtuous and sustainable practice.

Table 9. Occurrences of material-related keywords.

Position	Keyword	No. Occurrences	Position	Keyword	No. Occurrences
2	Waste	1156	108	Waste Material	142
20	Paper	472	126	Industrial Waste	119
23	Aggregate	444	129	Clay	114
24	Fly Ash	444	134	Heavy Metal	109
26	Ash	427	135	Precursor	108
37	Slag	310	140	Natural Resource	102
43	Fiber	284	141	Demolition Waste	101
53	Brick	263	144	Metal	98
59	Raw Material	247	155	Blast Furnace Slag	84
76	Water	197	159	Biochar	79
87	Residue	178	166	Recycled Aggregate	74
88	Solid Waste	176	169	Metakaolin	71
94	Glass	168	182	CDW	59
95	Sand	166	188	Natural Aggregate	54

For further elaboration, the main materials that emerged from the scientometric analysis were entered as keywords in the Dimensions search engine. The aim was to find explicit connections within the parameters studied (identified in Table 3). The results are summarized in Table 10 and are discussed in detail in Section 4.

Table 10. Number of articles found using material-related keywords as additional filters.

Material Precursor	Full Data No. Articles	Title and Abstract No. Articles	Material Precursor	Full Data No. Articles	Title and Abstract No. Articles
Waste	1239	5	Biochar	200	0
Paper	1129	1	Metakaolin	551	0
Fly Ash	1039	2	Kaolin	248	0
Slag	900	1	CDW	154	0
Glass	947	0	Demolition	476	0
Sand	855	0	Silica Fume	500	0
Clay	836	0	Rice Husk	502	0
Metal	884	0	Palm Oil	324	0
Tailing	320	0	Volcanic	195	0
Natural	1163	1	Gangue	116	0

It can be noted that by narrowing the field to recurring keywords in the title and abstract, the number of publications is drastically reduced. Furthermore, the five articles obtained using the 'waste' filter are the same articles obtained with the 'paper', 'fly ash', 'slag', and 'natural' filters.

3.4. Authors' Indexing

A possible method to evaluate the impact that a researcher has in a certain field of study is to consider both the quantity of papers that the researcher has published and the frequency with which other researchers have cited their publications, indicating that their work is relevant and influential in the advancement and innovation of that research area.

As anticipated, the investigation was conducted by setting 'co-authorship' and 'authors' as the type and UOA, respectively, analogous with scientometric analyses in the literature. The main difference is that the threshold was set to 5 for both 'minimum number of publications' and 'minimum number of citations'. This choice here was done also for the optimization of the results obtainable from the dataset of 5164 items. Of these, only 59 authors met the aforementioned parameters. Table 11 lists the main scholars in the field.

Table 11. Scholars with at least 10 publications in the research area.

Scholars	Affiliation	No. Pub.	No. Cit.
João António Labrincha	University of Aveiro, Portugal	17	425
Rui Miguel Teixiera Novais	University of Aveiro, Portugal	13	364
Maria Paula Seabra	University of Aveiro, Portugal	12	166
Bassam A Tayeh	Islamic University of Gaza, Palestinian Territory	12	835
Kinga Korniejenko	Cracow University of Technology, Poland	12	166
Afonso Rangel Garcez De Azevedo	State University of Norte Fluminense, Brazil	12	575
Mirja Illikainen	University of Oulu, Finland	11	334
Yassine Taha	Université Mohammed VI Polytechnique, Morocco	11	144
Mostafa Benzaazoua	Université Mohammed VI Polytechnique, Morocco	11	144
Rachid Hakkou	Cadi Ayyad University, Morocco	11	144
Mehrab Nodehi	Texas State University, United States	10	325

The authors with the most published papers are, firstly, João António Labrincha from the University of Aveiro (Portugal) with seventeen publications; secondly, Rui Miguel Teixiera Novais from the University of Aveiro (Portugal) with thirteen publications; and thirdly, Maria Paula Seabra from the University of Aveiro (Portugal), Bassam A Tayeh from the Islamic University of Gaza (Palestinian Territory), Kinga Korniejenko from the Cracow University of Technology (Poland), and Afonso Rangel Garcez De Azevedo from the State University of Norte Fluminense (Brazil) with twelve publications each.

Moreover, in Figure 10, it is shown how researchers from different areas of the globe are connected through co-authorship. This indicates the existence of an international network of knowledge sharing and collaboration among researchers in the investigated area.

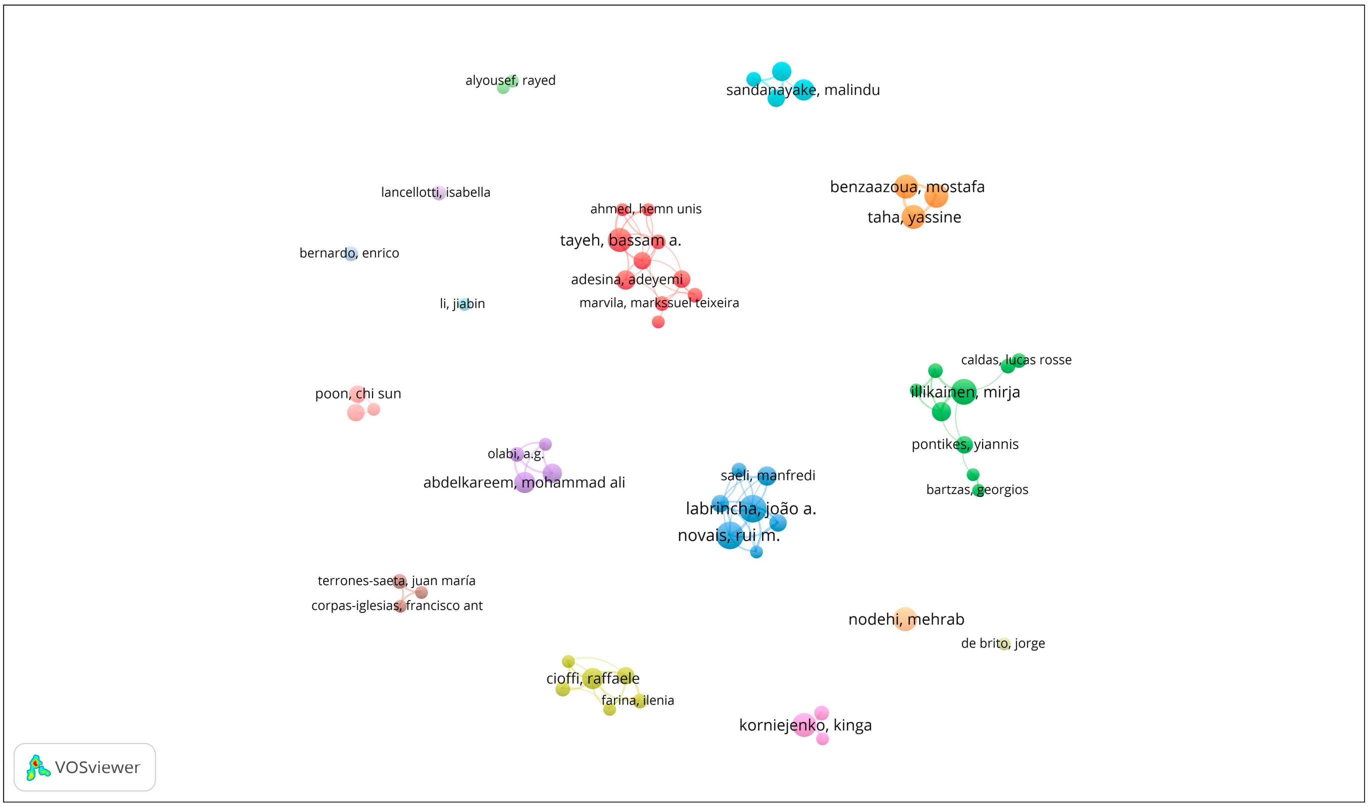

Figure 10. Network of main authors based on co-authorship.

The findings differ from those of the other scientometric analyses, but this is not surprising. It indicates that the topic of geopolymers from a circular economy perspective requires transversal expertise involving different research groups.

In Figure 10, bibliometric records appear divided into 16 clusters with 90 links, with a total link strength of 313, and connections occur exclusively within the same clusters. To extend our analysis, in Figure 11 it is possible to see the detailed composition of the larger cluster. It comprises 10 elements divided into three sub-clusters, with 22 links.

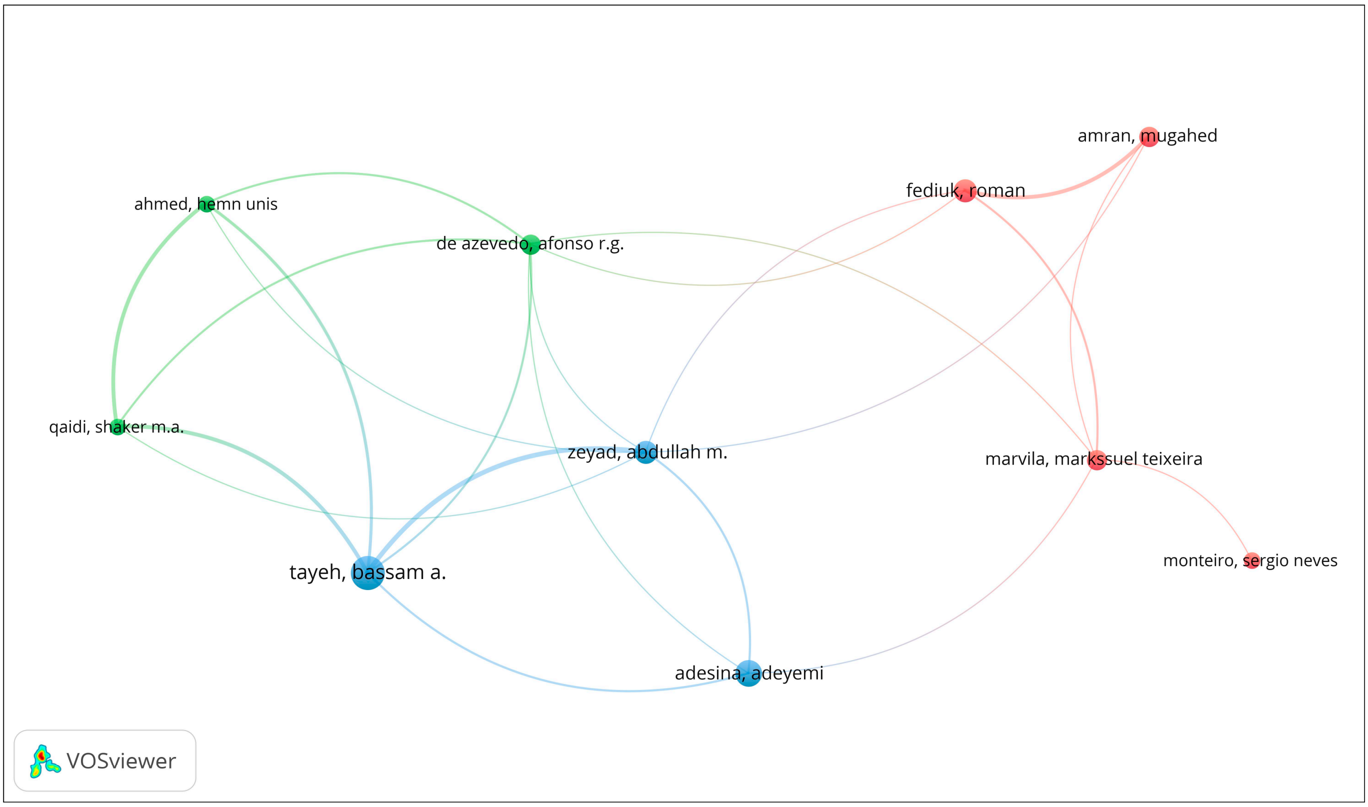

Figure 11. Larger cluster of main authors based on co-authorship.

3.5. Location of the Studies

Information about the leading countries in a certain research area can provide several benefits for the research community, such as encouraging more cooperation among researchers from different countries, enhancing the transfer of knowledge and best practices across borders, and even increasing the opportunities for joint funding from international agencies and organizations. To this end, Figure 12 presents a bibliometric mapping to help readers determine the locations that contributed the most research to the investigated area. The method of analysis examined co-authorship among researchers from different countries. This study focused on the relationships between countries rather than institutions. Moreover, to ensure the relevance of the data, the 'minimum number of documents' and 'minimum number of citations' were set both to 30. Of the 94 countries in the dataset, only 17 met these requirements. The countries were divided into three clusters, as shown in Table 12. Cluster 1 includes mainly highly developed countries, Cluster 2 mainly includes developing countries, while in Cluster 3 we find a small group of Latin-speaking countries.

The countries with the highest number of publications are China, India, the United Kingdom, Australia, and Italy, with 263 (19.5% of the total), 129 (9.6%), 94 (7.0%), 93 (6.9%), and 90 (6.7%), respectively.

This result shows that countries with high or increasing economic development have already recognized the advantages of studying geopolymers from a circular economy perspective and are exploring their suitability for the construction industry. In this respect, it is interesting to note that of the 17 selected countries, 7 are European (UK, Italy, Spain, Portugal, Poland, Germany, and Belgium), accounting for 33.8% of the total publications. However, developing countries are still underrepresented in the scholars' global network; specifically, Middle Eastern countries in our sample together contributed only 10.5% of the publications, while Latin America were responsible for 4% from Brazil alone, and there were no contributions from countries in Africa.

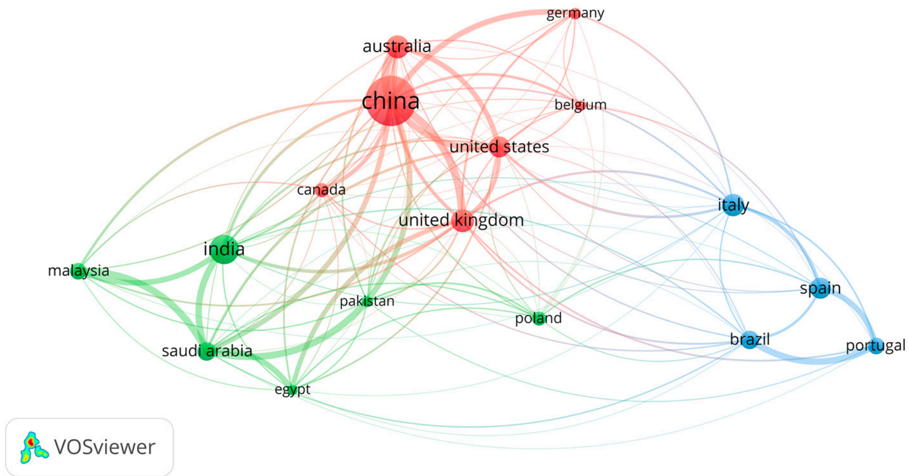

Figure 12. Mapping of the main countries.

Table 12. Co-authorship analysis using countries as UOAs (clusters and items).

Cluster 1 (Red)	Cluster 2 (Green)	Cluster 3 (Blue)
Australia	Egypt	Brazil
Belgium	India	Italy
Canada	Malaysia	Portugal
China	Pakistan	Spain
Germany	Poland	
United Kingdom	Saudi Arabia	
United States		

4. Discussion

The results revealed that there is a significant and consistently increasing trend in the literature on the topic of geopolymers as advanced green building materials that are studied from a circular economy perspective. This indicates that there is a growing interest and awareness among researchers of the potential benefits and applications of geopolymers as sustainable and circular materials for the construction industry. Furthermore, the circular economy promotes the best practices of waste management to decrease disposal impacts and the depletion of new land resources. Despite this growing trend, as presented in Section 3.1, geopolymers and the circular economy have not been sufficiently studied with respect to the wider category of green building materials, with a substantial gap still visible in the literature.

Moreover, the small number of journals publishing in this research area (only 22, using the threshold in Section 3.2) clearly represents a limitation for scholars contributing to this topic.

The analysis of keywords highlights the diverse research areas within the field of geopolymers. One of the most explored topics concerns the formulation of mixtures and therefore the raw materials that can be used. In more detail, the keywords relating to materials, listed in Table 9, represent 14% of the total recurring words. The subsequent in-depth analysis, however, shows that the number of publications that mention these material-related keywords explicitly in titles and abstracts is drastically smaller (Table 10).

This reduction can be traced back to the fact that scholars, when focused on specific materials to evaluate the possible uses or performances of geopolymer mixtures, neglect or do not explicitly take into consideration aspects related to the circular economy.

Another interesting aspect of the above-mentioned subsequent in-depth analysis is the number of items obtained. As evidence of this, only five articles were obtained from the 20 keywords in Table 10. The findings are summarized in Table 13.

The first is a review article on GPCs that places special emphasis on the environmental and economic aspects of sustainable development and the circular economy. Hence, specific fields in Table 13 remained unfilled. Shehata et al. [93] present an extensive review on potential applications in various construction sectors, from the scale of infrastructure (bridges, roads, etc.) to buildings (tiles, blocks, panels, etc.). Scalia et al. [94] evaluate the possible use of spent ground coffee (SCG) to produce geopolymers and natural mortars, proposing a multi-criteria approach for the process and product optimization. Similarly, Tian et al. [95] evaluate the use of different waste materials to produce porous geopolymers for thermal applications without compromising mechanical performance. Saeli et al.'s [96] study focuses on the use of ash and alkaline effluents from the paper industry's biomass to replace metakaolin in geopolymer binders and mortars. Finally, Shao et al. [97] evaluate the use of oyster shells to produce high-pressure geopolymer bricks, analyzing their mechanical performance (compression and flexural), abrasion resistance, and CO_2 emissions.

From a technical point of view, a relevant aspect that emerges from the current scientometric review is the difficulty in formulating and optimizing mix designs. This is also caused by the absence of standardized procedures, which forces scholars to rely on trial-and-error approaches.

Regarding the geographical areas involved in the research on geopolymers and the circular economy (Section 3.5), it can be noticed that, despite the massive presence of China as the leading country in this research and the consolidated attention toward the topic received from several advanced European countries, there is still a lack of interest from developing countries that have not yet engaged in this research area. This suggests that there is a need for more awareness and dissemination of the potential benefits and challenges of geopolymers and the circular economy for the sustainable development of these countries.

In this sense, a crucial aspect to consider is building regulations, which are widely acknowledged as powerful, scalable, and effective tools for achieving the objective of zero-emission buildings by 2050. Many countries are expanding their minimum performance standards and energy codes for buildings, and the uptake of efficient and renewable building technologies is accelerating. However, only a few countries (e.g., France, Australia, New Zealand, and the USA) have begun to adopt geopolymers within their building practices and regulations, representing an important legislative gap for the development of technology, especially considering that approximately 40% of new construction by 2030 will occur in regions without regulations or with regulations that are still being developed.

Table 13. Co-occurrence analysis: cluster and items.

Authors	Material	Alk. Conc.	L/S	Standards Used	Curing	Comp. Strength	Flex. Strength	Analysis
Shehata et al., 2022 [93]	Literature Review							
La Scalia et al., 2021 [94]	Spent coffee groundsBiomass fly ash (from paper) Metakaolin	10 M	0.76 0.82	European Standard EN 998-2:2016 UNI EN 196-1:2016 (specimens' preparation) UNI EN 1015-11:2007 (standard metallic molds) UNI EN 1015-3:1999 (consistency/workability) ISO 6946:2017 (thermal conductivity)	28 25 °C, 65% RH	21.66 ± 1.91 MPa	4.08 ± 0.72 MPa	SEM, flow table test, workability, bulk density, compressive strength, flexural strength, bending deflection, water absorption, thermal conductivity, economic impact
Tian et al., 2022 [95]	Fly ash Lithium slag Silica fume Slag Coal Gangue Aluminum powder (as foaming agent)			Chinese standard GB/T 8077-2012 (fluidity/workability) Chinese standard GB/T 1346-2011 (setting time fresh paste) Chinese standard GB/T 11969-2020 (compressive strength)	7 days precuring at 30 °C for 4 h; 60 °C, 95% RH for 3 days; ambient condition	1.76 MPa 4.50 MPa		Bulk density, compressive strength, slump flow, thermal conductivity, porosity, SEM, XRD, FTIR, thermal stability
Saeli et al., 2017 [96]	Biomass fly ash Alkaline effluent Metakaolin	10 M	0.76 0.82	European Standard EN 998-2:2016 UNI EN 1015-11:1999 (compressive and flexural test) UNI EN 1015-3:1999 (consistency/workability) UNI EN 1015-18:2002 (water absorption)	7–28 days 20 °C, 60% RH	22.15 ± 1.22 23.73 ± 0.69 MPa	~4 MPa	XRD, XRF, IPC, bulk density, micrograph, EDS, water absorption, compressive strength, flexural strength, consistency
Shao et al., 2022 [97]	Oyster shells Quenched blast furnace slag	6 M	0.2	Taiwan Standard CNS13295 (compressive test) Taiwan Standard CNS1234 (bending test) Taiwan Standard CNS13297 (abrasion test) CNS1223 (blast furnace slag)	7–14–28 days	13.00 MPa 39.57 MPa	3.6 MPa	Compressive strength, bending strength, abrasion resistance, bulk density, porosity, water absorption, TCLP, carbon reduction

4.1. Limitations

Although the scientometric method applied has analyzed a vast number of publications, some limitations can certainly be attributed to the database (Dimensions rather than Scopus or WoS) and dataset used (e.g., excluding conference papers and book chapters), to the non-consideration of similar terms (e.g., geopolymers, geopolymer composite, and geopolymer concrete instead of geopolymers, and green concrete or green cementitious materials instead of green building materials), and to the languages not selected (e.g., Chinese).

Another limitation is the difficulty in distinguishing collocations, whereby words such as 'paper', which may refer to different things (material or study), are counted in co-occurrence analyses regardless of their role in the text. Although these limitations can affect the accuracy of the results of the study, the findings are not expected to change significantly. This is due to the fact that the limitations are intrinsic to the type of analysis, and, for this reason, they were taken into consideration when selecting the different parameters.

4.2. Avenues for Further Research

This scientometric analysis aids in the identification of research gaps and aligning research with market demands. The latter aspect is crucial to ensure that research can be applied in real-world situations and also to increase the chances of the research of being funded and published.

An interesting avenue for further research could be the extension of such a methodology for the international comparison of geopolymer production using local raw and waste materials, with the aim of exporting best practices and green solutions from one part of the globe to another. The selection of building materials remains one of the most delicate steps in sustainable design due to the wide landscape to draw on and because of the lack of adequate information and guidance. Sustainability and CE, when applied to building materials, should be evaluated and defined individually, taking into account factors like location, energy sources, applications, conditions, and long-term performance. For example, the findings of this scientometric analysis show that studies aimed at minimizing the usage of activators such as sodium silicate and sodium hydroxide, which are the main pollutants of geopolymer production [45,49,58], should be further investigated. The exploration of novel bio-based alternatives to supplant traditional alkaline activators is pressing. Similarly, the adoption of geopolymer construction materials (e.g., binder, mortar, concrete, brick) for long-lasting applications in the AEC (architecture, engineering, and construction) industry could be further explored. In this regard, innovative applications such as additive manufacturing, which is beginning to appear for these innovative materials, should be further investigated. An advantage of this type of application is its user-friendliness. When discussing this last characteristic, it is noteworthy that a knowledge gap emerged in the analysis of the keywords concerning the study of one-part geopolymers. Possible future progress, therefore, concerns the construction of a mix design protocol suited for geopolymers for architectural uses. The best practices related to the circular economy could be brought into this protocol, fostering a societal perspective. According to the part of the analysis showing the most used inputs, future studies could concentrate on cost analysis and evaluate different policies and schemes, both monetary and non-monetary, that encourage the use of green technologies and materials from a societal perspective. Indeed, from a policy perspective, policymakers aiming to generate national income growth without wide and irreversible negative impacts on the environment (so-called green growth) can promote the use of R&D and production subsidies to foster the development of cleaner technologies and carbon taxes to accelerate the transition to green productions (the so-called Pigouvian subsidy and Pigouvian tax). Since subsidies are generally financed through taxation, future research could measure how much taxpayers are willing to pay for green geopolymer materials, applying both direct and indirect methods to assist scholars and policy makers in implementing environmental and financial sustainable measures.

5. Concluding Remarks and Policy Implications

The scope of this study was to conduct a scientometric evaluation of the vast bibliographic data retrieved from the Dimensions database on geopolymers, the circular economy, and green building materials. The dataset included 1330 articles ranging from 1 January 2000 to 31 December 2022. Scientometric analysis is a useful tool to visualize the most reliable sources and the latest developments. The most important keywords, authors, institutions, and countries that contributed to the research area of GP, CE, and GBMs are shown. Based on the analysis conducted, significant results were identified:

- Regarding publication sources, the top five most favored outlets for geopolymer research publication are *Construction and Building Materials*, the *Journal of Cleaner Production*, *Materials*, *Sustainability*, and the *Journal of Building Engineering*.
- João António Labrincha is the author with the largest number of publications in this area, totaling 17 articles. However, in terms of citations, Bassam A. Tayeh takes the lead with 835 citations.
- The co-occurrence analysis underscored the experimental nature of the research field, highlighting the significant activity focused on optimizing the production process and identifying suitable raw materials.
- The most recurring keywords related to raw materials were 'waste' (and its derivatives) and 'fly ash', recalling waste management issues and reinforcing the circular economy perspective of this study. Together, they cover more than 50% of the keywords in the field of materials research.
- Following the scientometric analysis approach performed in previous research, the innovative aspect of our findings mainly relates to the CE perspective that enables this issue to be studied from a societal perspective. Indeed, scholars have, in previous research, concentrated their attention on mechanical performance investigations, where the principal aim is to reach specific quality standards without taking into account (environmental or economic) costs.
- Economics analysis is crucial at this stage of research and development, since conducting research that is aligned with market demands can increase the chances of the research being funded and incentivize its practical implementations.
- Research on geopolymers has strong experimental features but is lacking a regulatory point of view.

Therefore, policymakers have a fundamental responsibility to not only regulate the energy efficacy of buildings but also to promote the utilization of materials that provide high performance without harming human health and the environment.

In this sense, a planned policy of long-term investments in R&D and the production of green materials, such as geopolymers for the construction sector, can foster the circular economy and increase sustainability. Considering our case study in detail, these kinds of subsidies appear particularly suitable given that the literature has already investigated the cost competitiveness of geopolymer building materials in relation to traditional alternatives, stating that they are generally more expensive (e.g., [64,71,98]). In this sense, the implementation of governmental subsidies for R&D activities and production is important, especially in the early stage of development, during which these new materials cannot be competitive in the market, to enhance the production of existing geopolymers and foster the implementation of new greener and better-performing formulations.

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