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Recent Advances in Polymer Analysis and Characterization Techniques for High-Performance Materials

Hemant Choudhary[1,*], Sarvesh P.S. Rajput[2], Amit Mandal[3]

Abstract

*Polymers play a vital role in various fields, from biomedical engineering to energy storage. Developing high-performance polymers requires a deep understanding of their structure, properties, and behavior. This review paper delves into recent advancements in polymer analysis and characterization techniques. This paper is a comprehensive bibliometric analysis which investigates the research landscape of geopolymer concrete incorporating construction and demolition waste (CDW) by analyzing 389 publications from the Web of Science database. The study reveals rapid growth in publication and citation trends, with an annual growth rate of 20.47% and a peak of 2440 citations in 2019. The research spans multiple disciplines, including civil engineering, materials science, environmental sciences, and sustainable technology, highlighting the interdisciplinary nature of the field. Keyword analysis reveals three main research clusters focusing on **mechanical properties** and durability aspects, mix design and **synthesis techniques**, and utilization of recycled aggregates and CDW. The most influential papers provide valuable insights into developing, characterizing, and optimizing sustainable concretes, emphasizing the potential of CDW-based geopolymer concrete in promoting circular economy principles. Prominent themes include the synergistic use of industrial by-products like **fly ash** and blast furnace slag as precursors, optimization of mix proportions and curing conditions, **microstructural** characterization, and assessment of key properties such as compressive strength, flexural strength, and durability indicators. The study identifies knowledge gaps and recommends future research directions, including long-term performance evaluation, standardized mix design guidelines, incorporation of diverse CDW materials, development of **hybrid composites** with enhanced functionality, and comprehensive life cycle and **thermal analysis**. The findings underscore the significance of this research field in advancing sustainable construction practices and addressing the environmental challenges associated with CDW management while promoting the development of high-performance, eco-friendly building materials.*

Keywords: Polymer, High-Performance Materials, Geopolymer concrete, Construction and demolition waste, Mechanical properties.

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INTRODUCTION

Geopolymer concrete has been recognized as a promising sustainable alternative to traditional Portland cement concrete due to its lower carbon footprint and superior durability properties (1,2). Geopolymers are obtained by the reaction of aluminosilicate precursors, like fly ash or metakaolin, with alkaline activators, which leads to the creation of a three-dimensional amorphous network (3). The rising environmental issues that come with the production of Portland cement, which is the main cause of significant greenhouse gas emissions, have attracted the attention of geopolymer concrete (4–6).

CDW is another big environmental problem that the construction industry has to face(7–9). CDW, which is made up of materials such as concrete rubble, bricks, tiles, and ceramics, is a big part of the total solid waste that is produced around the world (10). The CDW disposal in landfills not only takes up precious land area but also causes environmental pollution (11). Hence, the search for effective ways to recycle and apply the CDW has become a crucial issue in the field of sustainable construction (12–14).

Utilizing CDW as a raw material in geopolymer concrete not only reduces the environmental impact of cement production but also helps to manage the growing problem of construction waste(15,16). Thus, either partially or completely replacing natural aggregates with recycled aggregates from CDW, the demand for virgin raw materials can be reduced, which, in turn, leads to the conservation of natural resources and the decrease in the environmental footprint of construction activities (17, 18). Besides that, the use of CDW in geopolymer concrete can help divert waste from landfills, therefore reducing the environmental burden (19). Besides the favorable effect on the environment, the use of CDW in geopolymer concrete will be advantageous to properties such as strength, durability, and fire resistance(20, 21). The fact that recycled aggregates are porous can be turned into a positive factor by boosting the interfacial bonding with the geopolymer matrix, which in turn will give the overall mechanical performance a good boost(22). Finally, besides this, the unreacted calcium-rich particles in recycled concrete aggregates can help in the formation of more calcium silicate hydrate (C-S-H) gel, which in turn strengthens the geopolymer matrix (23).

People are becoming more and more interested in using CDW in geopolymer concrete, but there is still a lot to learn and understand about this topic. A bibliometric analysis can be a very powerful way to quantitatively evaluate the scientific literature, find the research trends, and map the intellectual structure of a given field (24–28). Through the process of bibliometric analysis of the research on geopolymer concrete made with CDW, many advantages can be gained.

Firstly, the bibliometric analysis can reveal the global trends and patterns of research activities, thus pointing out the countries, institutions, and researchers that are in the leading positions in this discipline (29). Thus, the data can help with cooperation, the sharing of knowledge, and the transfer of technology among scientists and experts. Besides that, the study of the most influential publications and their citation networks will be able to point out the seminal works and the research themes that have been the key factors for the development of this field(30). This can assist the researchers in finding the knowledge gaps, the ways of future research directions, and the areas of innovation.

Besides, the bibliometric analysis of keyword co-occurrence and research clusters can be used to expose the main topics and sub-domains within the field of geopolymer concrete made with CDW(31, 32). This data can be useful to the researchers in comprehending the relationship among the different research areas and finding the chances of interdisciplinary collaboration. The conclusions of the bibliometric analysis can help the policymakers, the industry stakeholders, and the funding agencies to know the present state of the research and the possibilities of geopolymer concrete made with CDW as a sustainable construction material, thus directing future investments and policy formulation.

The main aim of this study is to carry out a complete bibliometric analysis of the geopolymer concrete research field, which is made of construction and demolition waste (CDW). undefined

- What are the worldwide tendencies and patterns of research activities on geopolymer concrete made with CDW in terms of the number of publications and citations per year, subject categories, and geographical distribution?
- Who are the main researchers and countries involved in the research on geopolymer concrete with CDW, and how do they work together?

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- What are the principal research themes and sub-domains in the field of geopolymers concrete made with CDW, as shown by the keyword co-occurrence and research cluster analysis?
- What are the most famous publications and their main findings that have made the research on geopolymer concrete made with CDW the most influential in the geopolymer concrete industry?
- What are the potential knowledge gaps, future research directions, and consequences for sustainable construction practices based on the findings of the bibliometric analysis

METHODOLOGY

Data Collection

Databases Used

The information for this bibliometric analysis was obtained from the Web of Science (WoS) database, which is the most popular and the most comprehensive source of scholarly literature in different fields(33). WoS offers access to many citation indexes, including the Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (A&HCI), which will give you a wide coverage of the relevant research on geopolymer concrete made with construction and demolition waste (CDW).

Search String

The relevant documents were found by using a well-designed search string that was built by combining the keywords and the Boolean operators. The search string: TS= ((“construction and demolition waste” OR “construction & demolition waste” OR “C&D waste” OR “CDW”) AND (geopolymer*) AND (concrete)) was used to search for the records that contain the given terms in their titles, abstracts, or keywords. The * wildcard was employed to find variations of the word “geopolymer,” for example, “geopolymers” or “geopolymeric.

Timeframe and Inclusion/Exclusion Criteria

The data collection process did not put any particular time limit since the goal was to get all the relevant research on the topic from the very first entry in the database. The first record that was found was from 2012, and the search covered all the records from that year up to the date when the data was collected in 2024. The criteria for inclusion were restricted to articles and reviews written in English so as to guarantee the quality and ease of access to the analyzed documents. The article did not consider conference papers, book chapters, and other document types to keep the main focus on the peer-reviewed research articles and reviews. The process for the selection of data for analysis is shown in the PRISMA chart below (Figure 1).

Data Analysis

The bibliometric analysis comprised the examination of a variety of indicators to give a complete picture of the research situation. The annual publication and citation trends were studied to determine the growth and the impact of research on geopolymer concrete made with CDW over time (34). The study of the publication distribution over the different subject areas was made to find out the main fields of the research(35). The most important countries and the patterns of international collaboration were identified according to the number of publications and citations and through the analysis of co-authorship networks (36). The authors and the research groups that are the leading ones were detected by the author productivity and the co-authorship networks(37). Keywords were analyzed to discover the main research themes and trends, including the most frequent keywords and their co-occurrence networks (38). Last, the papers that were the most cited in the field were detected, and their main points were presented to give the readers an idea about the most important contributions to the field(39).

The bibliometric analysis was executed through VOSviewer (version 1.6.20), a very popular software program for creating and displaying bibliometric networks(40). VOSviewer was used to generate the co-authorship networks and keyword co-occurrence networks and to display the connection among the various bibliometric entities. Microsoft Excel was applied in the data preprocessing, cleaning, and making of charts and tables to show the bibliometric indicators and trends. The grouping of these tools made it possible to carry out a complete and visually attractive analysis of the research field on the geopolymer concrete made with CDW.

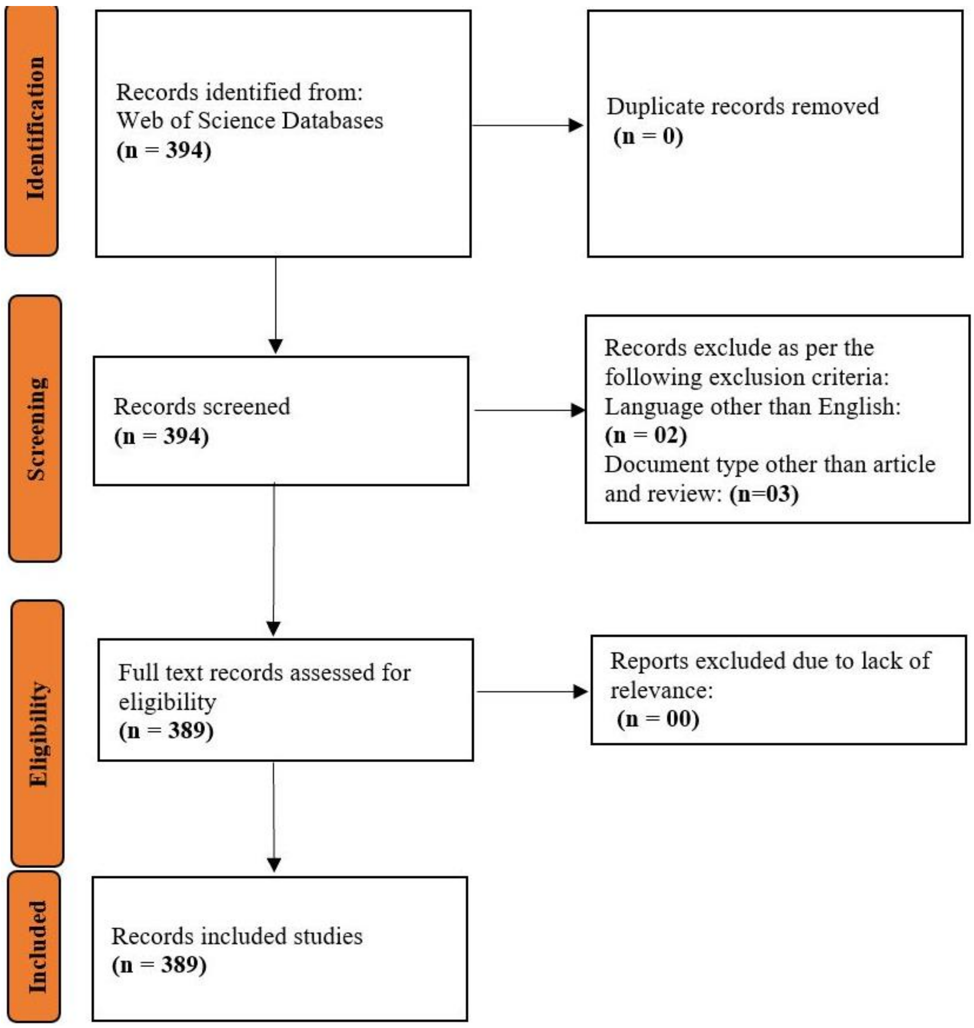

Figure 1. PRISMA Chart.

RESULTS

Annual Publication and Citation Trends

The bibliometric analysis of research on geopolymer concrete made with construction and demolition waste (CDW) showed a great increase in the number of publications annually over the past ten years. Figure 2 shows the annual publications and citation trends. In 2012, there were only 3 papers published on this topic, indicating that this research field was still in its infancy. The output was not that impressive, and it had only an average of 2-4 publications per year until 2015. Nonetheless, the year 2016 became a cornerstone, showing a sharp rise in the research interest, which is proved by the fact that 9 publications were published, which is more than twofold as compared to the previous year. Thus, the field has been going through a steady and large year-on-year increase in research output.

During the period 2017-2019, the annual publication count showed a steady upward trend, with 11, 14, and 30 papers published, respectively. This trend shows the fast growth of the research and study on the application of CDW in geopolymer concrete. The momentum increased further in 2020 and 2021, with a remarkable rise in research activity, as shown by the 41 and 64 publications, respectively. The most recent years have witnessed the highest research outputs, with 70 papers in 2022, 108 in 2023, and an impressive 31 publications already in the first quarter of 2024, which is a sure sign of a continued upward trajectory in this research domain.

Parallel to the growth in publications, the citation trend has also exhibited an overall upward movement, albeit with some fluctuations. The total yearly citations increased from 458 in 2012 to a remarkable peak of 2440 in 2019, underscoring the growing impact and visibility of research in this field. However, it is worth noting that the year 2014 witnessed a notable anomaly, with only 33 citations recorded, despite a consistent publication output compared to the adjacent years. Barring this exception, the citation trend has largely mirrored the publication pattern, with higher citation counts typically associated with years boasting a greater number of publications.

A comparative analysis of the publication and citation patterns unveils a strong positive correlation, indicating that years characterized by higher research outputs have generally garnered greater impact and attention within the scientific community. However, some lag effects can be observed, wherein peak citation years often follow 1-2 years after significant spikes in publication. A prime example is the citation peak observed in 2019, which succeeded the notable increase in publications witnessed in 2017 and 2018. Similarly, the second-highest citation count recorded in 2021 can be attributed to the publication surge observed in 2020.

Focusing on the most recent 3-year window (2022-2024), the publication and citation data paint a picture of a research field that continues to expand and mature rapidly. With an impressive 70-108 papers published annually and total yearly citations consistently exceeding 600, the research on geopolymer concrete incorporating CDW continues to attract significant interest and make substantial contributions to the broader scientific discourse.

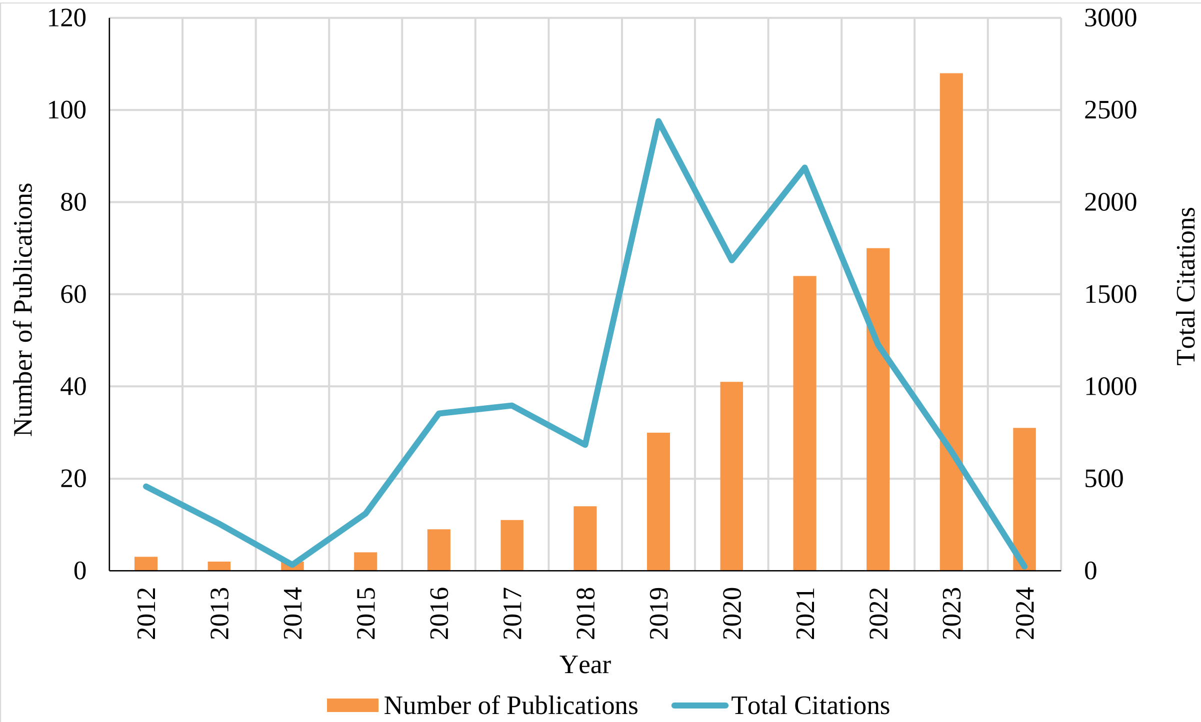

Figure 2. Annual publications and citation trends.

Subject Categories Analysis

Distribution of Publications Across Subject Categories

As depicted in Figure 3, the research on geopolymer concrete incorporating construction and demolition waste (CDW) spans a wide range of subject categories, with the top ten Web of Science categories being Engineering Civil (212 records, 54.5%), Construction Building Technology (202 records, 51.9%), Materials Science Multidisciplinary (196 records, 50.4%), Environmental Sciences (56 records, 14.4%), Green Sustainable Science Technology (48 records, 12.3%), Engineering Environmental (39 records, 10.0%), Physics Applied (34 records, 8.7%), Metallurgy Metallurgical Engineering (33 records, 8.5%), Physics Condensed Matter (27 records, 6.9%), and Chemistry Physical (26 records, 6.7%).

The predominance of Engineering Civil, Construction Building Technology, and Materials Science Multidisciplinary categories emphasizes the primary emphasis of this research domain on the creation and analysis of sustainable construction materials. Geopolymer concrete incorporating CDW exemplifies an innovative strategy for recycling waste materials and minimizing the construction industry's environmental footprint, aligning closely with the scope of these subject categories.

The prominent appearance of the Environmental Sciences and Green Sustainable Science Technology categories shows the environmental and sustainability features of this research area. The incorporation of CDW in geopolymer concrete not only solves the problem of waste disposal but also proves to be a significant step towards the creation of a more eco-friendly and sustainable construction industry. The articles that are in the mentioned categories explain the ecological benefits, life cycle assessment, and green merits of CDW-based geopolymer concrete.

The inclusion of Physics Applied, Metallurgy, Metallurgical Engineering, Physics Condensed Matter, and Chemistry Physical categories highlights the interdisciplinary character of this research field. These categories encompass investigations delving into the fundamental physical and chemical properties, microstructure, and performance attributes of CDW-based geopolymer concrete. The presence of these categories underscores the significance of comprehending the underlying scientific and engineering principles governing the behavior of this innovative construction material.

The overall distribution of publications across multiple subject categories reflects the multifaceted scope and interdisciplinary nature of this research area, indicating that advancing geopolymer concrete using CDW necessitates expertise and contributions from diverse scientific and engineering disciplines. This broad spectrum of subject categories involved in the research of CDW-based geopolymer concrete opens up opportunities for cross-disciplinary collaborations and knowledge exchange, fostering a holistic approach to the development and optimization of this sustainable construction material. By leveraging insights from various fields, researchers can work towards unlocking the full potential of geopolymer concrete by incorporating CDW, addressing technical challenges, and exploring innovative applications in the construction industry.

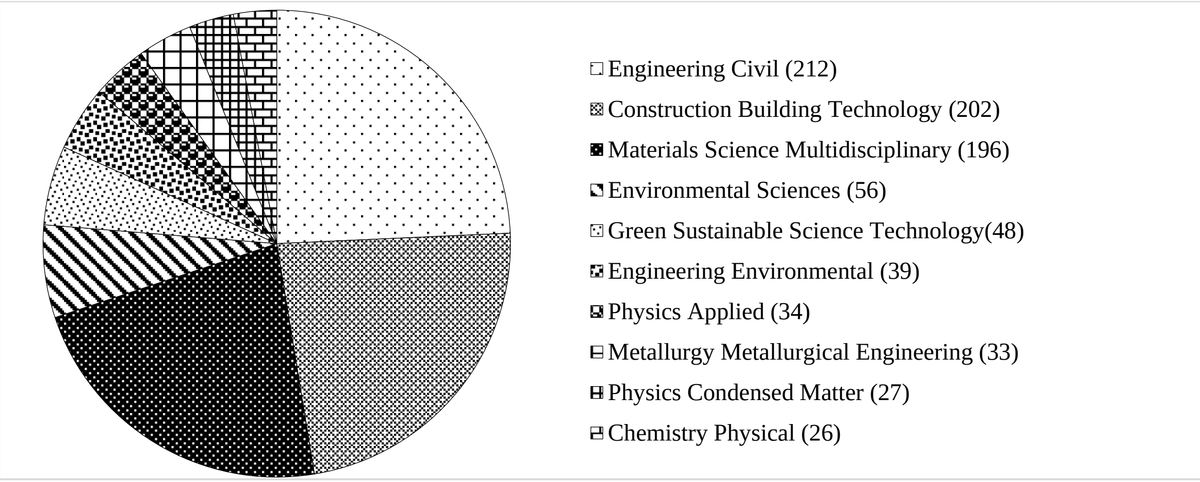

Figure 3. Distribution of publications across the top 10 subject categories.

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Most Influential Countries and International Collaboration

Top countries by Publication Count and Citation Impact

The bibliometric analysis reveals that the People's Republic of China leads the research on geopolymer concrete made with construction and demolition waste (CDW), with 116 publications accounting for 29.82% of the total research output in this field. Turkey follows with 53 publications (13.625%), Australia with 46 publications (11.825%), India with 42 publications (10.797%), and the United States with 33 publications (8.483%). Other notable contributors include Thailand (31 publications, 7.969%), Saudi Arabia (30 publications, 7.712%), England (18 publications, 4.627%), Pakistan (18 publications, 4.627%), and Egypt (17 publications, 4.37%). Table 1 presents the top countries ranked by their publication counts and total citation counts.

The high publication output from China can be attributed to several factors, including the country's rapid urbanization, massive construction activities, and the resulting generation of substantial amounts of CDW. China's strategic focus on sustainable development and circular economy principles has also fueled research into green construction materials like geopolymer concrete. On the other hand, the substantial participation of Turkey, Australia, India, and the United States in the field of sustainable construction could be related to large construction industries, government projects promoting sustainable construction practices, and the presence of proper research institutions and funding programs in these countries.

It is interesting to note that although China has the most publications, Thailand has the highest average citations per article (54.81), ahead of Australia (44.35) and the US (40.06). This indicates that the research emanating from these nations has had a notable influence and has been extensively acknowledged and referenced by the scientific world. The high citation impact may stem from the exceptional quality and originality of the research, the esteemed reputation of the researchers and institutions involved, and the pertinence of the findings to the wider domain of sustainable construction materials.

Table 1. Top countries by publication count and total citations.

Country/Region	Number of Publications	Percentage Share	Total Citations	Citations per Publication
Peoples R China	116	29.82	3339	28.78
Turkey	53	13.625	946	17.85
Australia	46	11.825	2040	44.35
India	42	10.797	1113	26.50
USA	33	8.483	1322	40.06
Thailand	31	7.969	1699	54.81
Saudi Arabia	30	7.712	1201	40.03
England	18	4.627	439	24.39
Pakistan	18	4.627	446	24.78
Egypt	17	4.37	345	20.29

Co-authorship Among Countries

The co-authorship network visualization (Figure 4) reveals significant international collaborations among countries researching geopolymer concrete made with construction and demolition waste (CDW). China, as the leading contributor, has strong co-authorship ties with the United Arab Emirates, Belgium, and the United States. Australia exhibits prominent collaborative links with Thailand, Germany, the United States, and Iran.

The red cluster in the co-authorship network comprises Australia, Belgium, Germany, Iran, China, Portugal, Thailand, the United Arab Emirates, and the United States, representing a diverse mix of developed and emerging economies with a shared interest in advancing sustainable construction practices through the utilization of CDW in geopolymer concrete. The green cluster, which includes Egypt, India, Iraq, Malaysia, Pakistan, Poland, and Saudi Arabia, highlights a regional collaborative network among Middle Eastern and South Asian countries, possibly driven by similar socio-economic challenges such as rapid urbanization, infrastructure development, and the need for sustainable waste management solutions. The exchange of knowledge and expertise within this cluster could facilitate the development of geopolymer concrete tailored to the specific needs and resources of these countries.

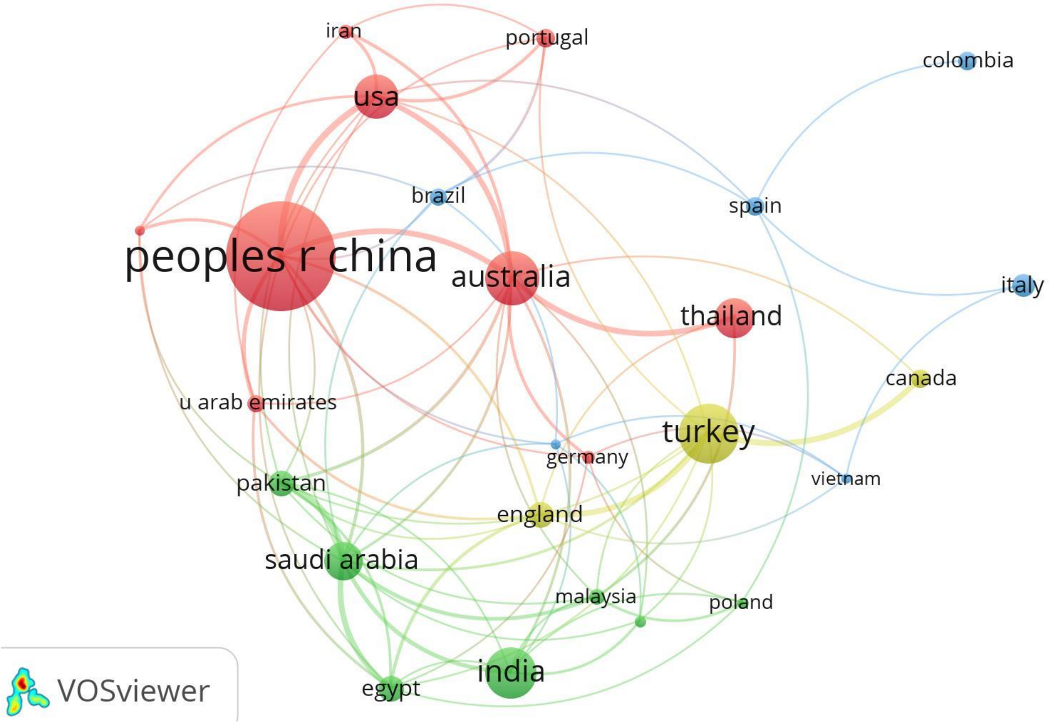

Figure 4. Co-authorship network among countries.

The blue cluster, encompassing Brazil, Colombia, Italy, Russia, Spain, and Vietnam, indicates a diverse group of countries collaborating on geopolymer concrete research, spanning different continents and regional contexts. This suggests a broad international interest in the topic, with the collaboration between European countries like Italy and Spain and emerging economies such as Brazil, Colombia, and Vietnam highlighting the potential for knowledge transfer and capacity building in the field of sustainable construction materials. The yellow cluster, consisting of Canada, England, and Turkey, represents a smaller but significant collaborative network, with the presence of two highly developed countries alongside an emerging economy with a rapidly growing construction industry, indicating a strategic partnership aimed at addressing the challenges of CDW management and promoting sustainable construction practices. The cross-cluster collaborations, such as those between China, the United States, and European countries, underscore the potential for global knowledge-sharing and technology transfer, which can accelerate the development and standardization of geopolymer concrete made with CDW, promoting its wider adoption in the construction industry worldwide.

Leading Authors and Author Collaboration

Most Productive Authors

The bibliometric analysis of research on geopolymer concrete made with construction and demolition waste (CDW) reveals that Sahmaran M. from Turkey is the most prolific author in this field, with 30 publications, accounting for 7.712% of the total research output. Chindaprasirt P. and Sata V. from Thailand follow with 19 (4.884%) and 17 (4.37%) publications, respectively. Other top contributors include Wongsa A. from Thailand (13 publications, 3.342%), Canpolat O., Yildirim G., and Uysal M.

from Turkey (12, 12, and 11 publications, respectively), Li W.G. from Australia (12 publications, 3.085%), Xie J.H. from China (11 publications, 2.828%), and Lachemi M. from Canada (10 publications, 2.571%).

Table 2 presents the top authors ranked by their publication counts, along with their total citation counts and citations per publication. Interestingly, while Sahmaran M. has the highest number of publications, Chindaprasirt P. and Sata V. have the highest total citation counts (1325 and 1315, respectively) and the highest citations per publication (69.74 and 77.35, respectively). This suggests that the research outputs of Chindaprasirt P. and Sata V. have had a significant impact and have been widely recognized and cited by the scientific community.

Table 2. Top ten authors and their publications.

Author	Country	Number of Publications	Total Citations	First Author Publications
Sahmaran M	Turkey	30	706	0
Chindaprasirt P	Thailand	19	1325	2
Sata V	Thailand	17	1315	2
Wongsa A	Thailand	13	705	1
Canpolat O	Turkey	12	135	0
Li WG	Australia	12	609	1
Yildirim G	Turkey	12	432	0
Uysal M	Turkey	11	133	1
Xie JH	People R China	11	797	6
Lachemi M	Canada	10	225	0

The high research productivity of these leading authors can be attributed to several factors, such as their expertise in the field of sustainable construction materials, their affiliations with well-established research institutions, and their involvement in influential research projects and collaborations. For example, Sahmaran M., Canpolat O., Yildirim G., and Uysal M. are all affiliated with prominent Turkish universities, which may have provided them with the necessary resources and support to conduct extensive research on geopolymer concrete made with CDW. Similarly, Chindaprasirt P., Sata V., and Wongsa A. are associated with leading Thai universities and have collaborated on several high-impact studies in this field. The international collaborations of authors like Li W.G. (Australia), Xie J.H. (China), and Lachemi M. (Canada) may have also contributed to their research productivity and the global visibility of their work.

Co-authorship Among Authors

The co-authorship network analysis, conducted using the LinLog modularity method and including authors with a minimum of five citations, provides valuable insights into the collaborative landscape of research on geopolymer concrete made with CDW. Out of a total of 1188 authors in this field, the analysis reveals the formation of distinct research clusters and collaborative partnerships that have significantly contributed to advancing knowledge and developing innovative solutions.

The network visualization (Figure 5) highlights the presence of several prominent author clusters, each focusing on specific aspects of CDW utilization in geopolymer concrete. The most productive cluster in green comprises researchers from Thailand, including Chindaprasirt P., Sata V., Wongsa A., and Nuaklong P., who have collectively produced a substantial number of high-impact publications. This cluster's strong co-authorship ties and research output underscore the effectiveness of their collaborative efforts in driving scientific progress.

Another significant cluster consists of Turkish researchers, such as Sahmaran M., Yildirim G., etc, whose close collaboration has resulted in a cohesive and productive research group. The co-authorship links within this cluster demonstrate the importance of regional collaborations in fostering knowledge exchange and resource-sharing, ultimately leading to high research productivity and impact.

The network analysis also reveals the presence of international collaborations, exemplified by the co-authorship links between Lachemi M. (Canada) and Sahmaran M. (Turkey). These cross-border partnerships highlight the global nature of research on geopolymer concrete made with CDW and the value of international cooperation in tackling complex challenges and developing innovative solutions.

The co-authorship patterns observed in this research field emphasize the crucial role of collaborative efforts in advancing scientific knowledge and developing sustainable construction materials. The formation of specialized research clusters and the presence of both regional and international collaborations have facilitated the exchange of expertise, methodologies, and resources, leading to high-impact research outputs and the rapid progress of this field. As the global community continues to seek sustainable alternatives to conventional construction materials, the collaborative networks identified in this analysis will likely play an increasingly important role in shaping the future of geopolymer concrete research and its applications in the built environment.

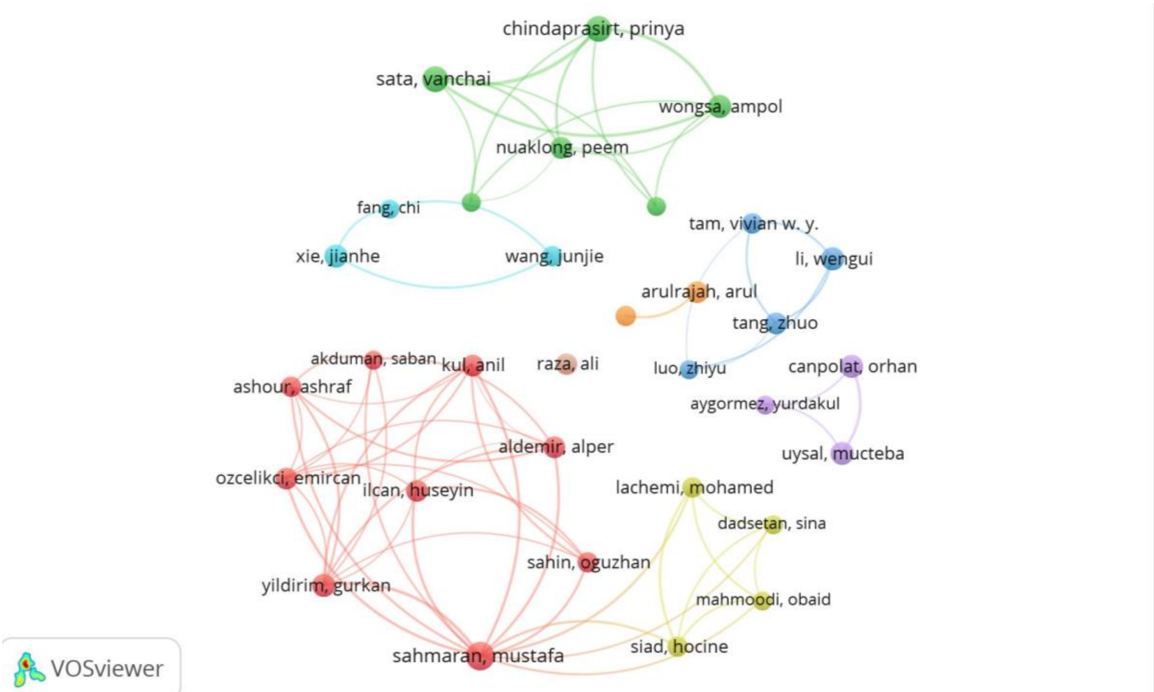

Figure 5. Co-authorship network among authors.

Keyword Analysis

Most Frequently Occurring Keywords(Table 3)

Table 3 shows the top ten keywords with a high frequency of occurrence. The top 10 most frequently occurring keywords in the research on geopolymer concrete made with construction and demolition waste are shown in the figure. These high-frequency keywords reflect the core focus and key aspects of research in this field. “Geopolymer” and “geopolymer concrete” are the central themes, highlighting the development and characterization of this sustainable alternative to conventional concrete. “Recycled aggregate,” “recycled concrete aggregate,” and “construction and demolition waste” emphasize the utilization of waste materials as a key component in geopolymer concrete production, aligning with the principles of circular economy and waste valorization.

“Fly ash” is a frequently used keyword, indicating its significance as a common precursor material in geopolymer synthesis. The high occurrence of “mechanical properties” and “compressive strength” underscores the importance of evaluating the performance and structural viability of geopolymer concrete made with recycled aggregates. “Microstructure” and “durability” are also prominent keywords, reflecting the interest in understanding the fundamental material characteristics and long-term performance of these sustainable concrete composites.

Table 3. Top ten keyword with high frequency.

Keywords	Frequency
geopolymer	99
geopolymer concrete	63
recycled aggregate	63
fly ash	51
mechanical properties	49
compressive strength	45
construction and demolition waste	33
microstructure	32
recycled concrete aggregate	24
durability	23

Co-occurrence and Clustering Analysis

The keyword co-occurrence analysis, performed using the LinLog modularity normalization method and VOSviewer software, reveals distinct clusters and themes within the research on geopolymer concrete made with construction and demolition waste.

Based on the clustering results, three major keyword clusters emerge. The first cluster, represented by the color red, focuses on the mechanical properties and performance aspects of geopolymer concrete. This cluster includes keywords such as “compressive strength,” “flexural strength,” “bond strength,” “drying shrinkage,” and “strength,” highlighting the importance of understanding and optimizing the mechanical behavior of geopolymer concrete. Additionally, this cluster encompasses keywords related to the life cycle assessment and sustainability of geopolymer concrete, indicating the growing interest in evaluating the environmental impact and long-term viability of this innovative construction material.

The second cluster, denoted by the color green, emphasizes the materials and mix design aspects of geopolymer concrete. Prominent keywords in this cluster include “fly ash,” “ground granulated blast furnace slag,” “metakaolin,” “alkali-activated materials,” and “mix design.” This cluster underscores the crucial role of precursor materials and mix proportions in the development and optimization of geopolymer concrete. By focusing on the selection and combination of various industrial by-products and aluminosilicate sources, researchers aim to enhance the performance and sustainability of geopolymer concrete formulations.

The third cluster, represented by the color blue, revolves around the utilization of recycled aggregates and construction and demolition waste in geopolymer concrete production. Keywords such as “recycled aggregate,” “recycled concrete aggregate,” “recycled fine aggregate,” “recycled coarse aggregate,” and “construction and demolition waste” are prominent in this cluster. This emphasis on waste valorization and circular economy principles highlights the potential of geopolymer concrete to incorporate recycled materials, thereby reducing the environmental impact associated with the disposal of construction and demolition waste. By exploring the use of recycled aggregates in geopolymer concrete, researchers aim to develop sustainable and eco-friendly alternatives to traditional concrete production methods.

These keyword clusters provide valuable insights into the main research themes and areas of interest within the field of geopolymer concrete made with construction and demolition waste. The red cluster emphasizes the importance of evaluating the mechanical performance and sustainability aspects of geopolymer concrete, while the green cluster focuses on the selection and optimization of precursor materials and mix design. The blue cluster highlights the significance of incorporating recycled aggregates and construction and demolition waste into geopolymer concrete production, aligning with the goals of waste reduction and circular economy.

In the keyword co-occurrence network visualization (Figure 6), nodes represent keywords that occurred a minimum of 5 times, with node size determined by the number of occurrences of each keyword. The network reveals strong co-occurrence links between keywords such as “geopolymer” and “geopolymer concrete,” “recycled aggregate,” and “construction and demolition waste,” and “fly ash” and “geopolymer.” These strong links indicate the close association and frequent co-occurrence of these concepts in the literature.

An interesting observation from the network is the central position of “geopolymer concrete,” connecting the clusters related to mechanical properties, materials, and recycled aggregates. This suggests that geopolymer concrete serves as a unifying theme, bridging the various research aspects in this field. The network also reveals some outlier keywords, such as “pervious concrete” and “steel fiber,” which may represent niche applications or specific areas of investigation within the broader context of geopolymer concrete made with construction and demolition waste.

Overall, the keyword co-occurrence analysis provides a comprehensive overview of the research landscape, highlighting the main themes, research priorities, and interconnections among key concepts in the field of geopolymer concrete made with construction and demolition waste. The insights gained from this analysis can guide researchers in identifying knowledge gaps, exploring new research directions, and fostering collaborations across different research clusters.

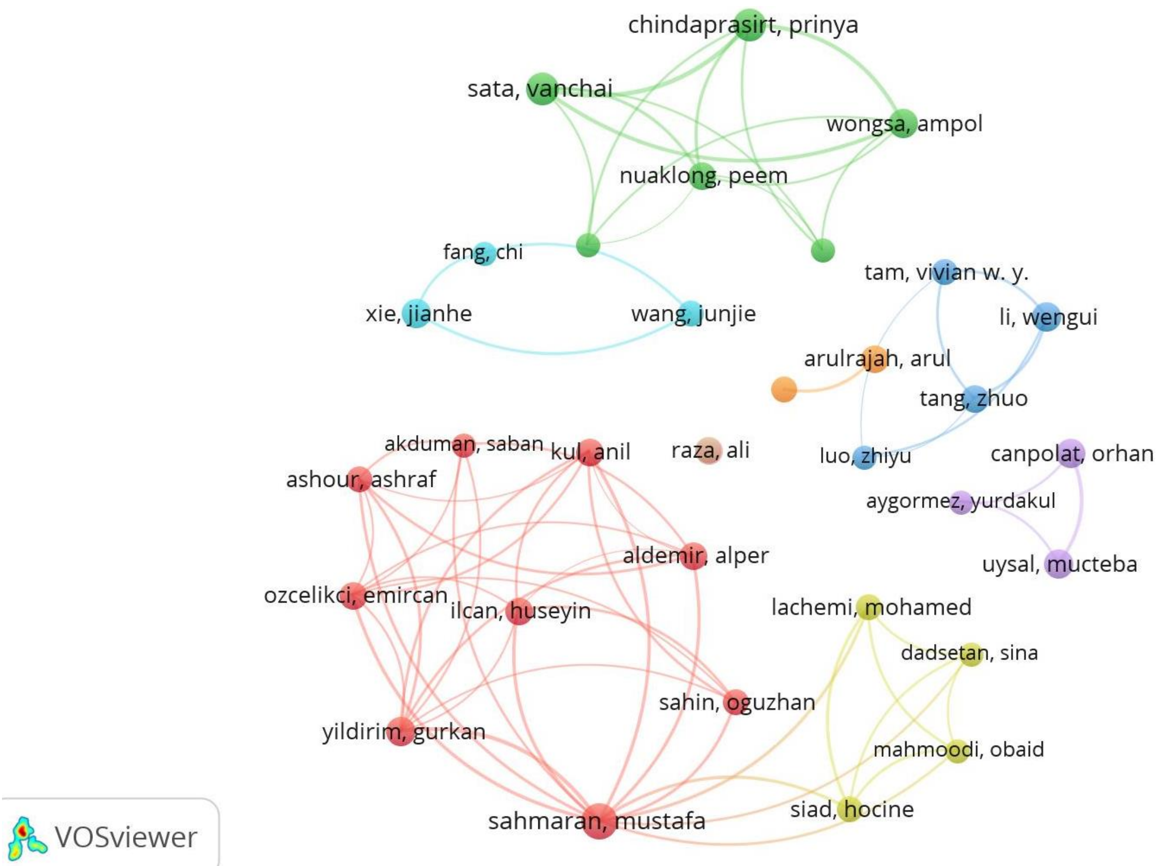

Figure 6. Keyword co-occurrence network.

Table 4. Top ten keywords with high frequency.

Article Title Total Citations	
Effects of combined usage of GGBS and fly ash on workability and mechanical properties of alkali activated geopolymer concrete with recycled aggregate	304
Use of geopolymer concrete for a cleaner and sustainable environment - A review of mechanical properties and microstructure	295
Production of geopolymeric binder from blended waste concrete powder and fly ash	245
Properties and utilization of waste tire rubber in concrete: A review	214
Influence of recycled aggregate on fly ash geopolymer concrete properties	203
Water absorption and electrical resistivity of concrete with recycled concrete aggregates and fly ash	195
Effect of synthesis parameters on the quality of construction and demolition wastes (CDW) geopolymers	187
Properties of pervious concrete containing recycled concrete block aggregate and recycled concrete aggregate	185
Properties of pervious geopolymer concrete using recycled aggregates	175
Influence of rice husk ash on mechanical properties and fire resistance of recycled aggregate high-calcium fly ash geopolymer concrete	171

Most Influential Papers and their Key Findings

The top 10 cited papers (Table 4) provide valuable insights into the development and characterization of sustainable concretes incorporating industrial by-products, recycled aggregates, and unconventional binders. Xie et al. (41)demonstrated the synergistic effects of combining ground granulated blast furnace slag (GGBS) and fly ash in alkali-activated geopolymer recycled aggregate concrete (GRAC), optimizing the mixture proportions for workability and strength. Hassan et al. (42)presented a comprehensive review of geopolymer concrete (GPC), discussing the influence of mix design factors on its properties, durability, microstructure, and applications. Ahmari et al. (43) showed that strong geopolymer binders can be produced from a blend of waste concrete powder and fly ash, with calcium from the waste enhancing strength through C-S-H gel formation. Siddika et al. (44) reviewed the properties and applications of rubberized concrete, highlighting the importance of optimizing rubber content, size, and surface treatment for improved performance. Nuaklong et al. (45)investigated the effect of using recycled concrete aggregate (RCA) as a coarse aggregate in high-calcium fly ash geopolymer concrete. Geopolymer concrete samples were prepared with RCA or crushed limestone coarse aggregates and tested for mechanical properties like compressive, tensile, and flexural strengths as well as durability aspects like water absorption, chloride penetration, and acid resistance. The results showed that RCA could be effectively utilized in fly ash geopolymer concrete, providing 76-93% of the strength of limestone aggregate concrete. Using a 12M sodium hydroxide solution gave an optimum performance in terms of strength and durability for both RCA and limestone aggregate geopolymer concretes. Kurda et al. (46)demonstrated that high volumes of fly ash improve the durability indicators of recycled concrete aggregate concrete, with combined effects surpassing individual contributions. Komnitsas et al. (47)investigated the geopolymerization potential of construction and demolition wastes (CDW) such as concrete, bricks, and tiles, revealing that tiles and bricks exhibit better reactivity and compressive strength compared to concrete due to their higher $SiO2$ and $Al2O3$ content. The study also highlighted the importance of optimizing synthesis parameters such as NaOH molarity, curing temperature, and particle size to achieve desired geopolymer properties. Zaetang et al. (48) showed that recycled concrete block aggregates (RBA) and recycled concrete aggregates (RCA) can enhance the strength and abrasion resistance of pervious concrete at optimum replacement levels. Sata et al. (49)produced pervious geopolymer concretes with acceptable strength and permeability using recycled concrete and brick aggregates, emphasizing the importance of optimizing NaOH concentration and aggregate content. Finally, Nuaklong et al. (2020)(50) established rice husk ash as a viable, sustainable alternative to nano-silica for improving the properties of ambient-cured recycled aggregate geopolymer concrete while noting the trade-off with reduced fire resistance. Further researches discuss Plant Fibers for Enhancing Properties of Bio composites [51], Biomass for polymer composite applications [52], Novel Ficus retusa L. aerial root fiber [53], natural fiber composites [54] Modified Laminated Veneer Lumber Made of Jabon Wood [55].

These studies collectively advance the understanding of sustainable concretes by exploring the synergistic use of waste materials, optimizing mixture proportions and processing conditions, elucidating microstructure-property relationships, and demonstrating technical viability for practical applications. They highlight the importance of holistic evaluation considering mechanical properties, durability, and thermal resistance. Further research should focus on addressing knowledge gaps, overcoming methodological limitations, and assessing the long-term impacts and scalability of these eco-friendly concretes. The findings have significant implications for promoting sustainable construction practices and policies, with potential economic, environmental, and social benefits in the context of green building and infrastructure development.

DISCUSSION

Interpretation of the Main Research Themes and Trends

The bibliometric analysis of the research on geopolymer concrete produced with construction and demolition waste (CDW) shows several main themes and trends. The keyword co-occurrence analysis highlights three main research clusters: The mechanical properties and performance aspects, the materials and mix design, and the utilization of recycled aggregates and CDW, which are the three main clusters of this discourse. These clusters highlight the main purpose of the research, which is about the mechanical behavior, durability, and sustainability of the geopolymer concrete that uses CDW. The strong emphasis on precursor materials, for example, fly ash, ground granulated blast furnace slag, and metakaolin shows how important it is to select and mix various industrial by-products and aluminosilicate sources in order to improve the performance and sustainability of geopolymer concrete formulations, The articles written on the subject of recycled aggregates and CDW show the increasing attention to the waste valorization and the circular economy principles that are used to reduce the environmental impact of the disposal of the construction and demolition waste. In general, the main research themes and trends demonstrate the intention to form geopolymer concrete that is not only environmentally friendly but also has high performance by using waste materials, mixing proportions, and fundamental microstructure-property relationships.

Identification of Research Gaps and Future Directions

Despite the significant progress in research on geopolymer concrete made with CDW, several knowledge gaps and opportunities for future research remain. One area that requires further investigation is the long-term performance and durability of geopolymer concrete incorporating CDW under various environmental conditions, such as freeze-thaw cycles, sulfate attack, and carbonation. Additionally, the development of standardized mix design guidelines and performance criteria for CDW-based geopolymer concrete is crucial to facilitate its wider adoption in the construction industry. Future research should also explore the potential of incorporating other types of CDW, such as recycled masonry, asphalt, and glass, into geopolymer concrete to further enhance its sustainability and valorize a broader range of waste materials. Moreover, the development of multi-functional geopolymer composites that combine CDW with other reinforcing materials, such as fibers or nanomaterials, presents an opportunity to achieve enhanced mechanical properties, durability, and functionality. Finally, conducting a comprehensive life cycle assessment and techno-economic analysis of CDW-based geopolymer concrete is essential to quantify its environmental benefits and economic viability compared to conventional concrete, thereby supporting informed decision-making and policy development.

Implications for Sustainable Construction and Waste Management

Although a large amount of research on geopolymer concrete developed with CDW is done, there are still a lot of knowledge gaps, and the aspects that can be studied in the future still exist. One field that needs to be studied in detail is the long-term performance and durability of the geopolymer concrete made of CDW under different environmental conditions, like freeze-thaw cycles, sulfate attack, and carbonation. Furthermore, uniform mix design guidelines and standards for CDW-based geopolymer concrete are currently needed to make it widely used in the construction industry. Future research needs to be done on the possibility of the other types of CDW, such as recycled masonry, asphalt, and glass, being used in the geopolymer concrete to enhance its sustainability and to incorporate a broader range of waste materials. Besides, the production of multi-functional geopolymer composites with CDW and other reinforcing materials, like fibers or nanomaterials, will increase mechanical properties, durability, and functionality. The life cycle assessment and the techno-economic analysis of CDW-based geopolymer concrete are important to show the environmental benefits and the economic viability compared to the conventional concrete which will in turn help the decision makers and the policy makers to be more specific.

CONCLUSION

The bibliometric analysis of the research on geopolymer concrete made with construction and demolition waste (CDW) has brought to light several important results. The annual publication and citation trends show how the research interest and the research output have been growing over the past decade, and the publications have been increasing significantly since 2016. The analysis of subject categories highlights the interdisciplinary nature of this research field, spanning engineering, materials science, environmental science, and sustainable technology. China, Turkey, Australia, India, and the United States have emerged as the leading contributors to research on CDW-based geopolymer concrete, with strong international collaborations evident in the co-authorship network. The most productive authors, such as Sahmaran M., Chindaprasirt P., and Sata V., have made significant contributions to the field, with their research having a high impact and citation count. The keyword analysis reveals three main research clusters focusing on mechanical properties and performance aspects, materials and mix design, and utilization of recycled aggregates and CDW. The most influential papers in the field provide valuable insights into the development, characterization, and optimization of sustainable concretes incorporating industrial by-products, recycled aggregates, and unconventional binders.

Contributions of the Study to the Field

This research brings forth remarkable results in the area of sustainable construction materials and waste management. Through a thorough bibliometric analysis of the research on geopolymer concrete made with CDW, this study gives a complete view of the research field and pinpoints the main researchers, research themes, and trends. The examination of publication and citation trends, subject categories, and international collaborations gives us information on the development and interdisciplinary nature of this research field and shows that the world is interested in the creation of sustainable construction materials. The discovery of the most productive authors and influential papers is a useful tool for researchers to know the current trends and the key developments in the field. The keyword analysis and determination of the main research clusters lead to a better understanding of the main focus areas and research priorities, guiding future research works and collaborations. In addition to that, the discussion of the research findings implications for the sustainable construction and waste management practices emphasizes the potential of CDW-based geopolymer concrete in promoting the circular economy principles, reducing the environmental impacts and supporting the development of green building standards and policies.

Limitations and Recommendations for Future Research

The bibliometric analysis of the research on geopolymer concrete made with CDW covers a wide range of topics, but at the same time, it is necessary to admit the weaknesses and offer suggestions for future research. One of the drawbacks of the analysis is that it is based on the information collected from a certain time and database (e.g. Web of Science), which may not include all necessary publications in the field. Future research could widen the sources of data and include a longer period to perform a more detailed examination. Besides, the research is also concentrated on bibliometric indicators and keyword analysis, which are not able to reveal the full details and the depth of the research material. Future research could be supplemented by the bibliometric analysis with a systematic review or meta-analysis of the most influential papers to gain a more in-depth view of the main findings, methods, and limitations. Besides, the study identifies research gaps and future directions based on the current state of the field, but it does not give a detailed roadmap for confronting these gaps. Future research should give importance to the identified areas like the long-term durability assessment, the standardized mix design guidelines, the inclusion of diverse CDW materials, the development of multi-functional composites, and the comprehensive life cycle and techno-economic analyses. Collaborative efforts among researchers, industry practitioners, and policymakers are essential to tackle these challenges and promote the widespread adoption of CDW-based geopolymer concrete in sustainable construction practices.

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