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Research Progress in Coal Gangue-Based Geopolymer Composites: A Scientometric Review

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Abstract

This study adopts a scientometric approach to systematically review and critically analyze the research progress on coal gangue-based geopolymer composites, with an emphasis on their implications for sustainable resource management and low-carbon industrial development. Based on literature retrieved from the Web of Science (WoS) database, a total of 225 relevant English publications published between 2012 and 2025 were selected. VOSviewer was employed to visualize annual publication trends and author keyword networks, enabling the identification of research hotspots and emerging themes in this field. The results show that since 2019, publications have increased significantly, driven by environmental regulations and carbon reduction goals, highlighting the importance of integrating solid waste management with low-carbon construction materials. Furthermore, this study provides a comprehensive synthesis of the major research themes, including the design and performance of geopolymer binders, the synergistic activation mechanisms of multiple solid wastes, and their applications in erosion-resistant materials, high-temperature-resistant systems, and the immobilization of hazardous substances such as heavy metals and radioactive elements. From a management perspective, these studies highlight the potential of coal gangue-based geopolymers to support the circular economy, improve resource efficiency, and enhance supply chain sustainability. Finally, key challenges include performance optimization, durability, economic feasibility, and large-scale application. The environmentally responsible use of alkaline activators remains critical. Future research should focus on greener activation technologies, lifecycle management, and stronger policy–industry collaboration to promote wider adoption.

Keywords: Coal Gangue, Geopolymer Composites, Scientometric Analysis, Vosviewer, Solid Waste Valorization, Sustainable Construction Materials

Introduction

China, as one of the world's largest coal-producing and coal-consuming countries, has generated an enormous quantity of coal gangue during long-term mining and processing activities (Gao et al., 2024). From a resource and environmental management perspective, coal gangue represents not only a major solid waste challenge but also a critical issue in sustainable land use and industrial waste governance. The long-term open-air stockpiling of coal gangue has led to land occupation, ecological degradation, and environmental pollution risks, including the release of toxic substances and spontaneous combustion (Zheng et al., 2024). According to statistics, the cumulative stockpile of coal gangue in China has exceeded 7 billion tons, covering approximately 70 km^2, and continues to grow at an annual rate of about 325 million tons (Tang et al., 2024； Zhang et al., 2023). This trend places increasing pressure on environmental regulation systems and highlights the urgent need for effective waste management strategies and policy-driven resource utilization pathways.

At the same time, the production of traditional Portland cement is characterized by high energy consumption and significant carbon emissions, particularly due to the calcination of limestone in the "two grindings and one calcination" process. As a major contributor to global greenhouse gas emissions, the cement industry has become a key target for carbon reduction policies and sustainable industrial transformation （Van Oss & Padovani, 2003； Zhang et al., 2014). In the context of global carbon neutrality goals and increasingly stringent environmental regulations, developing low-carbon alternatives to conventional cement is not only a scientific challenge but also an important issue in environmental governance and industrial management. Geopolymers, as a class of alkali-activated materials derived from aluminosilicate-rich solid wastes, provide a promising pathway to simultaneously address solid waste utilization and low-carbon material production. By converting industrial by-products such as coal gangue into value-added construction materials, geopolymers support circular economy practices, reduce reliance on natural resources, and promote sustainable industrial development (Nodehi & Taghvaee, 2022; Feng et al., 2024)

Therefore, this study aims to investigate the feasibility and performance of coal gangue-based geopolymer systems, with a particular focus on the synergistic utilization of multiple solid wastes. The research seeks to (i) evaluate the potential of coal gangue as a primary raw material for geopolymer production, (ii) analyze how multi-source solid waste interactions influence material properties, and (iii) assess the implications of this approach for waste management efficiency and low-carbon industrial development. The scope of this work includes material design, performance evaluation, and discussion of its relevance to resource management and sustainable policy frameworks.Through this integrated perspective, the study intends to provide both technical insights and management-oriented implications for the large-scale utilization of coal gangue and the advancement of green construction materials, as illustrated in Figure 1.

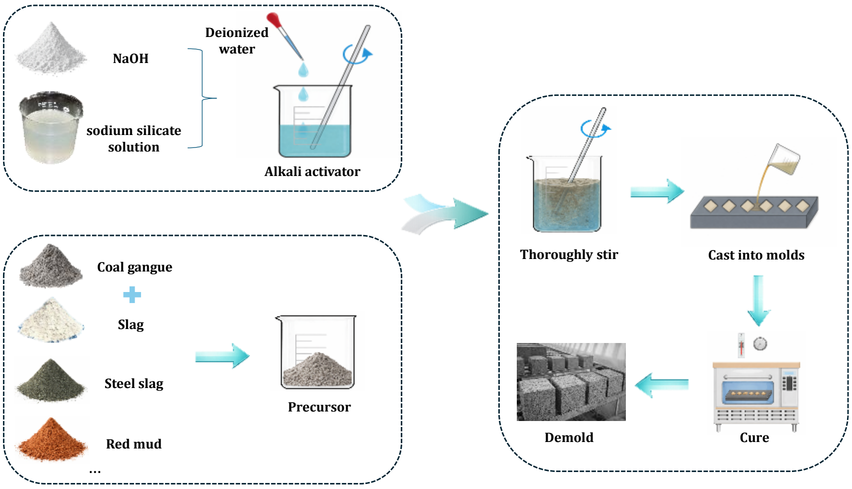

Figure 1: Preparation schematic of coal gangue-based geopolymer composites

Although substantial progress has been made in the utilization and treatment of coal gangue, scientometric analyses of coal gangue-based geopolymer composites are still lacking in depth. This study focuses on the scientometric analysis of coal gangue-based geopolymers, systematically introducing the utilization pathways of coal gangue and the synergistic use of coal gangue with multiple solid wastes, with the aim of providing suggestions and references for the further harmless and value-added utilization of coal gangue.

Methodology

Scientometric tools developed on the Java platform, such as VOSviewer, have been proven to be efficient and effective in bibliometric mapping and knowledge structure visualization (Van Eck & Waltman, 2010). Owing to its significant advantages in knowledge mapping, relationship identification, and tracking research evolution, VOSviewer 1.6.20 was selected in this study as the scientometric analysis tool to systematically review research related to coal gangue-based geopolymers. Based on the scientometric results generated by VOSviewer, a further critical analysis and review were then conducted.

Literature Retrieval

The relevant literature was retrieved from the Web of Science (WoS) database. During the search process, the keyword combination “Coal gangue” AND (“Geopolymer” OR “alkali-activated”) was adopted. The time span for data collection covered the period from 2012 to 2025, and the final sample consisted of formally published English journal articles.

Data Collection

In the literature retrieval stage, clear inclusion and exclusion criteria were established to improve the accuracy and representativeness of the literature sample. In the first step, the title field was selected as the search scope, and the search string “Coal gangue” AND (“Geopolymer” OR “alkali-activated”) initially yielded 261 articles. In the next stage, the language was limited to English, the document types were restricted to Article and Review Article, and the publication period was defined as from January 1, 2012 to December 31, 2025. It is worth noting that, in order to avoid interference from irrelevant publications in the scientometric results, the retrieved records were also manually screened, and studies with low relevance to the topic were excluded. Ultimately, 225 relevant publications were selected for the subsequent visualization analysis, and the data extraction process is illustrated in

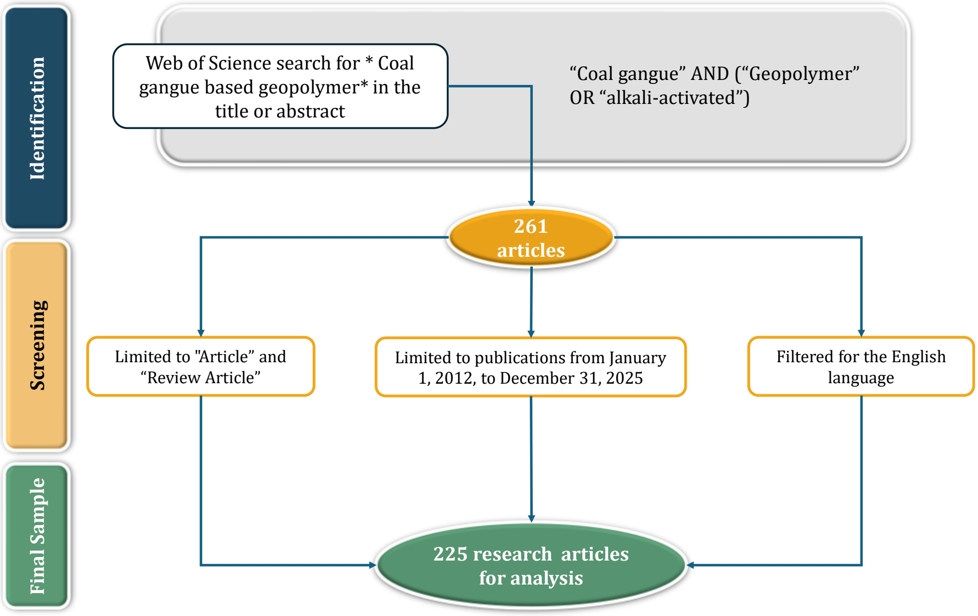

Figure 2.
Figure 2： Flowchart of literature retrieval and screening process

Scientometric Analysis
Research Trends

As shown in Figure 3, the annual number of publications in the field of coal gangue-based geopolymers remained at a relatively low level from 2012 to 2018. Since 2019, however, the number of publications in this field has begun to increase markedly. From 2021 to 2025, the annual publication output rose to 18, 25, 32, 39, and 75 papers, respectively, demonstrating a sustained upward trend. In particular, the publication output in 2025 reached the highest level within the surveyed period, approximately 75 times that of 2012.

Meanwhile, the cumulative percentage curve exhibited a pattern consistent with the annual publication trend. The slope of the curve increased noticeably after 2021, with the most rapid rise occurring during the period from 2023 to 2025, indicating that the majority of research were published in recent years. This trend reflects the growing attention that coal gangue-based geopolymer composites have received from researchers in the broader context of high-value solid waste utilization and the rapid development of green construction materials. Overall, the rapid growth in the number of publications in this field demonstrates the substantial contributions made by researchers toward promoting the green transformation of construction materials and advancing sustainable construction.

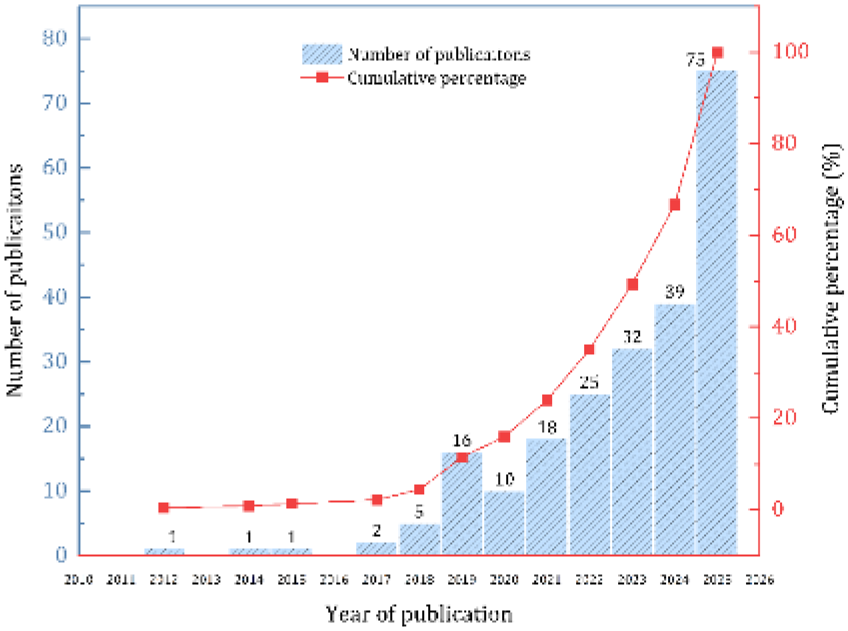

Figure 3: Annual publication trends and cumulative percentage in coal gangue-based geopolymer research

Research Keywords

Author keywords can provide a relatively direct indication of the main research themes and content characteristics of a given field. Therefore, conducting a co-occurrence analysis of these keywords is helpful for identifying the core hotspots and major research directions within the field. Based on VOSviewer software, this study performed a co-occurrence analysis of the author keywords extracted from the 225 selected publications, and the resulting dataset was used as the basis for visual mapping.

To improve the clarity and analytical effectiveness of the keyword network, the minimum occurrence threshold was set to six. Among the initially extracted 225 keywords, 49 met this threshold. However, because some keywords differed in plural forms, hyphenation, and capitalization, terms with the same or similar meanings were counted separately. To address this issue, a thesaurus file was further introduced to standardize and merge the keywords. After cleaning and unifying the dataset, a total of 46 keywords were retained for the subsequent co-occurrence analysis.

Figure 4 illustrates the distribution characteristics of the author keyword co-occurrence network, in which node size represents the total link strength of each keyword. A larger node indicates greater importance of the keyword within the network and also reflects its more frequent use in the existing literature. Among all high-frequency keywords, “coal gangue” was the most prominent, with a total link strength of 601 and an occurrence frequency of 116, indicating that coal gangue has become one of the most important precursors in geopolymer composite research. Meanwhile, coal gangue showed strong co-occurrence relationships and dense connections with keywords such as microstructure, geopolymer, fly ash, slag, and metakaolin, suggesting that current research in this field tends to focus on the synergistic preparation of geopolymer systems using multiple solid waste raw materials.

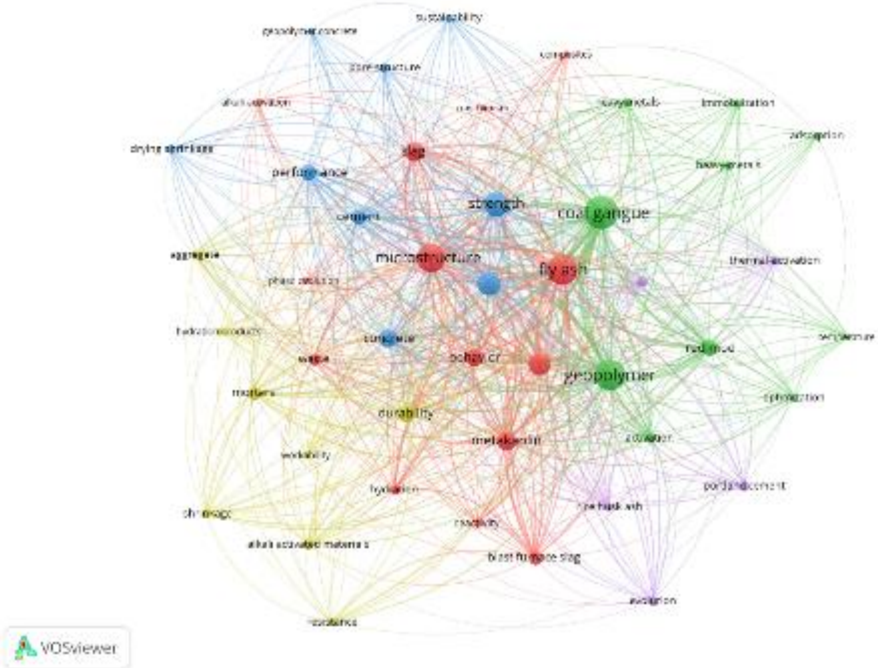

Figure 4: Keyword co-occurrence map of coal gangue-based geopolymer research

In addition, different colors in the figure represent different keyword clusters. In this study, the blue cluster mainly reflects the research hotspots of coal gangue-based geopolymers in heavy metal immobilization, adsorption and removal, environmental remediation, and composite material applications. The red cluster includes keywords such as strength, concrete, performance, mechanical properties, durability, cement, and drying shrinkage, and is primarily associated with studies on engineering performance and service behavior. The green cluster, represented by keywords such as microstructure, metakaolin, mortars, and alkali-activated material, mainly highlights microstructural evolution and the synergistic interaction mechanisms among raw materials. The yellow cluster, characterized by keywords such as slag, hydration, activation, and reactivity, is mainly concerned with activation behavior and reaction processes. Finally, the purple cluster, represented by thermal-activation, ash-based geopolymer, and sustainability, reflects research oriented toward thermal activation modification and sustainable development.

It is particularly noteworthy that the emergence of keywords such as thermal-activation and sustainability indicates that current research is no longer confined solely to material preparation itself, but has gradually expanded toward broader sustainability-related topics, including low-carbon development, synergistic utilization of solid wastes, and the advancement of green building materials.

Findings and Discussion

The principal distinction between research on coal gangue-based geopolymers and that on conventional geopolymers lies in the former's stronger emphasis on the activation and utilization of coal gangue as a solid waste precursor. This distinction has become a key factor driving the development of coal gangue-based geopolymer materials, particularly in meeting the diverse demands of green construction materials.

It is evident that current research is mainly focused on investigating the effects of multiple solid waste constituents and their interactions on coal gangue-based geopolymer systems. These studies primarily examine how such factors influence the microstructure, mechanical properties, durability, and environmental functional performance of the materials. Among the various research areas involved, the most prominent emphasis has been placed on enhancing the fundamental performance of coal gangue-based geopolymers as cementitious materials, as well as exploring their applications in erosion-resistant materials, high-temperature-resistant building materials, and hazardous element immobilization.

Coal gangue-based geopolymer cementitious materials

Coal gangue is rich in reactive silicon and aluminum components, enabling geopolymerization under alkaline conditions to form gel products with good mechanical strength and durability (Cheng et al., 2018). Due to its aluminosilicate-based composition, it has been increasingly recognized as a promising precursor for alkali-activated materials. From a management perspective, its utilization not only supports waste valorization but also contributes to reducing reliance on conventional raw materials, promoting resource efficiency and sustainable construction practices.

Coal gangue has shown promising application prospects in the preparation of geopolymer materials, and its performance is significantly influenced by the type of supplementary materials and the parameters of the alkali activation process. Wang et al. (2021) prepared thermally activated coal gangue-based geopolymer materials using sodium silicate and sodium hydroxide as strong alkaline activators, and found that the strength of the geopolymer increased with the activator modulus and the Na/Al ratio. When the Na/Al ratio was 0.62 and the activator modulus was 1.65, the compressive strength of the specimen reached as high as 52 MPa after 7 days of curing. Zhang et al. (2013) further used Na_2O and SiO_2 with mass fractions of 20.25% and 20.92%, respectively, as alkali activators to prepare geopolymers from sludge and coal gangue activated by calcination at 900 °C. Their results showed that when the coal gangue content was 60%, the material exhibited a denser structure and achieved a compressive strength of 39.8 MPa.

In addition to its use in conventional geopolymer cementitious materials, coal gangue has also demonstrated strong potential in geopolymer grouting materials. Guo et al. (2022） found that optimizing the proportion of coal gangue raw materials and process parameters could effectively improve material performance. When the coal gangue powder content was 40%, the sodium silicate modulus was 1.6, and the dosage was 12.2%, the geopolymer material exhibited the best workability, setting time, and compressive strength at both 3 and 28 days. Guo et al. (2023) further reported that when coal gangue was mixed with fly ash and bentonite at a mass fraction ratio of 23:27, and the NaOH content was 4%, the resulting grouting material showed the best overall performance, with a compressive strength of 10.11 MPa and a penetration strength of 2.38 MPa after 28 days of curing. These studies clearly demonstrate that coal gangue, as an industrial solid waste rich in reactive silicon and aluminum components, has broad application prospects in the field of green cementitious materials.

Synergistic Utilization of Multiple Solid Waste Components in Coal Gangue-Based Systems

Numerous studies have shown that the use of a single alkaline activator with a single solid waste precursor often fails to fully activate the reactive components (e.g., Si, Al, Ca), leading to limited material performance. In contrast, the synergistic utilization of multiple solid wastes can enhance reaction efficiency while promoting high-value waste utilization (Duan et al., 2018). Different solid wastes exhibit complementary characteristics, and their combined use can form Ca–Si–Al precursor systems, generating synergistic activation effects and improving the overall properties of geopolymers (Sadique et al., 2012; Yu et al., 2022). From a management perspective, this approach supports integrated waste management and resource optimization, contributing to more efficient and sustainable material production systems.

As a typical low-calcium aluminosilicate mineral material, coal gangue contains relatively little calcium. The lack of sufficient calcium makes the material more vulnerable to CO_2 attack during carbonation, thereby reducing its volume stability and carbonation resistance (Bernal et al., 2012). Based on this characteristic, the incorporation of an appropriate amount of calcium-containing components into multicomponent composite systems can effectively improve the performance of coal gangue-based materials through synergistic activation. Slag, as an industrial by-product rich in calcium and highly reactive, can provide the necessary calcium source for coal gangue and is therefore widely used to prepare high-performance geopolymer materials in combination with coal gangue. Ma et al. (2019) found that, compared with alkali-activated pure coal gangue specimens, the 28-day compressive strength of alkali-activated slag–coal gangue composite cementitious materials increased by 18.78%, 23.17%, 29.22%, 32.93%, and 55.98% when the slag content was 10%, 20%, 30%, 40%, and 50%, respectively, indicating that slag dosage has a significant effect on the strength of this system. Consistent with this, Huang et al. (2018) also pointed out that the low content of reactive calcium in coal gangue is one of the main reasons for the low strength of geopolymers. By adding slag and hydrated lime to prepare coal gangue-based geopolymers, they found that the strength increased with the calcium supplied by slag, until the strength growth gradually leveled off when the slag content exceeded 40%.

Furthermore, the improvement in the performance of coal gangue-based systems by slag is closely related to its regulation of reaction product types and microstructure. Liu et al. (2020) used a mixed alkaline activator composed of commercial sodium silicate and sodium hydroxide to activate coal gangue and slag for the preparation of coal gangue-based cementitious materials. Their experimental results showed that, with increasing slag content, C-S-H gels with higher Ca/Si, Ca/Al, and Si/Al ratios were formed, which was responsible for the increased compactness of the system as well as the enhanced compressive strength and sulfate resistance. In addition to conventional coal gangue–slag composite systems, related studies have also shown that other calcium-bearing or sulfate-containing activating components can further stimulate the latent reactivity of coal gangue. Zhang et al. (2015) prepared grouting materials with favorable performance by synergistically activating coal gangue with an appropriate amount of sodium sulfate and quicklime, demonstrating the positive role of multicomponent activating agents in promoting coal gangue activation. Meanwhile, at the geopolymer concrete level, Zhang et al. (2023) employed a combined $NaOH–Na_2SiO_3$ activator to activate the coal gangue system and found that both the workability and durability of geopolymer concrete were significantly improved with increasing slag content. Specifically, when the slag content reached 30%, the paste fluidity increased by approximately 25%; when the slag content was 40%, the 3-day compressive strength reached 25 MPa, representing an increase of about 40% compared with the specimen without slag. These findings further indicate that the incorporation of slag not only helps improve the mechanical properties of coal gangue-based materials, but also satisfies requirements for workability and durability.

In addition to the materials mentioned above, fly ash can also be combined with coal gangue to prepare high-performance geopolymer composites. This is because the reactive silicate phases and calcium oxide contained in fly ash can provide a favorable alkaline environment for geopolymerization, thereby enhancing the reaction rate and reactivity (Zhang et al., 2021). Moreover, fly ash particles are generally spherical and have a lower density than coal gangue, which allows them to exert a lubricating effect and thus effectively improve the workability and mechanical performance of geopolymer pastes (Siddique, 2011). Based on these advantages, many researchers have explored the performance of fly ash–coal gangue composite systems. Zhang (2017) found that fly ash–coal gangue geopolymers activated by an alkaline dry powder prepared from sodium hydroxide and calcium carbonate exhibited short setting times, low water absorption, and high compressive strength. When the sodium hydroxide content in the dry powder activator was 3%, the geopolymer specimens showed the lowest water absorption and the highest compressive strength. Building on this, Feng et al. (2023) further demonstrated experimentally that municipal solid waste incineration fly ash (MSWI FA), used as a calcium source for coal gangue, can effectively improve the strength of MSWI FA–coal gangue geopolymers, with the optimum MSWI FA dosage being 15%. Feng et al. (2023) also used an alkaline activating solution with a $NaOH/Na_2SiO_3$ ratio of 25:75, a liquid-to-solid ratio of 0.45, and a NaOH concentration of 8 mol/L to activate fly ash and bottom ash as calcium sources for the preparation of coal gangue-based geopolymers. Their results showed that when the fly ash content was 15%, the geopolymer achieved the highest unconfined compressive strength of 30.28 MPa.

Coal gangue-based geopolymers as erosion-resistant materials

Coal gangue-based geopolymers have attracted increasing attention due to their stable three-dimensional network structure and strong resistance to aggressive environments. Compared with traditional cement-based materials, they offer enhanced durability under complex service conditions and can mitigate alkali–aggregate reactions caused by ion migration. From a management perspective, these advantages support longer service life, reduced maintenance costs, and improved lifecycle performance of infrastructure systems.

In terms of sulfate resistance, the study by Su et al. (2025) showed that coal gangue-based geopolymer materials exhibit better overall performance than ordinary Portland cement in sulfate environments. The main reason is that, with the increase in Ground Granulated Blast Furnace Slag (GBFS) content, the Ca^{2+} concentration in the system rises, thereby promoting the geopolymerization reaction and generating more C-(A)-S-H gel products. These gels can fill defects in the matrix and residual pores in the aggregates, resulting in a denser internal structure and consequently improving both compressive strength and sulfate resistance. Meanwhile, Zhang et al. (2023) further reported that coal gangue-based geopolymer concrete prepared synergistically with GBFS also demonstrated good erosion resistance; when the GBFS content reached 50%, the chloride ion penetration resistance of the material improved by 50% compared with the control group.

The durability of coal gangue-based geopolymers in acidic environments is also worthy of attention. Gao et al. (2021) prepared geopolymers using coal gangue and red mud as raw materials and investigated their acid resistance. The results showed that, in a sulfuric acid solution with pH = 2, the compressive strength of the specimens first decreased and then increased with prolonged immersion time, and gradually became stable after 112 days of exposure. This indicates that although coal gangue-based geopolymers may experience a certain degree of early deterioration in strongly acidic environments, their internal structure can gradually stabilize through later-stage structural rearrangement or redistribution of reaction products, thereby maintaining relatively good service performance.

Coal gangue-based geopolymers as high-temperature-resistant materials

For high-performance concrete used as a structural material, not only its mechanical properties at ambient temperature but also its ability to maintain integrity after exposure to high temperatures or fire is critical for service safety evaluation (Chen et al., 2023). Studies have shown that geopolymers exhibit superior thermal stability, with lower mass loss, volumetric expansion, and thermal conductivity after calcination compared to ordinary Portland cement, indicating strong potential for high-temperature applications (He et al., 2020). From a management perspective, this enhances structural safety, reduces post-disaster repair costs, and supports more resilient infrastructure systems.

Existing studies have indicated that coal gangue-based geopolymers exhibit favorable thermal stability and structural integrity under high-temperature conditions. Liu et al. (2025) found that when a coal gangue-based geopolymer material with an alkali content of 0.6 was heated to 700 °C, its mass loss was only 1.9%, and the overall structure of the specimen remained intact, showing only a change in color. This is mainly because the formation of zeolitic phases in the system helps relieve local thermal stress concentration and, to some extent, suppresses volume expansion caused by phase transformation, thereby improving the high-temperature stability of the material. Sitarz et al. (2022) further pointed out that geopolymer foams prepared from coal gangue maintained relatively stable mechanical performance throughout the temperature range of 0–1000°C, with no obvious sudden strength loss, spalling, or macroscopic fracture observed during heating.

In addition to high-temperature structural stability, coal gangue-based geopolymer foams also show distinct advantages in thermal performance. Wang et al.(2025) reported that the thermal conductivity of coal gangue-slag-based geopolymer foamed concrete could be as low as 0.0781 W/(m·K). Compared with other geopolymer foamed concretes and conventional cement-based foamed concretes, this material exhibited superior thermal insulation capacity while maintaining relatively good mechanical performance. These findings indicate that coal gangue-based geopolymers possess not only good thermal stability at high temperatures but also low thermal conductivity, suggesting promising application prospects in the fields of high-temperature-resistant and thermal insulation materials.

Coal gangue-based geopolymers for the immobilization of heavy metals and radioactive elements

Coal gangue-based geopolymers have become an important focus in the immobilization of heavy metals and radioactive contaminants. For example, Long et al. (2023) used such materials to stabilize municipal solid waste incineration fly ash (MSWI FA), significantly reducing the leaching risk of toxic metals. Specifically, Cd, Pb, Cu, and Zn were transformed from mobile acid-soluble forms into more stable fractions, enhancing immobilization and lowering environmental risks. From a management perspective, this demonstrates their potential in hazardous waste treatment and environmental risk control, supporting safer and more sustainable waste management practices.

In addition to heavy metals, coal gangue-based geopolymers have also demonstrated good immobilization performance in the control of radioactive element contamination. Zhou et al. (2021) investigated the solidification effect of coal gangue-based geopolymer on uranium-contaminated soil, and the results showed that the maximum uranium immobilization rate could reach 77.44%. Zhou et al. (2020) further found that geopolymers prepared synergistically from red mud and coal gangue could also effectively immobilize heavy metals such as Pb^{2+}, Cr^{3+}, Zn^{2+}, and Cd^{2+} in MSWI FA. After 28 days of solidification, the leaching rates of all these heavy metals were below 0.4%. These findings clearly demonstrate the great potential of coal gangue-based geopolymer materials in the field of hazardous waste solidification and stabilization.

Conclusion

This study employed a scientometric approach to analyze 225 publications and systematically reveal the research progress of coal gangue-based geopolymer composites, with particular emphasis on their potential as low-carbon cementitious materials for resource-efficient construction. The steady increase in publications reflects growing attention driven by sustainable development goals, the demand for high-value solid waste utilization, and the transition toward green construction practices. From a management perspective, this trend highlights the increasing importance of integrating waste management, technological innovation, and sustainable supply chain development.

Although coal gangue-based geopolymer composites demonstrate promising performance in terms of mechanical properties, durability, and environmental benefits, several challenges remain. From a managerial and policy perspective, key issues include economic feasibility, large-scale implementation, standardization, and regulatory support. The future prospects can be summarized as follows:

(1) At present, the utilization of coal gangue is still dominated by low- to medium-value applications, with limited high-value development. From a management perspective, future efforts should focus on establishing standardized quality evaluation systems, improving technical specifications, and promoting industrial standardization to support large-scale commercialization.

(2) Alkaline activators play a critical role in determining both the efficiency and cost of geopolymer production. While conventional systems (e.g., NaOH and Na_2SiO_3) are effective, further optimization is needed. The development of alternative activators, such as waste-

derived or composite systems, is essential to reduce costs and improve environmental performance.

(3) More attention should be given to optimizing raw material proportions and enhancing the synergistic use of multiple solid wastes. This approach can improve resource efficiency while tailoring material properties for different applications, thereby supporting diversified utilization pathways and better alignment with sustainable resource management strategies.

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