

Review

Bibliometric Analysis of Zeolite in Concrete Using VOSviewer: Advancing Sustainable Construction Materials

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Abstract

A comprehensive bibliometric analysis of zeolite in concrete was conducted using VOSviewer software (version 1.6.21). The database was obtained from Scopus by searching for zeolite in concrete. A filter for the years 2000 to 2025 was applied. A total of 1001 documents related to zeolite concrete fulfilled the criteria and were downloaded. The co-occurrence networks and overlay technique were utilized to illustrate relationships. The publication trends, publication area, document types, and country-wise publications were considered for analysis. Also, the top universities/institutions and funding sources that supported zeolite in concrete-related research were considered. Furthermore, keyword analysis was used to find the past, current, and future research trends. The findings highlight the increasing importance of zeolite-based concrete, particularly from 2015 to 2024. Engineering accounted for the largest publication base, with 614 articles. Research articles represented the predominant document type, with a total of 664 publications. In contrast, only 40 of the 1001 articles are full-length review papers. The country-wise analysis indicates that Iran (163) and China (146) are at the top in scientific contributions. The keyword analysis indicates that most researchers focus on “Zeolite,” “Concrete,” “Compressive Strength,” and “Durability”. The bibliometric analysis further reveals a clear shift in zeolite-concrete research toward sustainability applications focused on durability, geopolymer, and self-compacting concrete. In addition, the study identifies several underexplored research themes, including shrinkage, creep, life-cycle assessment, and artificial intelligence-based mix optimization. The findings provide a research roadmap for advancing the next generation of sustainable zeolite-based concrete.



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Keywords: concrete; zeolite; sustainability; bibliometric analysis

1. Introduction

Bibliometric analysis is widely used for examining large bodies of scientific literature. The analysis allows researchers to trace how a field has evolved [1]. Bibliometric analysis serves as an important component of research [2]. A study [3] indicates that a repeatable bibliometric approach shows what is being studied. It also indicates how the research has changed. The main stages in bibliometric analysis involve collecting data from appropriate databases. Then, applying a range of bibliometric techniques collectively supports the production of reliable information [4]. Bibliometric analysis offers an overview of a research

domain by organizing information according to publications, contributing authors, and the journals in which the work appears [5].

In parallel with advancements, the growing awareness of sustainability issues has placed pressure on the concrete industry to lower its CO₂ emissions [6]. Limited natural resources are attracting researchers to identify alternative materials [7]. Concrete is one of the most widely utilized construction materials worldwide [8]. Therefore, significant innovations have emerged in the concrete industry to enhance its sustainability [9]. Such innovations include the incorporation of alternative materials such as fly ash [10], silica fume [11], ground granulated blast-furnace slag (GGBS) [12], metakaolin [13], rice husk ash [14], limestone powder [15], volcanic ash [16], palm oil fuel ash [17], sugarcane bagasse ash [18], and other supplementary cementitious materials (SCMs).

However, natural zeolite possesses several unique characteristics that distinguish it from conventional SCMs such as fly ash, silica fume, and GGBS. Natural zeolite is a naturally occurring hydrated aluminosilicate mineral with a framework structure [19,20]. Furthermore, zeolite has a highly porous structure and excellent ion-exchange capacity. Also, its internal pore structure provides internal curing, moisture regulation, and pore refinement. A recent review also highlights that zeolite shows promise as a viable alternative to cement with positive effects on durability [21]. The engineering performance of zeolite depends on its mineralogical composition, with certain types such as clinoptilolite, mordenite, and chabazite exhibiting different pozzolanic reactivity. The distinctive characteristics differentiate zeolite from other SCMs and justify the need for a dedicated bibliometric analysis.

According to one study, it is clear that the global utilization of waste is increasing yearly, and recycling rates remain far below what is required to meet climate goals [22]. Factories produce a wide range of goods on a large scale, and this trend is expected to generate substantial amounts of solid waste [23]. Rapid global development and a continuously growing population lead to the demand for new infrastructure and buildings at an increasing rate [24], highlighting the urgency of identifying sustainable concrete solutions.

In addition to industrial by-products, naturally occurring SCMs have also attracted considerable attention for sustainable concrete. Among these SCMs, natural zeolite has emerged as a promising SCM because of its pozzolanic activity, internal porous structure, and ability to improve the performance of concrete. The findings indicate that the SCM mix made with NZ can be effectively used in many conventional applications, such as walls and columns. However, the higher zeolite percentages in concrete require attention during transportation and handling [25]. The concrete mixes made with 10% zeolite show the highest compressive and flexural strengths as compared to the other mixes [26]. Another study indicates that compressive and flexural strengths decreased with zeolite at an early age (7 days). However, at later ages (28 and 90 days), the mix shows better performance as compared to the control mix. The improvement is attributed to the pozzolanic reaction of zeolite. The pozzolanic reaction generates additional secondary CSH gel. The secondary CSH gel contributes to a denser binder, which leads to a more compact interfacial transition zone (ITZ) [27]. Also, a study [28] concluded that the pore size distribution is the key indicator of zeolite contribution in mixes. Accordingly, the findings indicate that a slight increase in pore volume (0.01 to 0.1 μm) was observed for concrete mixes made with up to 20% zeolite. Similarly, another study's results show that 20% zeolite is the most suitable option [28]. A study [29] recommends that 15% zeolite in concrete mix appears to be a suitable option for enhancing the characteristics of concrete.

2. Research Significance

The cement industry releases significant amounts of harmful gases, particularly CO₂. Furthermore, it also consumes considerable natural resources. Also, the cement industry requires a huge amount of energy and further increases its cost of production. Therefore, the partial replacement of cement with natural zeolite contributes to reducing the environmental impact of concrete by lowering cement consumption and improving concrete performance. Furthermore, the inclusion of zeolite in concrete reduces the cost of production while improving concrete performance in terms of durability, strength, and sustainability.

A bibliometric study is important because it offers an in-depth overview of research trends, identifies research gaps, and highlights major researchers, institutions, and funding sources [30–33]. These aspects help researchers and engineers to remain aware of recent advancements, avoid repeating previous work, and focus on areas that require further study. Also, it improves collaboration among researchers and helps funding organizations allocate their resources toward important research areas.

Previous reviews [34] presented limited bibliometric mapping and science-mapping techniques to support systematic literature reviews on natural zeolite in concrete. However, these analyses were primarily intended to assist literature selection and keyword visualization rather than provide a comprehensive bibliometric evaluation of the research field.

Therefore, this research aims to conduct a comprehensive bibliometric analysis of zeolite in concrete. It focuses on many important bibliometric analysis aspects, including publishing trends to assess the annual distribution of research, publication area to determine the major disciplines, and document types to classify publications such as journal articles, conference papers, and reviews. In addition, this research also examines publications according to country to determine the geographical distribution of research contributions and evaluate the major contributors. The research also identifies top universities/institutions and significant funding sources that financially support zeolite in concrete-related research. The study also performed keyword analysis to find the past, current, and future research trends. Finally, this research identifies a weak area (research gap) and recommends future research needed to improve zeolite concrete performance.

The present bibliometric study identifies how scientific priorities have changed over time. The analysis reveals a transition from studies highlighting material characterization and compressive strength toward durability, sustainability, geopolymer, and advanced concrete applications. The keyword evolution analysis identifies several underexplored research areas and provides a roadmap for future investigations. Therefore, the insights extend beyond descriptive publication statistics and offer practical guidance for researchers and industry in identifying future research priorities for sustainable zeolite concrete.

3. Research Methodology

In this research, a bibliometric analysis was conducted through VOSviewer software (version 1.6.21), which can visualize co-occurrence networks and map relationships among the various key terms. Bibliographic data were retrieved from the Scopus database using the search query “zeolite in concrete.” The search strategy was selected to retrieve publications specifically focused on the application of zeolite in concrete and to ensure a reproducible bibliometric dataset. Scopus provides comprehensive coverage of peer-reviewed literature in engineering, materials science, and construction. Therefore, it is one of the most widely used databases for bibliometric studies.

A filter for the years 2000 to 2025 was applied to select only articles published during that period. The bibliographic data were downloaded from Scopus on 20 February 2025.

Therefore, the records for 2025 represent a partial publication year, and publications indexed after the download date were not included in the analysis. A total of 1001 articles were found relevant and downloaded for analysis. The “Author keywords” were identified using a complete counting technique, setting a minimum occurrence threshold of 10 to determine the most relevant terms, giving a total of 34 keywords. Data visualization methods, including co-occurrence networks and overlays, were employed to clarify links among terms and evaluate the development of study aspects over time. This method offers an extensive analysis of trends and advancements in zeolite concrete research while identifying areas for further studies.

4. Bibliometric Analyses of Zeolite in Concrete

Bibliometric analysis is a method of study that applies statistical approaches to assess and analyze academic paper publications. This study obtained the data from the Scopus database by searching the keywords “zeolite AND concrete,” with a time filter covering papers published from 2000 to 2025. A total of 1001 papers discussing the application of zeolite in concrete were identified. The detailed analysis follows:

4.1. Publications Trends

Figure 1 shows the publication trends of zeolite in concrete from 2000 to 2025. The findings indicate that the number of publications gradually increased up to 2012 and significantly increased in 2013, which shows 48 publications. Most papers published from 2000 to 2012 probably concern preliminary investigations, fundamental research, and the investigation of potential applications. The significant increase in 2013 might be due to new findings, technological advances, or emerging trends in the construction and material sciences fields, which attracted research interest in the use of zeolite in concrete. However, there was a temporary decline observed during 2014, with publication of only 27 articles. This present bibliometric analysis does not provide evidence to determine the reasons for this fluctuation.

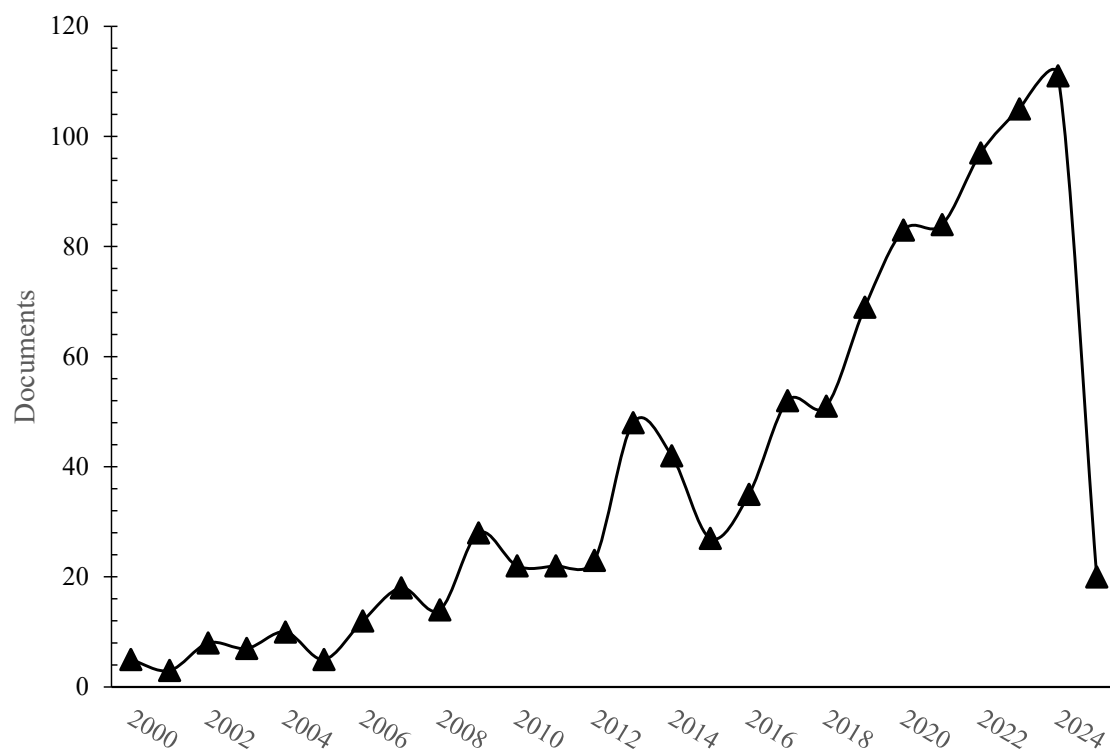


Figure 1. Publication trends from 2000 to 2025.

Furthermore, a constant increase in publications was noted from 2015 to 2024, with 111 publications in 2024. This publication trend in research on zeolite in concrete highlights the ongoing development of materials science research and the growing need for sustainable and efficient construction materials. In addition, it should be noted that the apparent decline in publications during 2025 should not be interpreted as a reduction in research interest. The bibliographic data were downloaded from the Scopus database on 20 February 2025. Therefore, the records for 2025 represent only a partial publication year and do not reflect the publication results for the entire year.

4.2. Area of Publications

Figure 2 shows the research areas of publications related to zeolite in concrete from 2000 to 2025. The distribution of publications within different areas shows that the engineering field has the largest number of zeolite-related publications (614 total publications) as compared to the other subject areas. The highest number of publications in the engineering field highlights its importance, particularly civil and structural engineering, which continually explores the practical uses of zeolites in concrete. Engineers focus on improving the mechanical characteristics, durability, and sustainability of concrete by the incorporation of zeolites. The higher publication rate in the engineering field indicates considerable industry interest and continuous study in the improvement of concrete by utilizing zeolites. The second highest research area of zeolite in a concrete-related is in materials science, with 422 total publications. Materials science researchers study the microstructural properties of zeolites, their interactions with other constituents in concrete, and their role in the development of strong concrete mixes. Environmental science contributes 181 total publications that highlight the environmental benefits of zeolite concrete. Zeolite-based concrete mitigates the environmental effects of concrete by improving waste management, improving durability, and reducing energy use. Environmental researchers tend to highlight the environmental advantages of zeolites in concrete, such as enhancing concrete recyclability, conserving natural resources, reducing carbon emissions during production, and increasing structural durability. The fields of physics and astronomy have produced 133 articles. Physics and astronomy researchers mostly examine the behavior of zeolites at atomic and molecular levels, particularly with their contribution to enhancing the physical properties of concrete materials. Earth and planetary science follows with only 119 publications, which mainly focus on the natural occurrence and properties of zeolite minerals. Energy significantly contributes with 73 total papers, and chemistry accounts for 68 publications, highlighting its substantial impact on the scientific environment. Zeolites have considerable energy-related uses in concrete. The decrease in thermal conductivity indicates that zeolite-modified mortar possesses better insulating characteristics. Compared to other areas, chemistry and chemical engineering have only a small number of articles: 68 and 54, respectively. Thus, relatively few studies have investigated the chemical composition of zeolites and their reactivity, despite their importance in determining performance. Therefore, the authors recommend a more detailed study in this area. Agricultural and biological sciences contribute only 36 publications that examine the ecological and agricultural effects of incorporating zeolite into concrete, particularly its effects on plant development and ecosystems. Computer science accounts for only 29 articles, although this field of research plays an important role in the modeling, simulation, and optimization of zeolite-infused concrete. Therefore, the authors recommend further studies in this field to enhance the utilization of computational methods in improving zeolite-based concrete research.

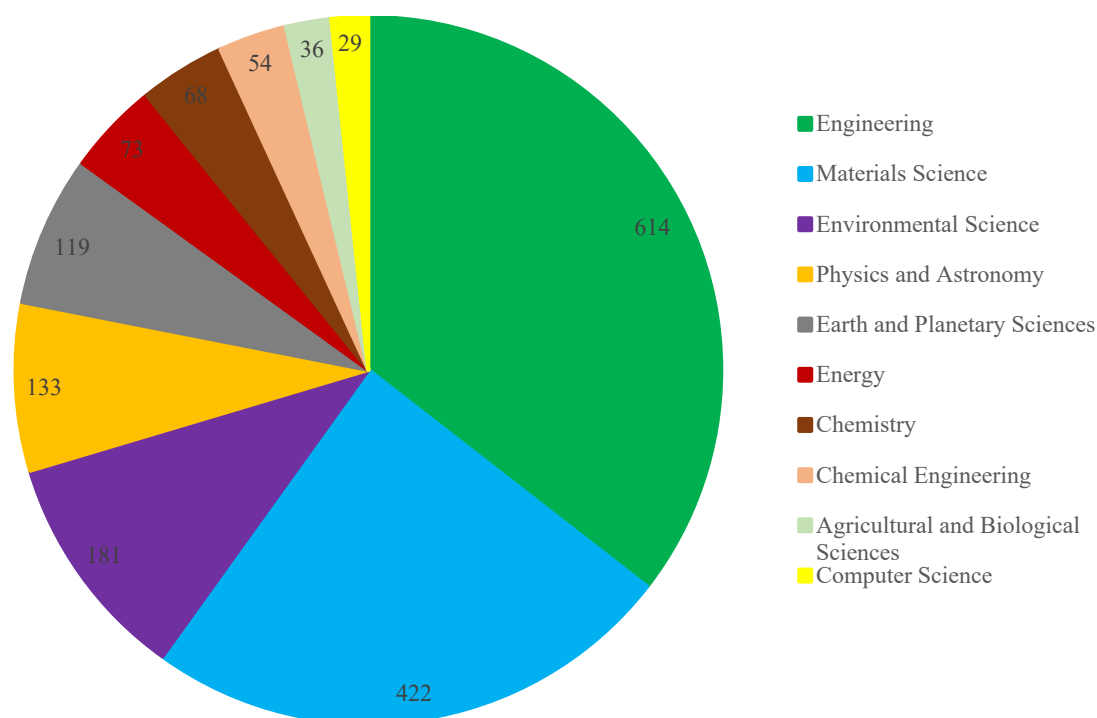


Figure 2. Top 10 research areas of publications related to zeolite in concrete.

4.3. Country-Wise Publications

The worldwide distribution of publications discussing zeolite in concrete indicates considerable worldwide research interest and contribution to the advancement of concrete construction. The statistics indicate that Iran and China are among the top countries publishing articles related to zeolite in concrete, as shown in Figures 3 and 4, with 163 and 146 publications, respectively. Therefore, Iran and China's contributions are significant to the advancement of research on zeolite-based concrete.

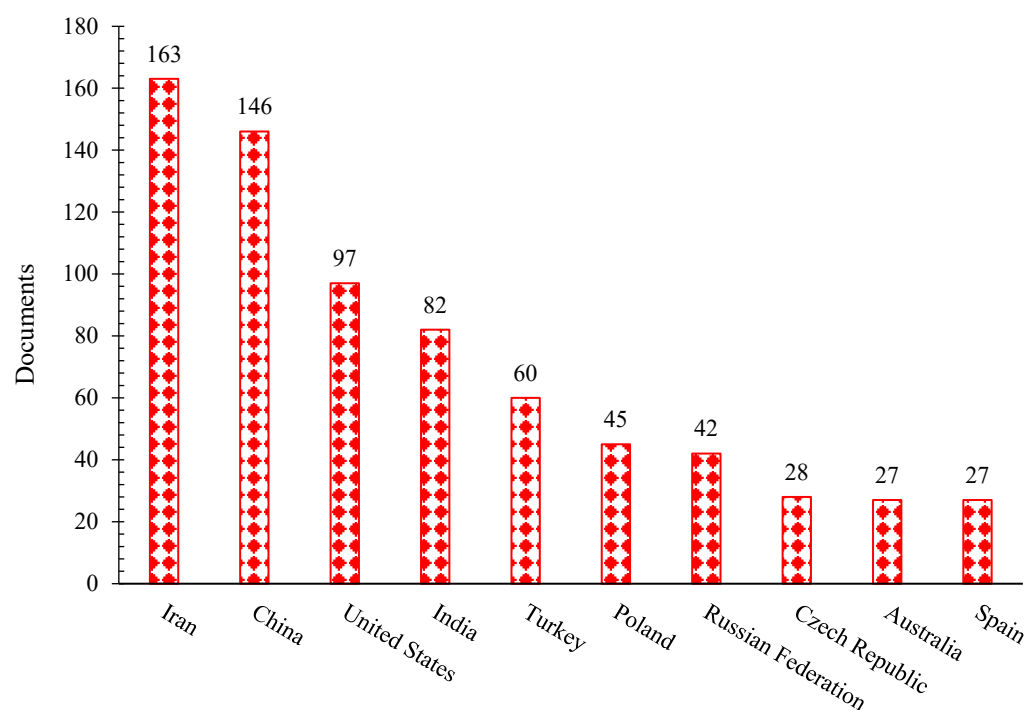


Figure 3. The top 10 countries in the worldwide distribution of publications.

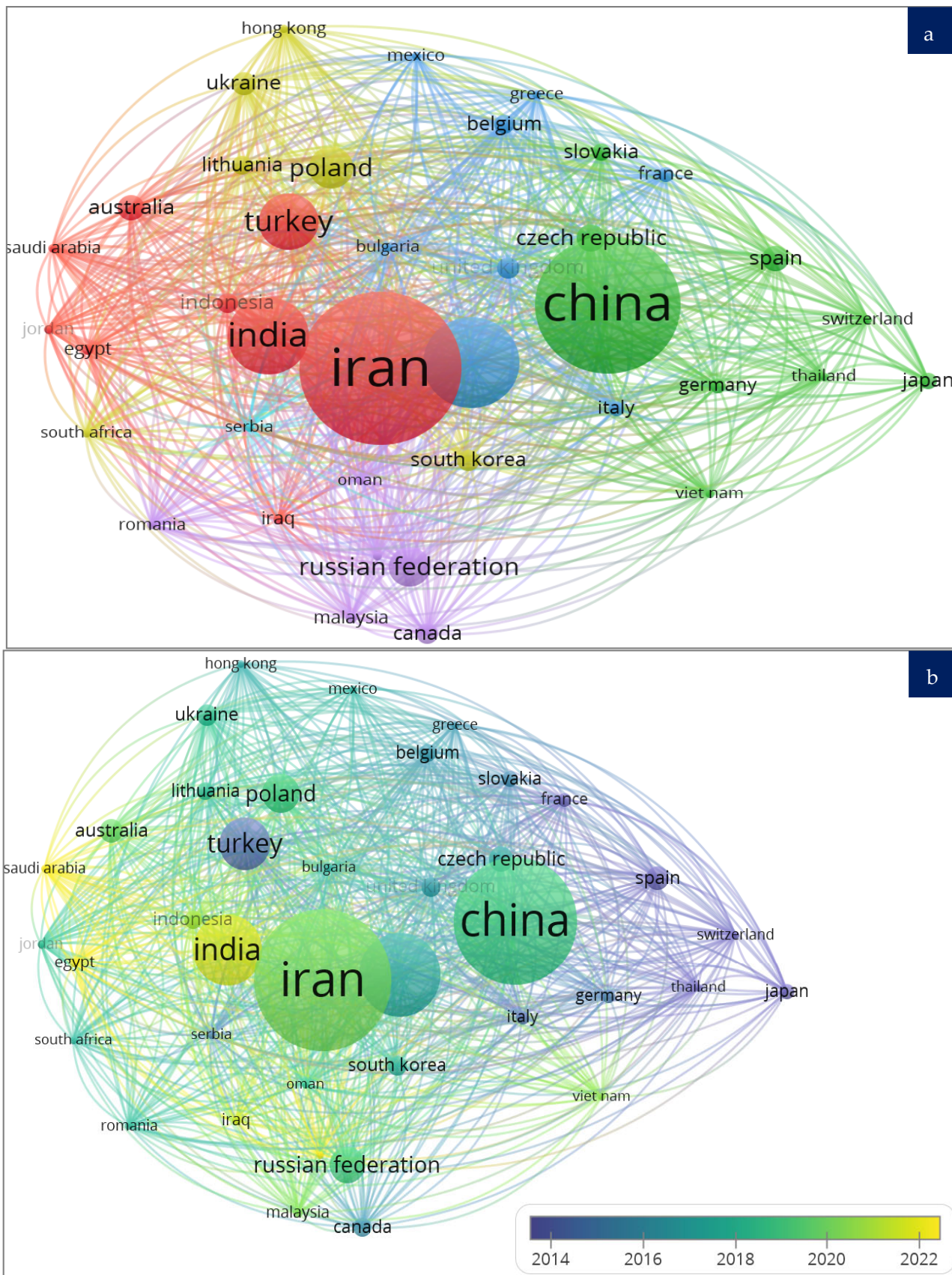


Figure 4. Country-wise publications: (a) network visualization and (b) overlay visualization.

India shows 97 and 82 publications related to zeolite concrete, respectively, which indicates significant contributions. The United States and India possess strong research

infrastructures and a history of generating important academic results. Their participation in zeolite concrete-related research is motivated by the continuous search for alternative sustainable construction solutions. Countries such as Turkey (60 publications), Poland (45 publications), and the Russian Federation (42 publications) also show a moderate number of articles but significant contributions to zeolite in concrete-related studies. Countries like the Czech Republic, Australia, and Spain show a small number of publications related to zeolite in concrete, with each providing 27 publications. Although the contributions of these countries are low, it indicates that these countries have ongoing research interest in zeolite-based concrete, but on a reduced scale relative to the other countries. Therefore, the worldwide distribution of publications indicates an increasing international collaboration in zeolite in concrete-related research, with Iran and China at the top, while other nations participate in the collective effort to promote sustainable concrete. The high publication output from Iran can be attributed to the country's abundant natural zeolite resources. The widespread availability has encouraged extensive research on the application of natural zeolite in sustainable concrete. China's focus is on reducing carbon emissions and promoting low-carbon construction. Although the present bibliometric analysis was not designed to perform country-specific keyword mapping, the publication trends indicate that both countries (Iran and China) have played important roles in advancing sustainable zeolite concrete research. It should be noted that the publications presented in this study represent absolute bibliometric results and were not normalized according to country-level indicators such as gross domestic product (GDP) and population. Therefore, the results show research productivity rather than research intensity or efficiency. Consequently, the comparison should be interpreted with caution, as countries with larger scientific communities are naturally expected to produce a large volume of publications. Future bibliometric studies should incorporate normalized national indicators to enable more meaningful comparisons of research performance across countries.

4.4. Document Types

Figure 5 shows the distribution of different types of documents related to zeolite in concrete. The findings indicate that the main document type is articles, with a total of 664 documents.

The articles are generally peer-reviewed and have case study results. Articles are fundamental to academic publication, particularly in the scientific area, as articles present a comprehensive analysis of the preferred medium for sharing new information. Conference papers are the second most common document type, which includes 192 publications related to zeolite in concrete. Conference papers include initial research results or overviews that are delivered at academic conferences through presentation. Conference papers are often published more rapidly than articles and are essential for sharing ideas and interacting with the academic community. Conference reviews show 71 documents related to zeolite concrete, which offer a comprehensive assessment or criticism of the current research field in a certain domain and are mostly published after a conference or symposium. The conference reviews provide significant information on developing trends, difficulties, and limitations in the area. Review articles contribute only 40 documents, which is much smaller compared to the number of research articles (664). Review articles generally provide extensive reviews of current literature on a certain issue, summarizing previously published results and identifying opportunities for further study. Reviews are essential for summarizing and interpreting previous studies and providing a comprehensive overview of a field's advancement. They also identify current research progress and future research. Book chapters account for 24 re-

lated to zeolite concrete, and are usually found in edited volumes or textbooks. Book chapters present in-depth analyses of specialized subjects within a broader scope. The other document types, such as retracted (4), book (2), erratum (2), note (1), and short survey (1), show significantly lower numbers compared to the total document types. Although important, a limited number of review articles (40) are available as compared to research articles (664). In the future, the authors recommend that researchers carry out detailed reviews of various aspects of zeolite concrete.

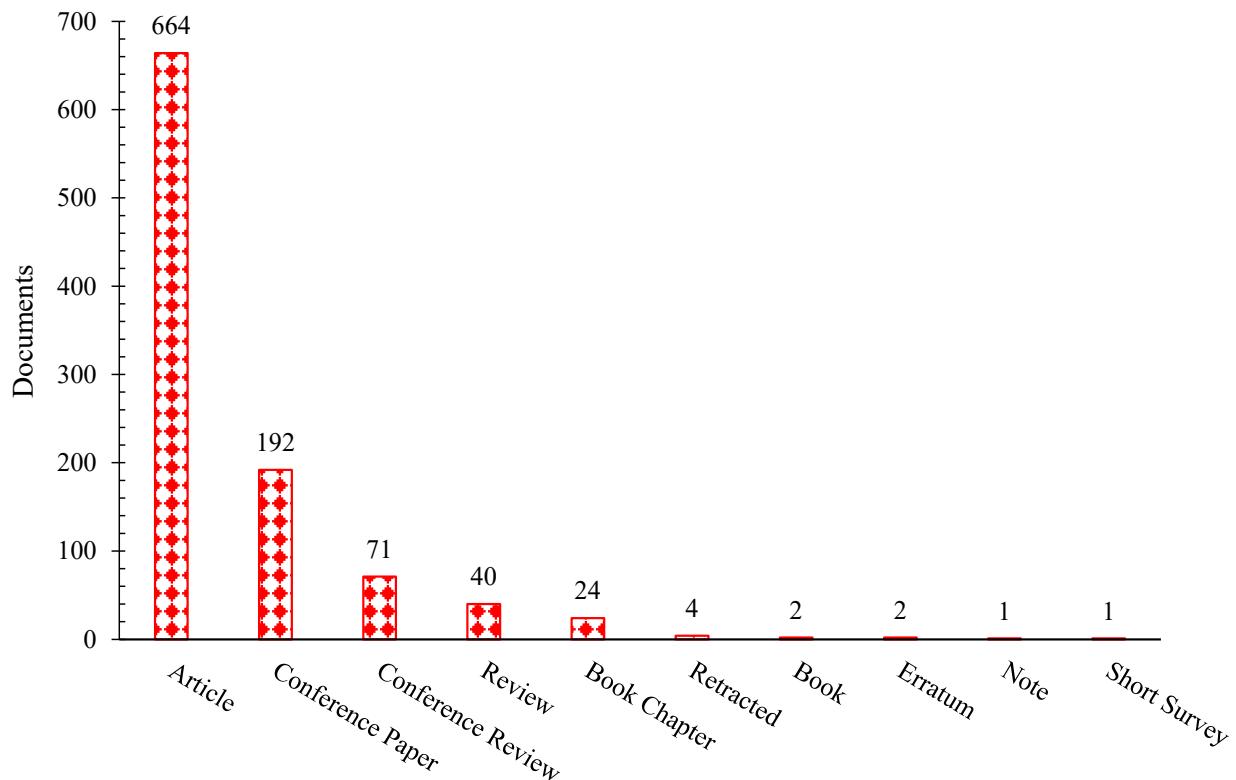


Figure 5. Classification of publications by document type.

4.5. Authors Contributions

The analysis of authors' contributions was performed using a systematic bibliometric method with VOSviewer and imposing a minimum threshold of five documents and five citations per author to include only those documents with significant research output in zeolite concrete. The minimum threshold of five documents and five citations was selected to improve the clarity of the bibliometric network. Therefore, the findings represent established research rather than recent.

Out of 2907 authors, only 32 fulfilled the established criteria, indicating a refined selection of highly creative scholars. Table 1 and Figure 6 demonstrate the authors' contributions regarding the number of publications, citations, and total link strength. The findings indicate that Shekarchi, M. is the most active contributor, having published 22 documents with 1929 citations and 272 total strength links, which highlight Shekarchi's significant contribution to research and sharing studies on the substitution of zeolite in concrete.

Furthermore, Ahmadi, B. and Černý, R. published 13 (1116 citations and 203 total strength links) and 10 publications (262 citations and 35 total strength links), respectively, and have also made significant contributions, reinforcing their positions as leading scholars in zeolite-based concrete research. Also, Shekarchi, M. is identified as a central node, suggesting that Shekarchi's research publications are among the most often cited

within the network (Figure 6a). Shekarchi's research underscores the increasing focus on improving the sustainability of concrete with new materials. Also, Vejmelková, E. and Shirzadi Javid, A. A., published 9 and 8 articles, respectively. The large number of publications by these researchers on zeolite in concrete indicates a continuing and active interest in zeolite as an environmentally friendly option, while also indicating an increasing transition towards sustainable construction materials. The color-coded representation illustrates the development of citation activity over time. Darker nodes indicate older, foundational publications with established significance, whereas lighter nodes denote recent contributions that are gaining importance and influencing upcoming research directions (Figure 6b). These findings highlight the capacity of zeolite in concrete to provide not only performance improvements but also considerable environmental advantages, demonstrating the growing demand in both academic and practical investigations of sustainable construction materials.

Table 1. Authors' contributions.

Author	Documents	Citations	Total Link Strength
Ahmadi, Babak	13	1116	203
Akbarzadeh Bengar, Habib	6	765	62
Azarijafari, Hessam	5	229	55
Farzin, Saeed	5	103	16
Feng, Nai-Qian	5	134	20
Girskas, Giedrius	7	197	26
Hadiwardoyo, Sigit Pranowo	5	17	0
Jackowski, Mateusz	6	17	8
Jalal, Mostafa	6	190	7
Karakurt, Cenk	5	293	42
Karami, Hojat	5	112	14
Keppert, Martin	5	191	18
Kocak, Yilmaz	5	98	11
Konstantynovskyi, Oleksandr	6	36	0
Kordnaeij, Afshin	5	116	3
Małek, Marcin	6	17	8
Mousavi, Sayed-Farhad	5	112	14
Najimi, Meysam	5	443	106
Nematzadeh, Mahdi	5	220	13
Rudenko, Igor	6	36	0
Samimi, Kianoosh	5	264	69
Saradar, Ashkan	5	52	5
Shahmansouri, Amir Ali	7	860	65
Shekarchi, Mohammad	22	1929	272
Shirzadi Javid, Ali Akbar	8	113	54
Teymouri, Ehsan	6	84	17
Vaičiukynienė, Danutė	5	36	11
Vejmelková, Eva	9	168	20
Wachowski, Marcin	5	6	8
Wang, Jiaqing	5	65	2
Zyciński, Wojciech	5	6	8
Černý, Robert	10	262	35

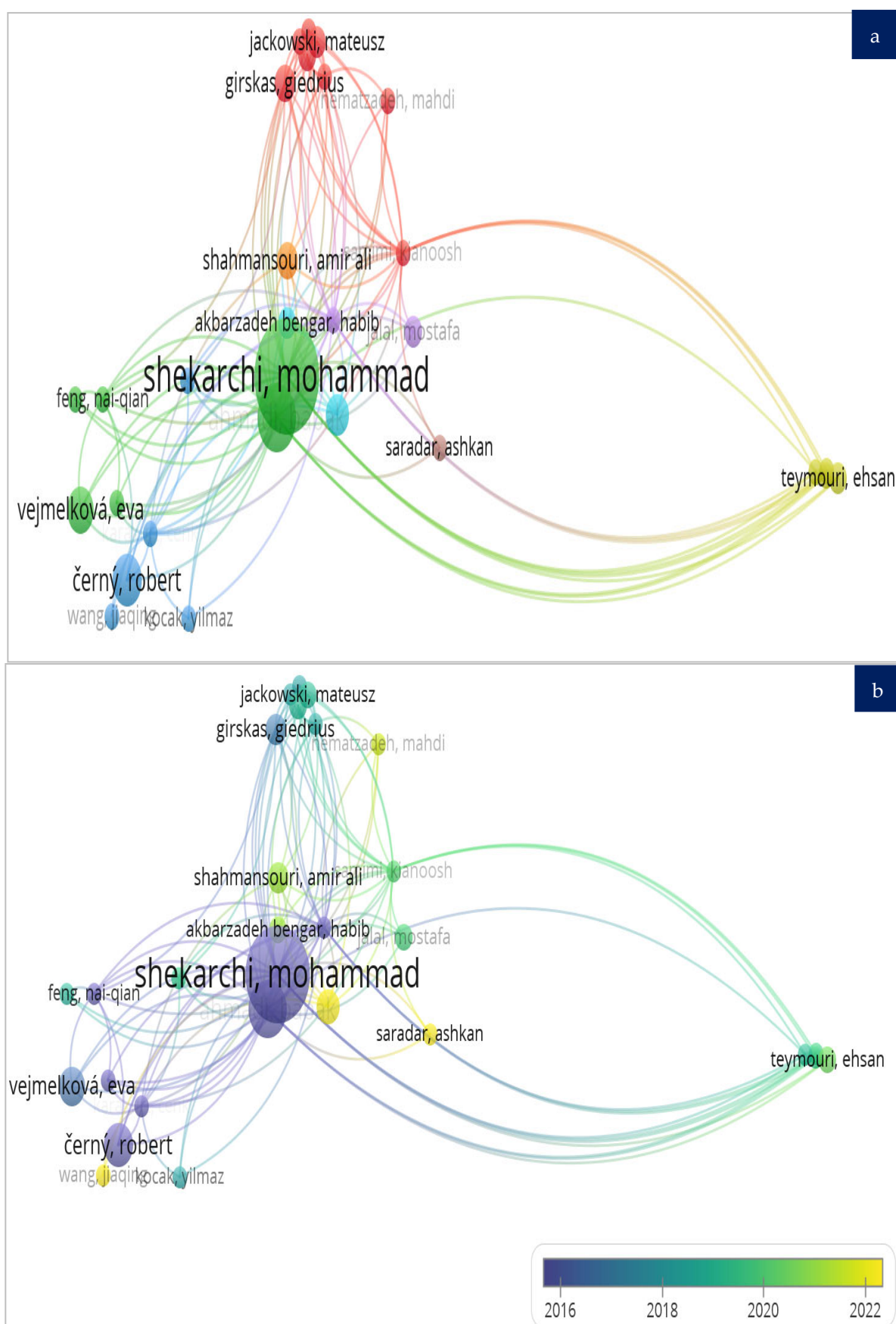


Figure 6. Authors' contributions: (a) network visualization and (b) overlay visualization.

4.6. Distribution of Publications Among Journals

Figure 7 illustrates the distribution of publications among the top 10 sources that relate to the substitution of zeolite in concrete research. The findings indicate that the *Construction and Building Materials* journal leads the list with 99 paper publications related to zeolite concrete, which establishes the most significant and often referenced source in the dataset. Subsequently, the *Advanced Materials Research Journal* contributed 32 publications, the *Materials Journal* contributed 25 publications, and the *AIP Conference Proceedings* contributed 24 publications. Therefore, these journals exhibit significant involvement in zeolite concrete research.

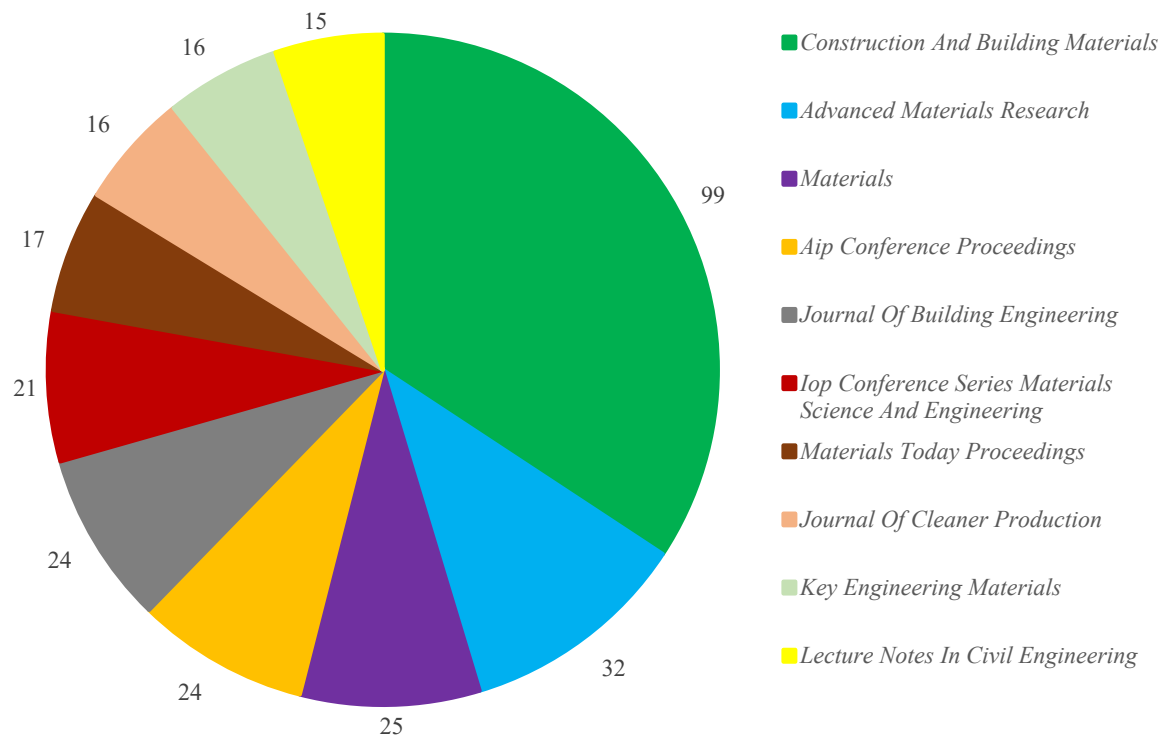


Figure 7. Distribution of publications across the top 10 journals.

Additional notable sources are the *Journal of Building Engineering*, which contributed 24 publications, *IOP Conference Series: Materials Science and Engineering* contributed 21 publications, and *Materials Today Proceedings* contributed 17 publications. Each of these sources significantly contributes to the overall distribution, highlighting the wide and growing interest in zeolite concrete research. Furthermore, publications such as the *Journal of Cleaner Production* (16), *Key Engineering Materials* (16), and *Lecture Notes in Civil Engineering* (15) complete the top 10 sources of zeolite concrete. The *Construction and Building Materials* journal is an important source, demonstrating considerable interrelation with other journals such as *Materials*, *Advanced Materials Research*, and *Journal of Building Engineering* (Figure 8a). The journal *Construction and Building Materials* also plots near the center of the network (Figure 8b), with the yellow indicating its growing influence in recent publications. Furthermore, journals such as *Advanced Materials Research* and *Key Engineering Materials* have also increased in importance in recent publications. The dominance of *Construction and Building Materials* indicates that zeolite concrete research is focused on concrete performance, durability, and sustainable construction. In contrast, the *Journal of Cleaner Production* focuses on environmental sustainability. Also, *Materials* and the *Journal of Building Engineering* highlight cementitious materials and structural applications. Therefore, the publication patterns demonstrate the growing integration of engineering performance with sustainability research.

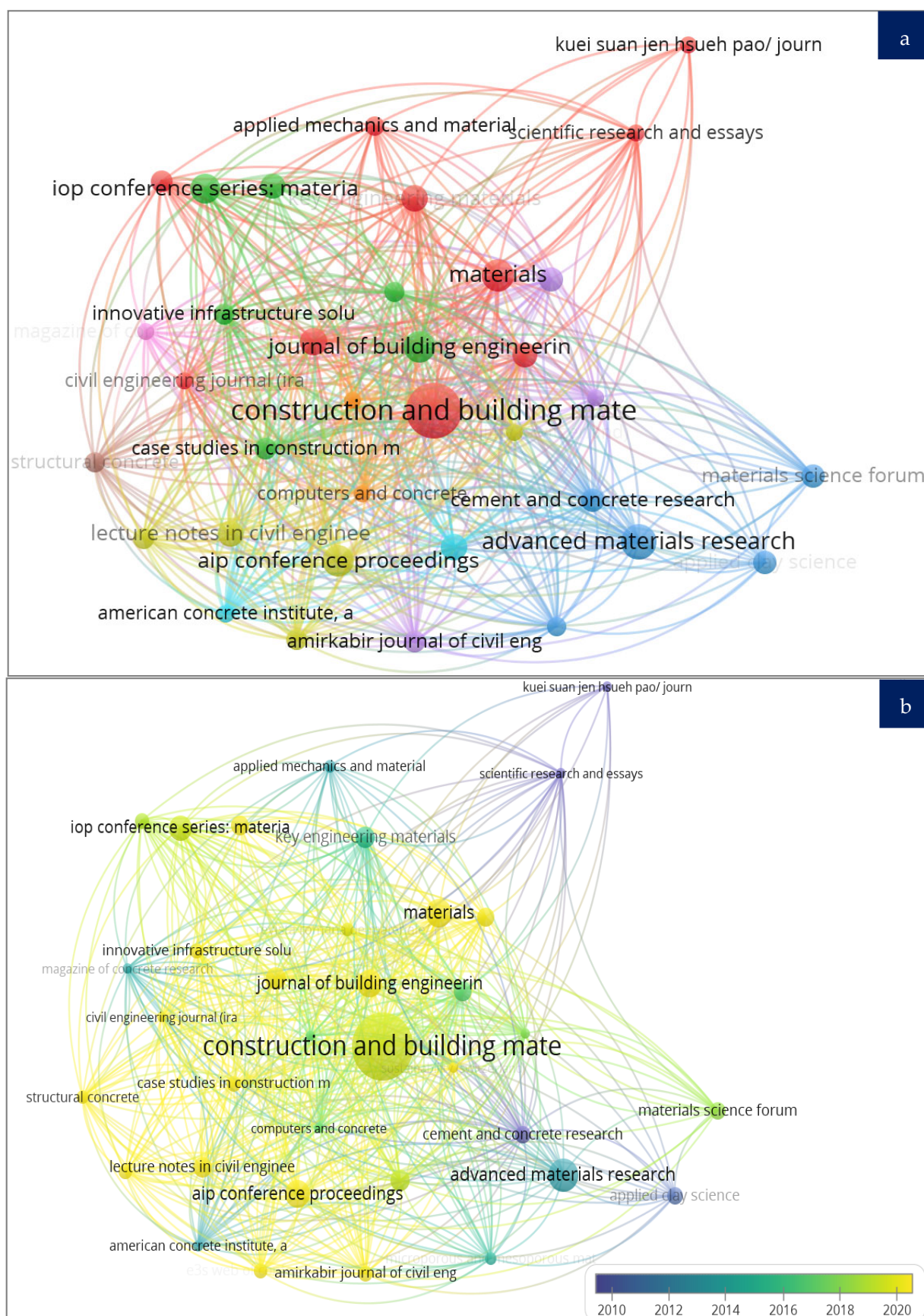


Figure 8. Distribution of publications: (a) network visualization and (b) overlay visualization.

4.7. Affiliation or Institution

Table 2 shows the distribution of documents published by the 20 top affiliations (institutions) in zeolite-based concrete-related research. The findings indicate that the University of Tehran stands as the outstanding institution, having contributed 30 published documents, proving itself as the most productive contributor to zeolite concrete-related research.

Table 2. Top affiliations in zeolite concrete research.

Affiliation	Documents
University of Tehran	30
Semnan University	21
Czech Technical University in Prague	18
Tsinghua University	15
Kyiv National University of Construction and Architecture	15
University of Guilan	14
Imam Khomeini International University	14
Iran University of Science and Technology	13
Consejo Superior de Investigaciones Científicas	12
Technická Univerzita v Košiciach	12
Ministry of Education of the People's Republic of China	11
North-Eastern Federal University	11
Vilniaus Gedimino Technikos Universitetas	11
University of Mazandaran	10
Southeast University	10
Siberian Branch, Russian Academy of Sciences	10
Kaunas University of Technology	9
Kharazmi University	8
Gazi Üniversitesi	8
Düzce Üniversitesi	8

Furthermore, Semnan University has published 21 documents, while Czech Technical University in Prague and Tsinghua University have contributed 18 and 15 publications, respectively. Further remarkable universities include Kyiv National University of Construction and Architecture and the University of Guilan, with 15 and 14 documents, respectively. Imam Khomeini International University and Iran University of Science and Technology published 14 and 13 documents, respectively, highlighting the important contribution in developing sustainable concrete construction. Moreover, several other universities and research institutes are significant contributors to the field of zeolite-based concrete. These universities and institutes are the Consejo Superior de Investigaciones Científicas (12), the Technical University of Košice (12), and the Ministry of Education of the People's Republic of China (11). The institutions, including North-Eastern Federal University and the Vilnius Gedimino Technical University, have significantly contributed by each publishing 11 documents on zeolite concrete-related research. Additional institutions, including the University of Mazandaran, Southeast University, Siberian Branch, and the Russian Academy of Sciences, have significantly contributed by each publishing 10 documents related to zeolite concrete. The Kaunas University of Technology contributed 9 documents, and the Kharazmi University, Gazi Üniversitesi, and Düzce Üniversitesi contributed 8 documents related to zeolite concrete materials. The distribution shows the broad participation of several institutions from various countries that contribute to the advancement and promotion of sustainable construction materials.

4.8. Funding Source for Zeolite Concrete

Table 3 highlights the distribution of funding sources for zeolite concrete research, indicating the top 20 funding supporters of zeolite concrete-related research. The analysis indicates that the National Natural Science Foundation of China is the main funding source, having funded 60 articles. Therefore, the National Natural Science Foundation of China is the main funding source for zeolite concrete research. The Ministry of Science and Technology of the People's Republic of China supported 16 publications, whilst the Grantová Agentura České Republiky and the National Key Research and Development Program of China funded 11 documents. It can also be observed that the two major funding sources are from China: the National Natural Science Foundation of China (60 publications) and the Ministry of Science and Technology of the People's Republic of China (16 publications). This demonstrates that China is contributing significantly in terms of funding to promote sustainable zeolite-based concrete research, demonstrating its commitment to developing environmentally friendly and sustainable solutions for the future. Other significant funding sources are the Fundamental Research Funds for the Central Universities, which supported 10 publications, the European Commission, the Ministry of Education and Science of Ukraine, and the National Science Foundation.

Table 3. Top funding sources for zeolite concrete research.

Funding Source	Documents
National Natural Science Foundation of China	60
Ministry of Science and Technology of the People's Republic of China	16
Grantová Agentura České Republiky	11
National Key Research and Development Program of China	11
Fundamental Research Funds for the Central Universities	10
European Commission	7
Ministry of Education and Science of Ukraine	7
National Science Foundation	7
European Regional Development Fund	6
Natural Science Foundation of Jiangsu Province	6
University of Tehran	6
Natural Science Foundation of Shandong Province	5
China Postdoctoral Science Foundation	4
Ministry of Education of the People's Republic of China	4
Narodowe Centrum Badań i Rozwoju	4
National Research Foundation of Korea	4
U.S. Department of Energy	4
Unitatea Executiva pentru Finantarea Invatamantului Superior, a Cercetarii, Dezvoltarii si Inovarii	4
Agentúra na Podporu Výskumu a Vývoja	3
Consejo Nacional de Ciencia y Tecnología	3

Additional funding sources are the European Regional Development Fund (6), the Natural Science Foundation of Jiangsu Province (6), and the University of Tehran (6), each contributing considerably to the development of sustainable construction materials. Further funding sources, including the Natural Science Foundation of Shandong Province (5), China Postdoctoral Science Foundation (4), and various governmental and academic funding agencies from Poland, Korea, and the U.S. Department of Energy, highlight the support for zeolite concrete research. The funding distribution shows the international collaboration in promoting sustainable zeolite-based construction materials. The range of financing sources illustrates the significance of international and government support in promoting innovation and sustainability in concrete technology. The National Natural Science Foundation of China reflects the country's investment in low-carbon construction mate-

rials. Although the present study did not classify publications according to individual funding programs, the associated keywords indicate that funded research increasingly addresses durability, microstructure, geopolymer, and sustainable cementitious materials. Therefore, this demonstrates balance between fundamental material science and practical engineering applications.

4.9. Citation Analysis

Citation analysis was performed using VOSviewer to identify the most influential publications. A minimum threshold of 15 citations per document was applied to improve the clarity of the citation network. Among the 1001 retrieved documents, 306 satisfied the citation threshold. The top 10 most influential publications identified through citation analysis are presented in Table 4. Also, the largest connected citation network of zeolite concrete research is presented in Figure 9. The findings revealed that Ahmadi and Shekarchi (2010) constitutes the most influential publication, which received 365 citations and the highest network connectivity (78 citation links). Ahmadi and Shekarchi (2010) established the use of natural zeolite as a supplementary cementitious material and has served as an important study for subsequent investigations on the mechanical performance and durability of zeolite concrete. Other publications include Sabet et al. (2013) (288 citations), Najimi et al. (2012) (285 citations), Valipour et al. (2013) (221 citations), and Tran et al. (2019) (177 citations). These studies investigated the durability characteristics, pozzolanic reactivity, transport properties, and microstructural behavior of zeolite-incorporated cementitious composites. The citation network demonstrates that research on zeolite concrete is organized around several interconnected clusters representing major research themes. Publications with high total citation links occupy central positions within the network and indicate significant influence on the development of subsequent studies and their role in shaping current research directions in sustainable materials.

Table 4. Top 10 most influential publications.

Rank	Publication	Citations	Links
1	Ahmadi (2010)	365	78
2	Sabet (2013)	288	29
3	Najimi (2012)	285	68
4	Valipour (2013)	221	37
5	Tran (2019)	177	32
6	Markiv (2016)	153	28
7	Valipour (2014)	137	22
8	Feng (2005)	125	26
9	Shahmansouri (2019)	117	13
10	Samimi (2017)	115	20

4.10. Co-Citation Analysis

Co-citation analysis was performed using cited references as the unit of analysis with the full counting method. A minimum threshold of 15 citations per cited reference was applied. Among the 35,060 cited references extracted from the 1001 Scopus-indexed publications, only nine cited references met the selection criterion and were included in the final co-citation network (Table 5). The analysis ranked the selected references according to their co-citation frequency and total link strength.

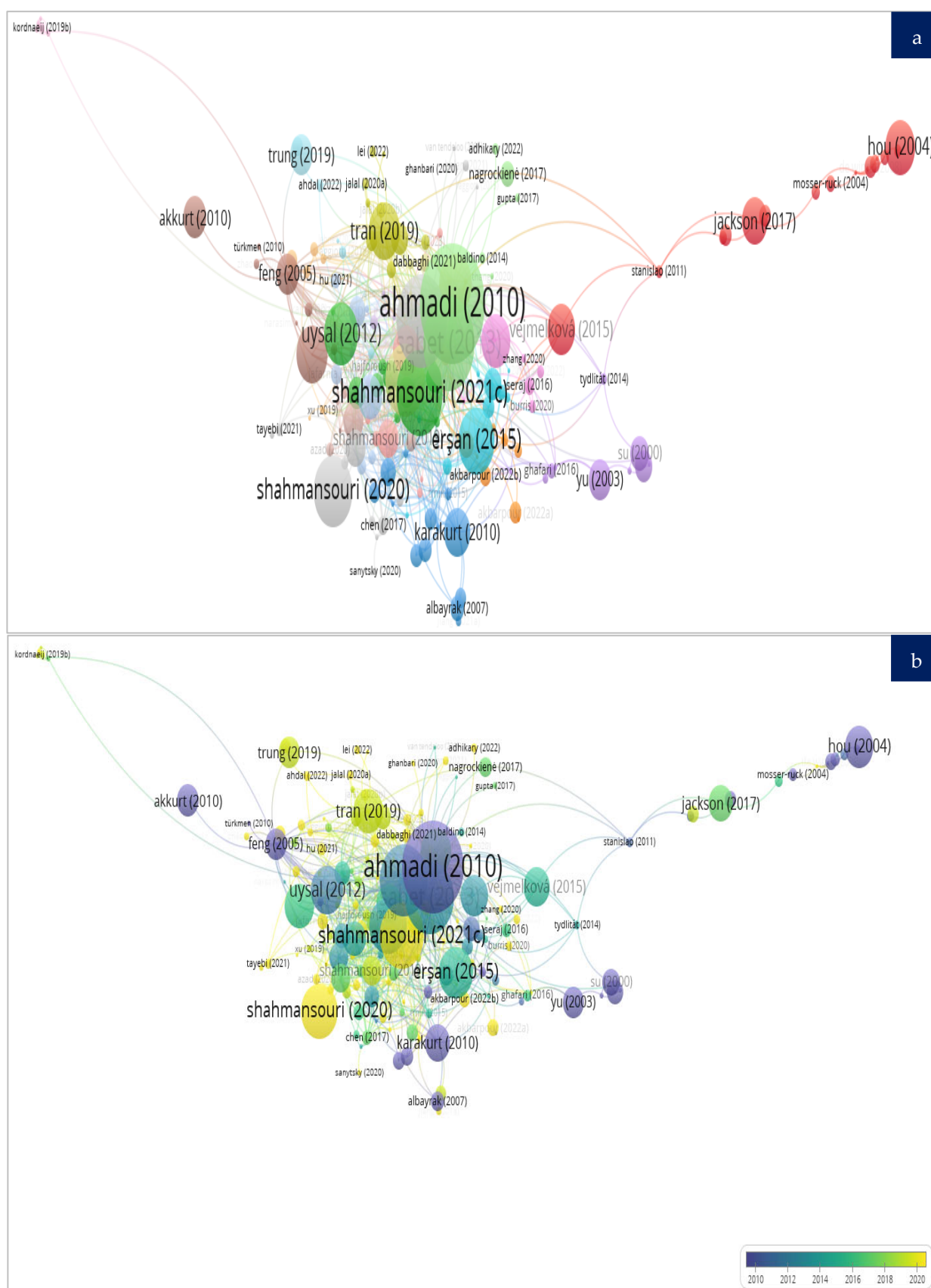


Figure 9. Citation analysis: (a) network visualization and (b) overlay visualization.

Table 5. Co-citation analysis.

Cited Reference	Citations	Total Link Strength
Ahmadi B., Shekarchi M., Use of natural zeolite as a supplementary cementitious material, <i>Cem. Concr. Compos.</i> , 32, 2, pp. 134–141, (2010)	26	30
Ahmadi B., Shekarchi M., Use of natural zeolite as a supplementary cementitious material, <i>Cem. Concr. Compos.</i> , 32, pp. 134–141, (2010)	21	16
Ahmadi B., Shekarchi M., Use of natural zeolite as a supplementary cementitious material, <i>Cement and Concrete Composites</i> , 32, 2, pp. 134–141, (2010)	20	17
Nagrockiene D., Girskas G., Research into the properties of concrete modified with natural zeolite addition, <i>Constr. Build. Mater.</i> , 113, pp. 964–969, (2016)	25	34
Najimi M., Sobhani J., Ahmadi B., Shekarchi M., An experimental study on durability properties of concrete containing zeolite as a highly reactive natural pozzolan, <i>Constr. Build. Mater.</i> , 35, pp. 1023–1033, (2012)	21	0
Najimi M., Sobhani J., Ahmadi B., Shekarchi M., An experimental study on durability properties of concrete containing zeolite as a highly reactive natural pozzolan, <i>Constr. Build. Mater.</i> , 35, pp. 1023–1033, (2012)	38	48
Najimi M., Sobhani J., Ahmadi B., Shekarchi M., An experimental study on durability properties of concrete containing zeolite as a highly reactive natural pozzolan, <i>Construction and Building Materials</i> , 35, pp. 1023–1033, (2012)	27	19
Valipour M., Pargar F., Shekarchi M., Khani S., comparing a natural pozzolan, zeolite, to metakaolin and silica fume in terms of their effect on the durability characteristics of concrete: a laboratory study, <i>Constr. Build. Mater.</i> , 41, pp. 879–888, (2013)	21	33
Valipour M., Pargar F., Shekarchi M., Khani S., comparing a natural pozzolan, zeolite, to metakaolin and silica fume in terms of their effect on the durability characteristics of concrete: a laboratory study, <i>Construction and Building Materials</i> , 41, pp. 879–888, (2013)	15	15

The findings indicated that Najimi et al. (2012) recorded the highest co-citation frequency (38 citations) and the greatest total link strength (48), which indicates its central role in the development of research on the durability performance of concrete. Nagrockiene and Girskas (2016) ranked second in terms of network connectivity with a total link strength of 34, followed by Valipour et al. (2013) (33) and Ahmadi and Shekarchi (2010) (30). It should be noted that some cited references appear multiple times in Table 5 because the Scopus database stores references in different citation formats, including abbreviated and full journal titles. Consequently, VOSviewer recognizes these variations as separate reference strings. Although this results in duplicate entries, it does not affect the overall interpretation of the co-citation network or the identification of the core literature in the field.

4.11. Lotka's Law

Lotka's Law was applied to evaluate the distribution of scientific productivity among authors. The empirical distribution closely follows the inverse power-law relationship

proposed by Lotka (Figure 10). The estimated Lotka exponent ($\beta = 2.11$) was very close to the theoretical value of 2.0. Therefore, the observed author productivity aligns well with the expected bibliometric distribution. The fitted model achieved a satisfactory coefficient of determination ($R^2 = 0.763$), indicating approximately 76.3% variation in author productivity. Moreover, the Kolmogorov–Smirnov goodness-of-fit test produced a p -value of 0.153 (greater than the significance threshold of 0.05). Previous bibliometric investigations have similarly employed the Kolmogorov–Smirnov and chi-square tests to evaluate the applicability of Lotka’s Law. In line with this, Lakshminarasimhappa et al. (2025) [35] validated author productivity patterns in heart transplantation research using these statistical tests. However, the findings indicated that the empirical distribution did not conform to the theoretical inverse-square distribution. This comparison demonstrates that the applicability of Lotka’s Law can vary across research domains depending on the characteristics and maturity of the scientific literature.

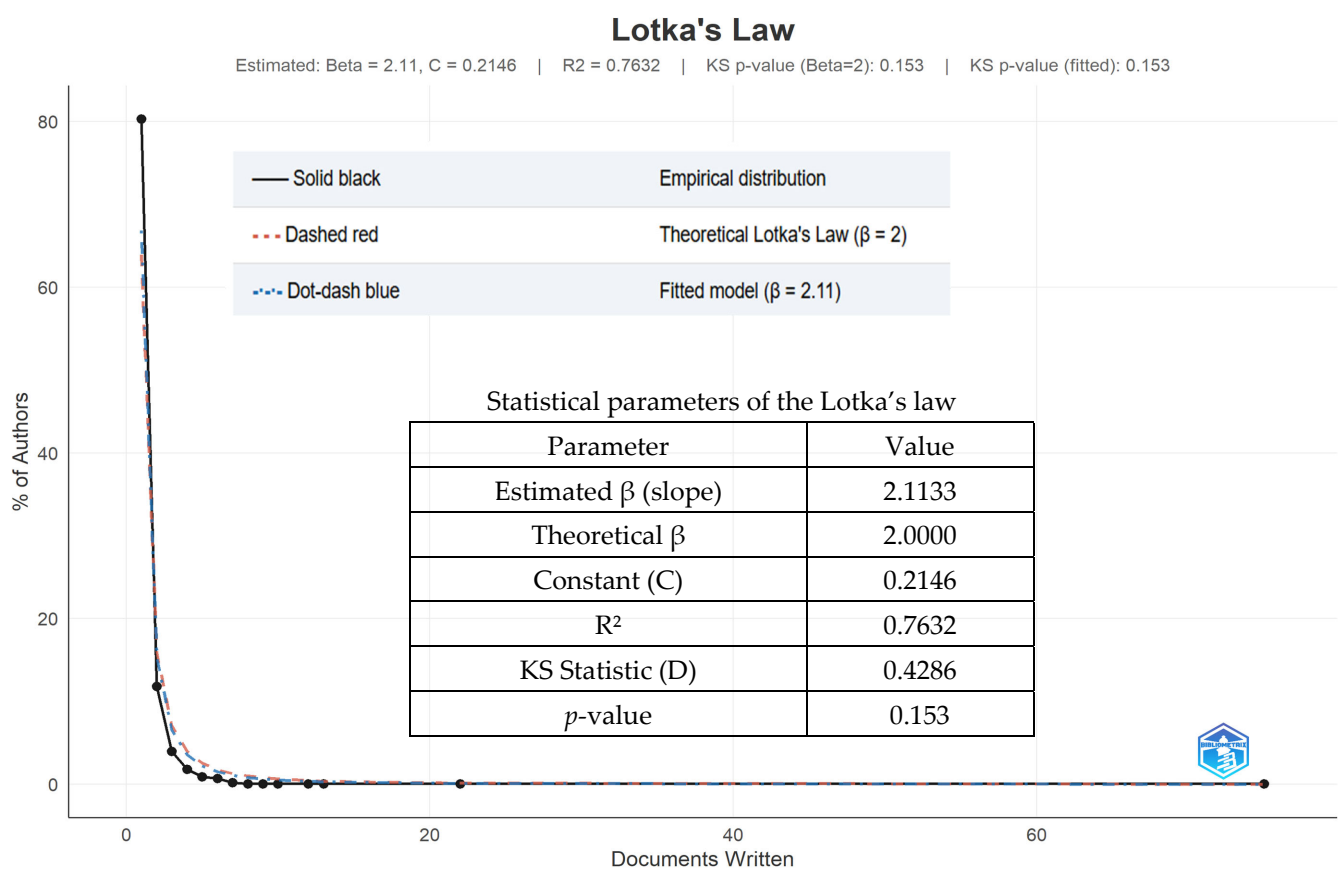


Figure 10. Distribution of author productivity according to Lotka’s Law.

4.12. Bradford’s Law

Bradford’s Law was applied to examine the distribution of scientific publications across journals. The retrieved literature was distributed across 402 journals, which were classified into three Bradford zones according to their publication productivity (Figure 11 and Table 6). The core zone contained 14 journals and accounted for 342 publications, thus highlighting a strong concentration of scientific output within a limited number of journals. Zone 2 contained 83 journals and contributed 326 publications. Zone 3 included 305 journals that produced 333 publications. The distribution demonstrates that approximately one-third of the published literature is concentrated within a small group of core journals. The remaining publications are dispersed across a larger number of less productive sources.

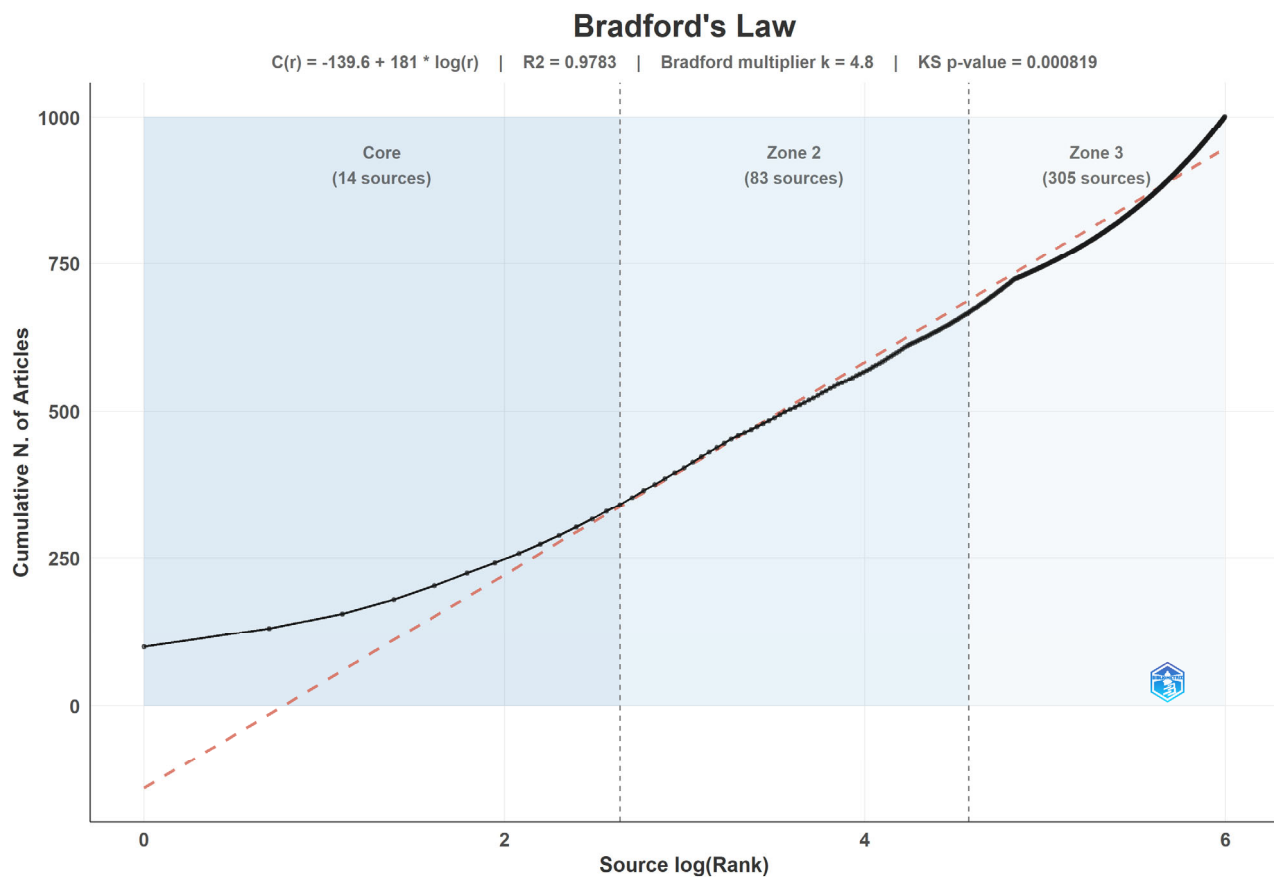


Figure 11. Bradford's Law analysis.

Table 6. Distribution of journals across Bradford's zones.

Bradford Zone	No. of Sources	% Sources	No. of Articles	% Articles
Zone 1 (Core)	14	3.5	342	34.2
Zone 2	83	20.6	326	32.6
Zone 3	305	75.9	333	33.3
Total	402	100	1001	100

The Bradford model exhibited an excellent coefficient of determination ($R^2 = 0.9783$), as shown in Table 7. This indicates that the logarithmic Bradford function adequately described the distribution of publications among journals. The estimated Bradford multiplier ($k = 4.8$) reflects the increasing number of journals required in successive zones to produce a similar volume of publications. The findings suggest that the progressive dispersion of research output lies beyond the core literature. However, the Kolmogorov–Smirnov goodness-of-fit test yielded a statistically significant result ($KS = 0.1393$, $p = 0.000819$), indicating that the empirical distribution differs significantly from the ideal Bradford distribution. The deviations are not uncommon in rapidly expanding and multidisciplinary research fields. Also, the publication patterns are influenced by the emergence of new journals and increasing interdisciplinary collaboration. Nevertheless, the Bradford zoning effectively identified the principal journals that constitute the core knowledge base of the field. Therefore, it provides a reliable framework for recognizing the most influential publication sources.

Table 7. Statistical parameters of Bradford’s law.

Parameter	Value
Intercept (a)	−139.61
Slope (b)	180.9984
Bradford Multiplier (k)	4.8
R ²	0.9783
KS Statistic	0.1393
p-value	0.000819

Note: a = intercept, b = slope, and k = Bradford multiplier in Bradford’s law.

4.13. Keyword Analysis

In this study, co-occurrence analysis has been selected for keyword analysis with “Author keywords” as the basis for analysis. The results of the keyword analysis are presented in Table 8 and Figure 12.

Table 8. Keyword analysis.

Keyword	Occurrences	Total Link Strength
Autoclaved aerated concrete	10	13
Bentonite	13	19
Carbonation	11	17
Cement	36	54
Clinoptilolite	27	44
Compressive strength	80	114
Concrete	107	171
Corrosion	13	26
Drying shrinkage	11	30
Durability	62	117
Fly ash	50	85
Geopolymer	25	41
Geopolymer concrete	14	21
Internal curing	11	16
Leaching	11	18
Lightweight concrete	11	13
Mechanical properties	58	83
Metakaolin	25	64
Microstructure	34	55
Natural zeolite	96	148
Permeability	19	35
Porosity	13	24
Porous concrete	10	12
Pozzolan	20	44
Pumice	12	16
Self-compacting concrete	17	18
Silica fume	41	102
Strength	26	45
Supplementary cementitious materials	11	16
Synthetic zeolite	10	6
Water absorption	13	42
Zeolite	219	251
Zeolite powder	16	19
Zeolites	25	17

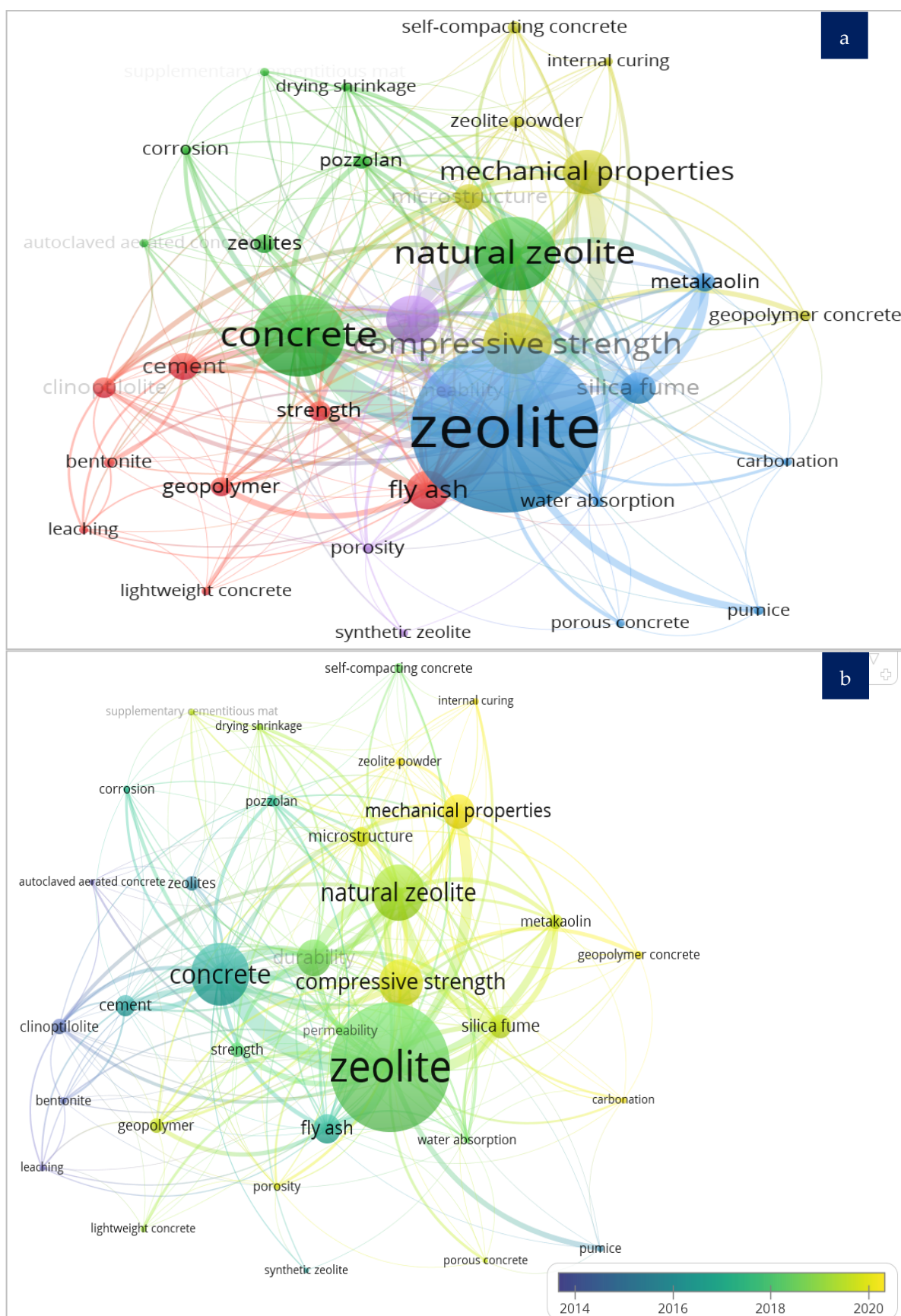


Figure 12. Keyword analysis: (a) network visualization and (b) overlay visualization.

A full counting approach has been applied, indicating that each occurrence of a term is added in total rather than being proportionally distributed among several occurrences. This method increases the visibility of often-used terms, promoting a deeper comprehension of the topic's significance. Furthermore, the minimum occurrence criterion for the keyword is 10. The dataset was reduced from 2299 keywords to 34 keywords. The criteria ensure that only the most prevalent and relevant words are incorporated into the analysis while minimizing unnecessary information and improving the clarity of the findings. The use of such a criterion is important in bibliometric studies, as it allows researchers to identify prevalent study themes while excluding unnecessary information. The keyword occurrence analysis indicates that "Zeolite" appears most frequently, with 219 occurrences, followed by "Concrete" with 107 occurrences and "Natural Zeolite" with 96 occurrences. The findings suggest that zeolite and its derivatives represent an important area of focus in the field of construction materials. Furthermore, terms like "Compressive Strength" (80 times), "Durability" (62 times), and "Mechanical Properties" (58 times) indicate a significant study focus on the mechanical and structural characteristics of zeolite-containing materials. Other words include "Fly Ash" (50 occurrences) and "Silica Fume" (41 occurrences), both of which are widely utilized as secondary cementitious materials. The co-occurrence network visualization (Figure 12a) reinforces these findings by depicting the connections among keywords. The findings indicate that "Zeolite" is identified as the most prominent node, indicating its important position within the research network. The strong connections between "Concrete," "Natural Zeolite," and "Compressive Strength" indicate that a significant body of research pays attention to examining the impact of zeolite on concrete performance. However, the existence of related words, such as "Microstructure," "Metakaolin," and "Geopolymer," indicates continued attempts to better understand the microstructural and chemical interactions of zeolite-based materials. Also, detailed analysis is required within the limited research areas of shrinkage and creep properties in zeolite-based concrete. The pozzolanic reactivity and particle size are important for secondary cementitious materials. However, the authors did not find these within the top 20 keywords. Therefore, the authors recommend more detailed research on pozzolanic reactivity and the impact of zeolite particle size on concrete performance. It can also be observed that keywords related to high-strength concrete, ultra-high-performance concrete, and engineered cementitious composites did not appear among the keywords that met the minimum occurrence threshold. Therefore, the findings indicate that these topics are comparatively less represented in the bibliometric network, suggesting further study.

Furthermore, life-cycle assessment did not appear among the keywords that met the minimum occurrence threshold, suggesting that LCA has received comparatively less attention. Therefore, the authors recommend a detailed study on LCA to determine the environmental benefits of zeolite concrete. Furthermore, overlay visualization increases the understanding of the past and recent progress of zeolite in concrete research over time. The findings indicate that prior studies (2014–2016) focus on essential aspects such as "Concrete" and "Strength," and later studies (2018–2020) focus on "Zeolite Powder," "Internal Curing," geopolymer concrete, lightweight concrete, and "Self-Compacting Concrete," as shown in Figure 12b. This trend indicates a transition from basic material characterization to more sophisticated applications and developments focused on sustainability.

5. Conclusions

In this research, a bibliometric analysis of zeolite in concrete is carried out using VOSviewer software (version 1.6.21). The database was obtained from Scopus by searching for zeolite in concrete, and a filter was applied for only articles that appeared from 2000 to 2025. A total of 1001 documents related to zeolite concrete were downloaded. The key

aspects of analysis include publishing trends, publication area, document types, country-wise publications, universities/institutions, and funding sources. The study also performed keyword analysis to find the past, current, and future research trends. The detailed conclusions are as follows:

- The publication trends indicate inconsistent interest in zeolite concrete, with initial research increasing in 2013, then a decline in 2014, and a consistent increase from 2015 to 2024, which highlights the increasing importance of sustainable construction materials.
- The area of publication indicates that engineering leads in zeolite-concrete research with 614 publications, highlighting its focus on enhancing sustainability in concrete construction.
- The research articles (664) provide the major document type, demonstrating their significance in scientific contributions, followed by conference papers (192) and conference reviews (71). Despite their importance in summarizing research, limited full-length review articles (40) are available, indicating a gap in summarizing existing research.
- The country-wise analysis indicates that Iran (163) and China (146) lead in zeolite concrete research, followed by the United States (97) and India (82), indicating considerable contributions that highlight the increasing global collaboration in sustainable concrete technology.
- The author analysis indicates that Shekarchi, M. has 22 publications with 1929 citations and a total link strength of 272, followed by Ahmad, B. with 13 publications and 1116 citations, and Černý, R. with 10 publications and 262 citations. Furthermore, Shekarchi and Ahmadi are highly cited researchers focusing on sustainability.
- The journal analysis indicates that *Construction and Building Materials* leads with 99 papers, followed by *Advanced Materials Research* (32 publications) and *Materials* (25 publications), which demonstrate increased interest in zeolite-based concrete.
- The National Natural Science Foundation of China is the main funding source for zeolite concrete research, which funded 60 articles related to zeolite concrete research. Other main funders are the European Commission and several universities, which highlights strong international collaboration for the advancement of sustainable zeolite-based concrete technology.
- The keyword analysis shows “Zeolite” (219 occurrences) and “Concrete” (107) as the main focus, with a major focus on “Compressive Strength” and “Durability.” Furthermore, the study changed direction from basic material characterization (2014–2016) to advanced applications such as “Geopolymer” and “Self-Compacting Concrete” (2018–2020).

6. Recommendation

Although significant progress in zeolite concrete research was observed, several critical areas need further research. These areas include the following:

- The area of publication indicates that chemistry and chemical engineering have limited publications, with 68 in chemistry and 54 in chemical engineering. The analysis shows comparatively fewer publications in chemistry, chemical engineering, and computer science than in engineering and materials science. Although this does not necessarily indicate a research gap, it suggests opportunities for interdisciplinary collaboration. Therefore, the authors recommend further study with the utilization of computational methods such as simulation models and artificial intelligence in improving zeolite concrete performance.
- The analysis of document types indicates limited full-length review articles (40). Therefore, further review studies are recommended to synthesize existing knowledge and support future research in zeolite-based concrete.

- Keywords related to high-strength concrete, ultra-high-performance concrete, engineered cementitious composites, and life-cycle assessment did not meet the selected occurrence threshold. Therefore, these topics appear less represented in the bibliometric network and represent promising directions for future research. Therefore, the authors recommend detailed studies on these aspects to improve zeolite concrete performance.
- The zeolite concrete performance can be improved significantly by addressing key research gaps as mentioned in the recommendation. It will improve the zeolite concrete strength, durability, and sustainability while also mitigating the environmental effects of concrete.

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