



Research Frontiers and Thematic Evolution in Tailings-Based Supplementary Cementitious Materials: A Bibliometric Network Analysis

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Abstract: The sustainable application of mine tailings as supplementary cementitious materials (SCMs) has pulled increasing attention as the construction sector explores low-carbon alternatives to conventional binders. Nevertheless, investigations into tailings-based binders continue to be distinguished in terms of type of materials, methodology, and performance metrics. This research projects an extensive bibliometric network analysis to establish the intellectual framework and theme development of world-wide studies on tailings-based SCMs from 2000 to 2025. Peer-reviewed papers and reviews were obtained from the Lens-database and evaluated utilizing VOSviewer (v1.6.x). Co-occurrence, co-citation, and co-authorship networks were analysed to explore influential keywords, leading sources, and emerging directions in the field. Statistics have shown that the research focus is changing from studies of the feasibility of materials to more advanced study of performance, durability, and environmental impact. Overlay graphics show that in the last few years, there has been a gradual shift toward innovation that is driven by sustainability and the development of low-carbon, resource-efficient binder systems. The results give a comprehensive picture of the cutting-edge research and point out standardization, large-scale validation, and eco-efficiency assessment of tailings-based cementitious materials in the future.

Keywords: Mine tailings; Supplementary cementitious materials (SCMs); Blended cements; Research trends

I. INTRODUCTION

The worldwide cement and concrete industry remains a significant participant in CO₂ emissions, responsible for approximately 8 percent of total CO₂ emissions. The production of ordinary Portland cement (OPC), which is a primary material for infrastructure and construction, has now received more attention about its energy use and carbon emissions. Decarbonizing the cementitious binders is crucial for attaining sustainable development goals. Thus, the identification and application of supplementary cementitious materials (SCM) has become a crucial research matter. In this context, tailings, the fine-grained residual materials following mineral beneficiation and ore processing, present a significant yet underutilized source of solid waste. If properly treated, they may partially replace the cement in cementitious systems. Two different advantages exist: (i) Relocating mine tailings from extensive tailings storage areas and landfills, so mitigating the environmental and other hazards associated with tailings storage, and (ii) advancing low-carbon binder technologies. Over the past decade, there has been an increase in the number of studies that have investigated the use of mine tailings as SCM. Due to the myriad types of tailings (iron ore, copper, phosphate, gold, bauxite, etc.), diverse preprocessing methods and varying performance metrics, it is imperative to employ bibliometric network analysis to elucidate the development of research, identify dominating themes, recognize key contributors, and ascertain future directions. Bibliometric analysis provides insights on co-authorship network, keyword co-occurrence, and co-citation, offering a quantitative perspective on the evolution of ideas within the field over time. Particularly in growing domains such as tailings-based SCMs, this type of mapping can identify clusters of subdomains, transition in research emphasis, and opportunities for standardization or industrial application. This study aims to provide a comprehensive bibliometric analysis of global research on tailings based SCMs in the period of 2000 to 2025, utilizing the Lens-database and visualization tools like VOSviewer. The various objectives are to (a) discern publication trends and growth boundaries, (b) delineate the foremost countries and institutions, and collaborations, (c) keyword co-occurrence and thematic cluster analysis (d) analysis of co-citation networks to check about the influential articles and sources, and (e) track thematic development with time to extract research frontiers and deficiencies. This study aims to provide a systematic framework for tailings-based SCM research.

II. LITERATURE REVIEW

As part of world-wide efforts to promote a circular economy and reduce Green House Gas (GHG) emissions in cement



manufacturing, the process of converting mine tailings into SCMs has evolved. Guo et al. [1] demonstrated that properly arranged tailings can be used as pozzolanic as well as alkali-activated binders, providing an environmentally friendly approach for clinker reduction. Zaid et al. [2] similarly have shown significant improvements in the mechanical performance and durability of ultra-high-performance and fiber-reinforced concrete prepared with these tailings, underscoring their value in low-carbon construction. Jeong et al. [3] exhibited remarkable mechanical performance using molybdenum mining waste in self-compacting concrete, whereas Guo et al. [1] proved the repeated advantages of circularity and improved early strength in alkali-activated tailings concretes. Liang and Ji [4] showed that the mixture of red mud and blast furnace slag gives a geopolymer binder with improved strength and reduced permeability, aligning with the trend towards alkali-activated binder systems. Bobirica et al. [5] and Bajpai et al. [6] undertook additional research work on geopolymer composites of red mud, waste glass, and silica fume, identifying critical microstructural parameters that enhance performance. Newer studies have focused on microstructural analysis and durability performance. Studies by Vo et al. [7] and Krishna et al. [8] indicated that mine tailings can work as a partial replacement for cement without compromising long-term durability performance, especially when integrated with different industrial by-products. Prior investigations by Ahmari and Zhang [9] projected the influence of activator chemistry and curing temperature on copper tailing-based composites, demonstrating that suitable processings like alkali activation can achieve a compressive strength of 40–50 MPa after 28 days. Parallely, studies on environmental safety and heavy-metal immobilization confirmed that geopolymer composites are effective at capturing harmful compounds. Comprehensive sustainability evaluations also support this valorization strategy. Singh et al. [10] demonstrated that mine tailings can serve as feedstock for nanomaterials and SCM. Behera et al. [11] expanded this viewpoint to encompass paste backfill uses, emphasizing the importance of waste minimization and resource utilization. Recent assessments have clubbed these progressions from both bibliometric and material perspectives. Zhang et al. [12] investigated the use of iron tailings-derived SCMs for sustainable concrete, projecting its performance comparisons to traditional SCMs like fly ash and slag. The literature regularly demonstrates a change from feasibility and material characterization to durability evaluation, sustainability assessment, and industrial applications, giving a quantitative foundation for the bibliometric network analysis performed in this study.

III. METHODOLOGY, STUDY AREA AND DATA COLLECTION

This research paper examines the global research landscape on the use of mining tailings as SCM. Here, the "study area" refers to the whole intellectual field that includes experimental, analytical, and environmental research on the binders made from mine tailings. To offer a thorough and impartial view, bibliographic data were collected from the Lens.org database, which incorporates metadata out of CrossRef, PubMed, Microsoft Academic Graph, and Dimensions. Many of these repository index journals are recognized under Scopus and the Science Citation Index (SCI), ensuring that the data collected represents high-quality, peer-reviewed research works. The bibliometric dataset was prepared to include research output from around the world on topics such as mine tailings, valorization of tailings, alkali activation, durability, pozzolanic reactivity, geopolymerization and sustainability assessment. The database was adopted due to its extensive coverage, clear open-access interface for most of the articles, and compatibility with bibliometric visualization tools like VOSviewer (v1.6.20). The data collection and extraction was done in October 2025 and covered the years ranging from 2000 to 2025 i.e. 25 years of scientific progress in this domain. Using Boolean operators, a structured search query was generated that included the main terms related to the subject of the research. The following terms were used as examples: ("mine tailings" OR "mining waste" OR "red mud" OR "bauxite residue" OR "iron ore tailings" OR "gold tailings" OR "zinc tailings" OR "granite slurry" OR "marble slurry") AND (cement OR concrete OR "blended cement" OR "supplementary cementitious material" OR SCM OR geopolymer OR "alkali-activated") AND (replacement OR binder OR pozzolanic OR durability OR microstructure). This way it ensured the inclusion of studies on different types of tailings, binders, and performance-based investigations in cement-concrete, thereby including all the parts of research on tailings-based cementitious materials. To keep academic rigor or discipline, only peer-reviewed journal articles and review papers were included in the database. Conference papers, book chapters, and any reports were not included because of the fact that they might include duplicate or incomplete metadata. The collected dataset had the following fields: title, date published, publication year, publication type, source titles, ISSNs, publisher, source country, authors, abstract, volume, end-page number, issue number, start-page number, field of study, keywords, DOI, and number of citations importantly. Data collected in the form of a CSV file for preprocessing. The process of data cleaning included getting rid of any duplicates, making sure that author and keyword spellings were the same, and combining words that mean the same thing or like synonym using a custom thesaurus file (for example, "mine tailing" and "mining tailings" were combined as "mine tailings"; "SCM" was changed to "supplementary cementitious materials"). This ensured consistency across the dataset and improved the accuracy of network connections avoiding any chances of duplicity of the dataset directly or indirectly. The final dataset obtained was of 4,347 documents from different countries, well-known research groups, and cooperation between different areas of study in materials science, environmental engineering, and sustainable construction. The prepared dataset was the basis for other studies of co-occurrence, co-authorship, citation, and bibliographic coupling. The workflow included getting data from [Lens.org](https://lens.org) as mentioned and then showing it on a network with VOSviewer.



IV. RESULTS AND DISCUSSION

A. Worldwide Publication Landscape

The bibliometric dataset collected from Lens.org included 2,143 academic records (Belongs to Civil Engineering & Structural Engineering strictly) published between 2000 and 2025, encompassing journal articles, reviews, and conference proceedings. Fig. 1 illustrates the number of publications country-wise. China unequivocally dominates the global total, possessing 776 papers. India stood second with 406, it is then followed by the United States with 233, Australia with 145, Canada with 129, Brazil with 107, the United Kingdom with 105, Spain with 81, Italy with 78, and Turkey with 71. This data supports earlier bibliometric analyses by Guo et al. [13], Bernal et al. [14], which demonstrated that Asian countries, particularly China and India, have emerged as central hubs for research and development on mine-tailings valorization, driven by their rapid infrastructure development and governmental emphasis on sustainable practices. Out of these even a comparable frequency of Chinese and Indian research-networks has been recorded in the broad field of alkali-activated and geopolymer binders [4], [6] & [15]. The substantial contributions from the United States, Australia, and Canada align with their valuable mining sectors and their longstanding efforts to reuse the tailings [16], [17]. Contributions from regions like Europe, especially the United Kingdom and Spain, often highlight carbon sequestration and the integration of circular economy principles [2], [26]. Collectively, these data indicate that world-wide research on mine tailings-based SCMs is geographically affected yet conceptually unified in its emphasis on decarbonization and waste utilization.

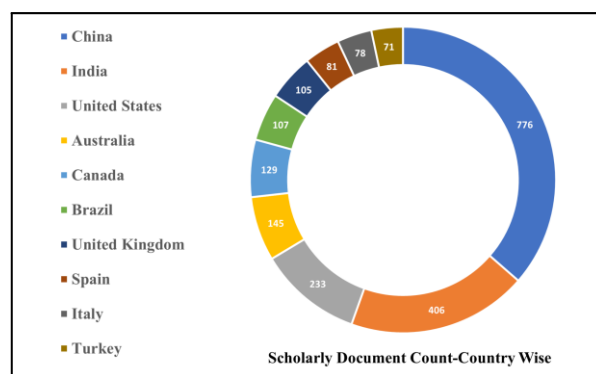


Fig. 1 Worldwide Publication Landscape

B. Keyword Co-Occurrence and Thematic Structure

The co-occurrence network Fig. (2-a) shows a strong thematic link between words like mine tailings, mechanical properties, alkali activation, microstructure, sustainability, geopolymers and circular economy etc. These phrases give the highest overall link strength, indicating their essential role in academic discussions. Rashid et al. [18] and Amran et al. [19] identified analogous thematic cores, confirming that alkali-activated binders and geopolymeric matrices are predominant in sustainability-oriented cement based research works.

The overlay map Fig.(2-b) clearly shows a change over time: older papers (2000–2010) focused on heavy-metal stabilization and leaching [20], [21], [22], [23], [24], [25], [26], while recent papers are based on mechanical performance [27], [28], [29], [30], microstructural evolution [31], [32], [33], [34], and life-cycle assessment [35], [36], [37]. This trend is in tune with what Li et al. [38] and Naqi and Jang [39] found. Alkali-activated binders are studied from being possible to being optimized for performance. The density display Fig.(2-c) supports these patterns by showing hotspots presenting mechanical properties and sustainability. Bernal [14] validated the same by demonstrating that compressive strength, chloride resistance, and carbonation depth are now recognized parameters for evaluating the durability performance. The co-occurrence analysis thus projects a methodological transition in the discipline from the initial exploratory immobilization research to cohesive, performance-driven material design based research.

C. Collaboration Networks and Scholarly Connectivity

The co-authorship network Fig.(3-a) shows that writers from all over the world are working hand in hand. It shows that prolific authors like Benzaazoua, Liu, and Tsang have worked together to strengthen the study on tailings-based binders [40], [41], [42], [43]. The overlay visualization Fig.(3-b) shows that there has been a rise in the partnerships across multiple authors and institutions since 2018. This is similar with the trend that Murugesan et al. [44]. Fig. (3-c) shows that East Asian and European



institutions work together a lot, especially in places where state laws promote the use of low-carbon building materials. This finding is found similar with the work of Barbhuiya[45] and Mahjoubi et al. [46].

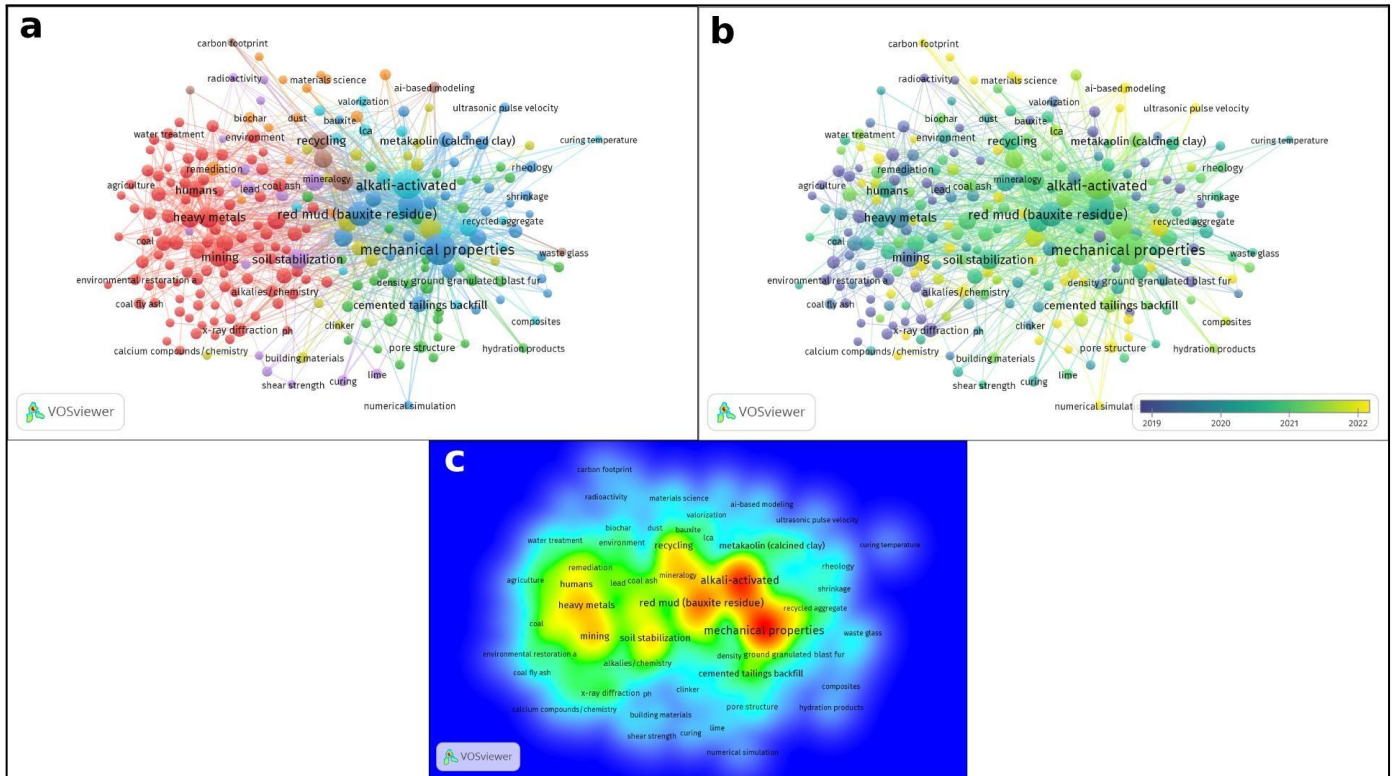


Fig. 2 Keyword Co-Occurrence Analysis

a. Co-Occurrence Network b. Overlay Visualization c. Density Visualization (Clockwise)

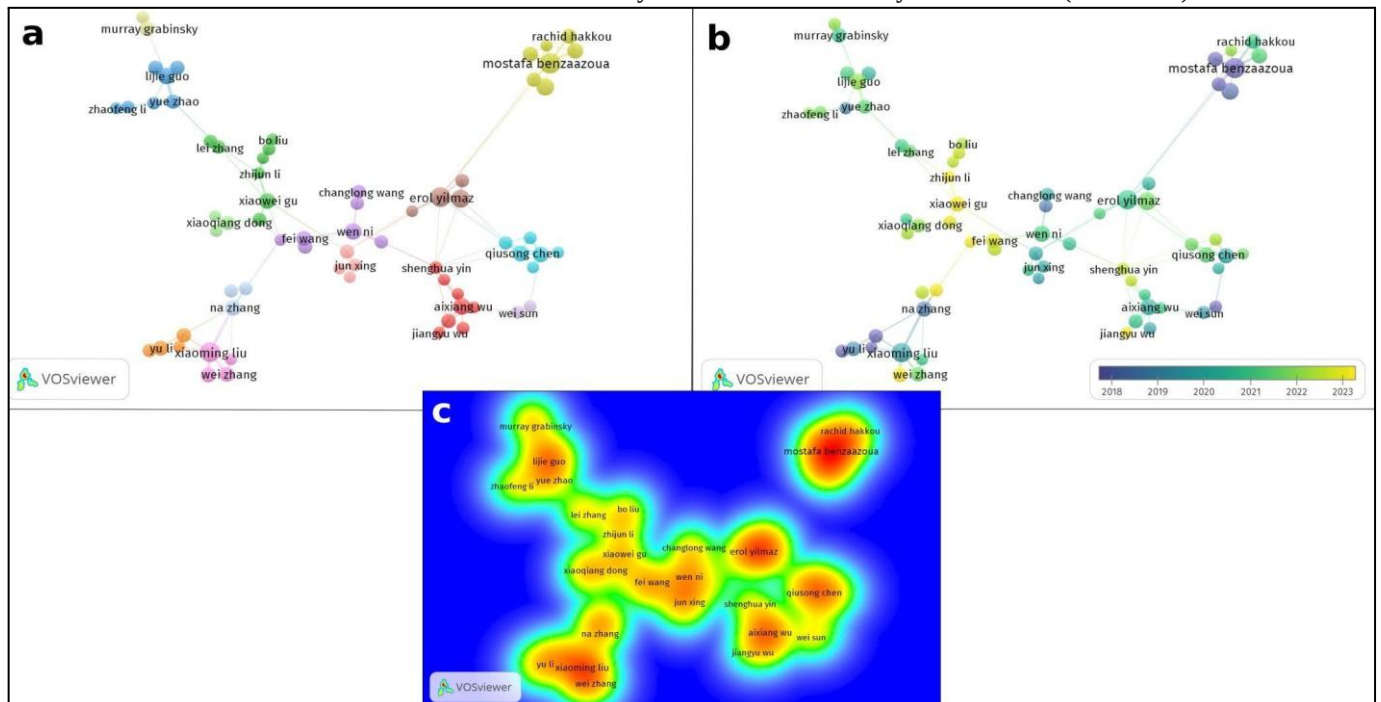


Fig. 3 Co-Authorship Analysis

a. Co-Authorship Network b. Overlay Visualization c. Density Visualization (Clockwise)



D. Author-Level Intellectual Structure Analysis

In Fig. 4 (a), author clusters show field-defining subject domains. Every network node represents an author, its dimensions indicate citation frequency, and its proximity indicates co-citation strength. Mostafa Benzaazoua [47] governs the red cluster in mine tailings geochemical analysis, stabilisation/solidification, and valorisation for sustainable structures. Zhao and Zheng [48] studied tailings-based binders' mineralogical and environmental executions. The green cluster belongs to environmental engineering and the circular economy focuses on metal recovery, resource recycling, and mining waste reuse under Daniel C.W. Tsang [49] and Koen Binnemans [50]. A yellow category around Xiaoming Liu [51] shows alkali-activated material and geopolymerization kinetics testing adopting red mud and metallurgical wastes as pozzolanic precursors. Fig. 4 (b and c) shows intellectual influence's journey. With cooler (blue–green) contributions, Benzaazoua (2005–2012) and Gadd (2009) [52] pioneered tailings conversion as a valuable resource. Tsang, Binnemans, and Liu (2019–2024) are yellow to indicate the transformation toward transdisciplinary materials science, environmental chemistry, and circular economy. Benzaazoua, Tsang, and Liu have red high-intensity zones in the density visualization (Fig. 4-d), representing their constant scholarly work and relationship. Snellings, Abdullah, and Fall assessed binder systems and geopolymeric composites' microstructural and mechanical performance in average-density locations. Abdellatif El Ghali and Moisés Frías' contributions emphasize geographical diversity and industrial applications in Africa, the Middle East, and Europe.

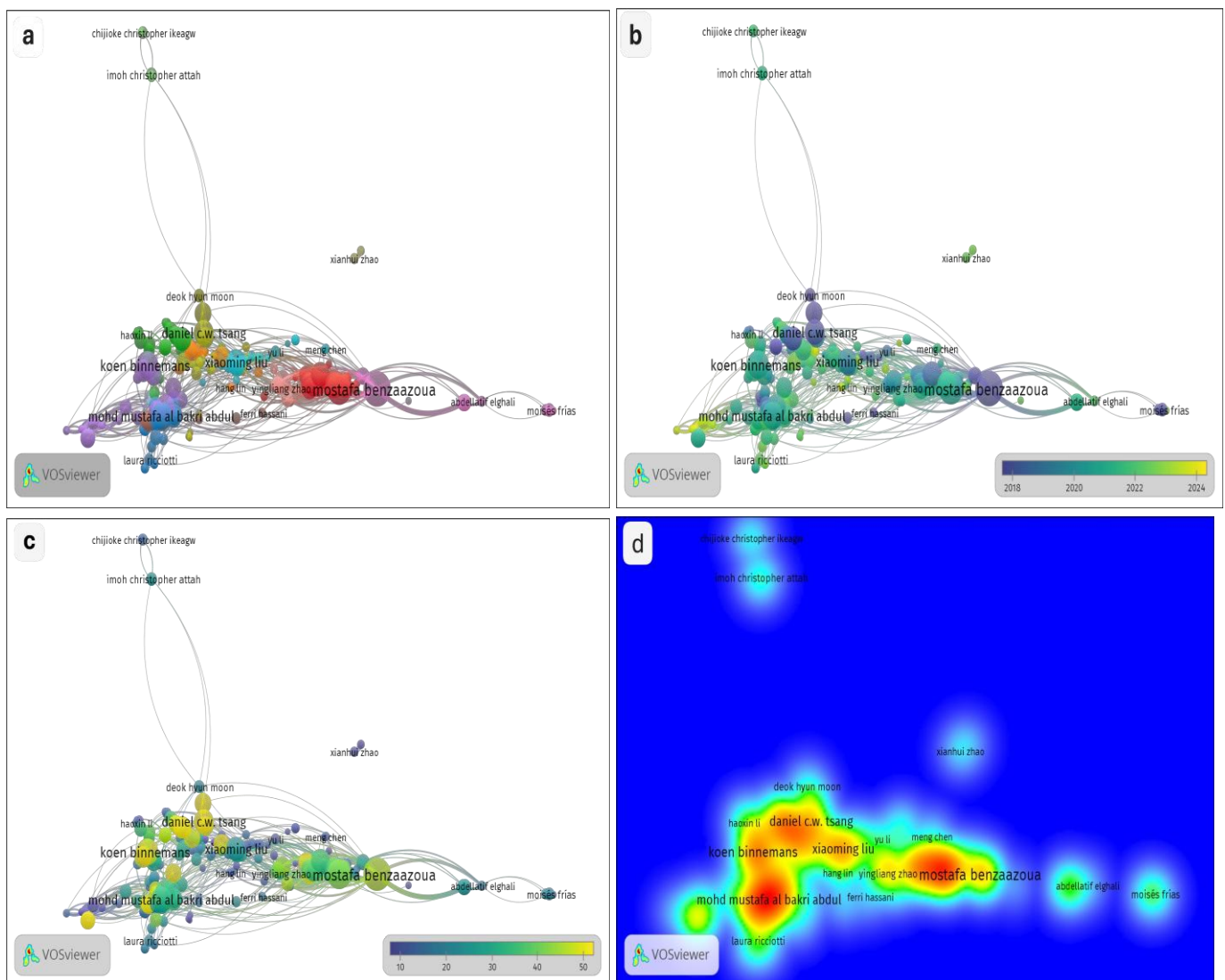


Fig. 4 Author-Level Intellectual Structure Analysis

- a. Author-Level Intellectual Structure b. Overlay Visualization With Time c. Overlay Visualization With Citations
d. Density Visualization (Clockwise)



D. Document-Level Intellectual Evolution

The co-citation analysis of the documents Fig.5 (a-d) substantiates the dominance of elementary works on red-mud geopolymerization and alkali-activation [30], [53], [54], [55], [56], [57], [58]. Newer studies often use combined study of mechanical, environmental, and sustainability perspectives [59]. Li et al. [55] demonstrated a relationship between binders' pore-structure refinement and chloride ingress, whereas work done by Mohamed et al. [60] meets the influence of activator content on permeability. The empirical results collectively support the theoretical propositions proposed by Bernal et al. [14] regarding gel chemistry and durability. The increasing citation of LCA-based studies [61], [62] further illustrates that the research is grouped around performance criteria that simultaneously include mechanical reliability and environmental advantages, confirming the overall development drawn in the bibliometric maps.

E. Bibliographic Coupling:

Author-level coupling brings attention to three dynamic clusters. The preliminary focus is on the combination of red-mud and iron-ore tailings with slag or fly ash to achieve structural-grade performance [63], [64]. The second is about leaching and durability measures that meet environmental engineering standards [65], [66], [67]. The third looks at curing and mineralization that uses CO₂ itself to make carbon-negative binders [68], [69]. Experimental findings by Jalal et al. [70] and Rashid et al. [18] validate the themes projected here.

Document-level coupling Fig.6 (b&c) projects the most adequate correlations among studies employing advanced characterization methods (SEM, XRD, FTIR, TGA) to relate hydration products to its performance [28], [71], [72], [73], [74]. This supports Wang et al.'s [75] claim that measuring the microstructure is now essential for ensuring the performance.

Source-based coupling Fig.6 (d) identifies Construction and Building Materials, Materials (Basel), and Sustainability as the leading publications, supporting the Amran et al.'s [19] outcomes that these publications represent the important trinity for sustainable cement research. Journals that emphasize on the environment, such as Waste Management and Environmental Science and Pollution Research, are very important for research that shows how poisonous and leachable tailings are if not utilised properly [76], [77], [78], [79], [80], [81].

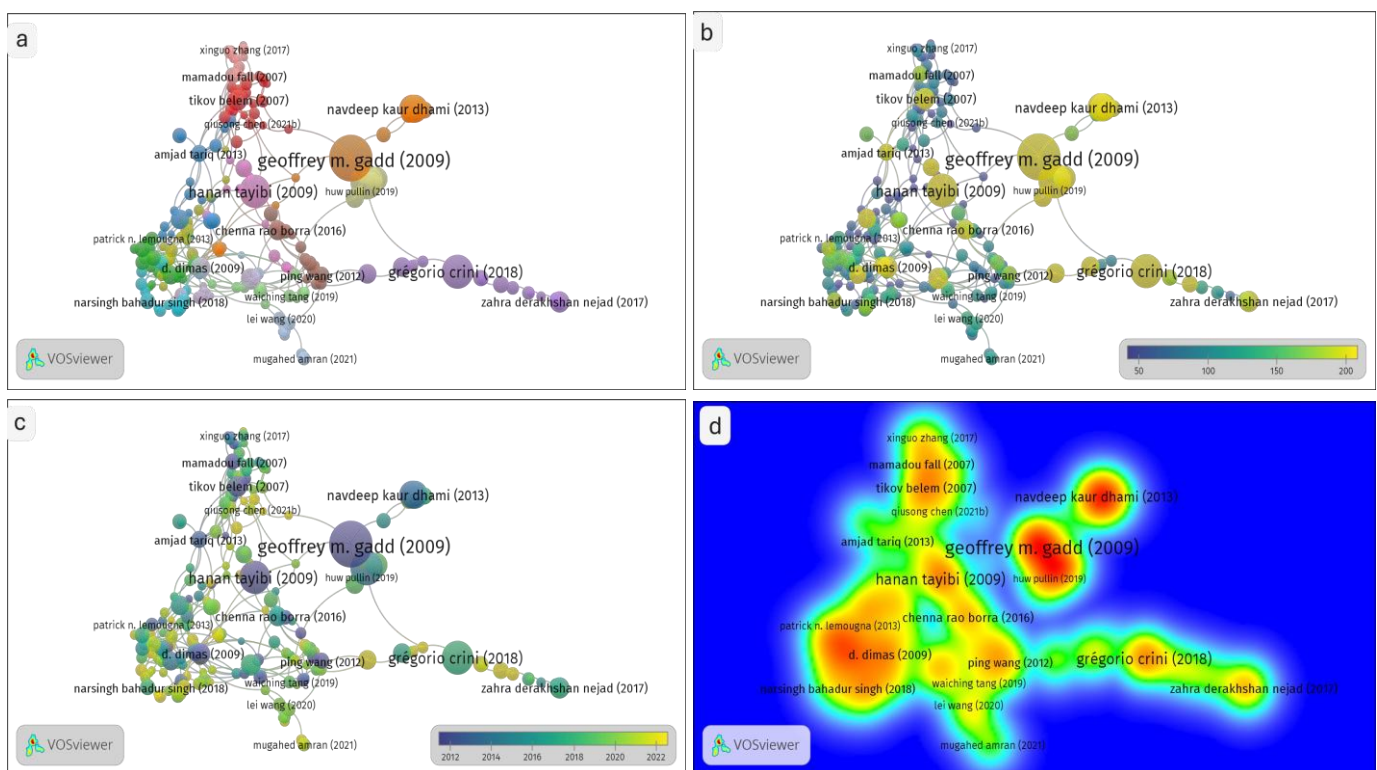


Fig. 5 Document-Level Intellectual Structure Analysis

b. Document-Level Intellectual Structure b. Overlay Visualization With Time c. Overlay Visualization With Citations
d. Density Visualization (Clockwise)

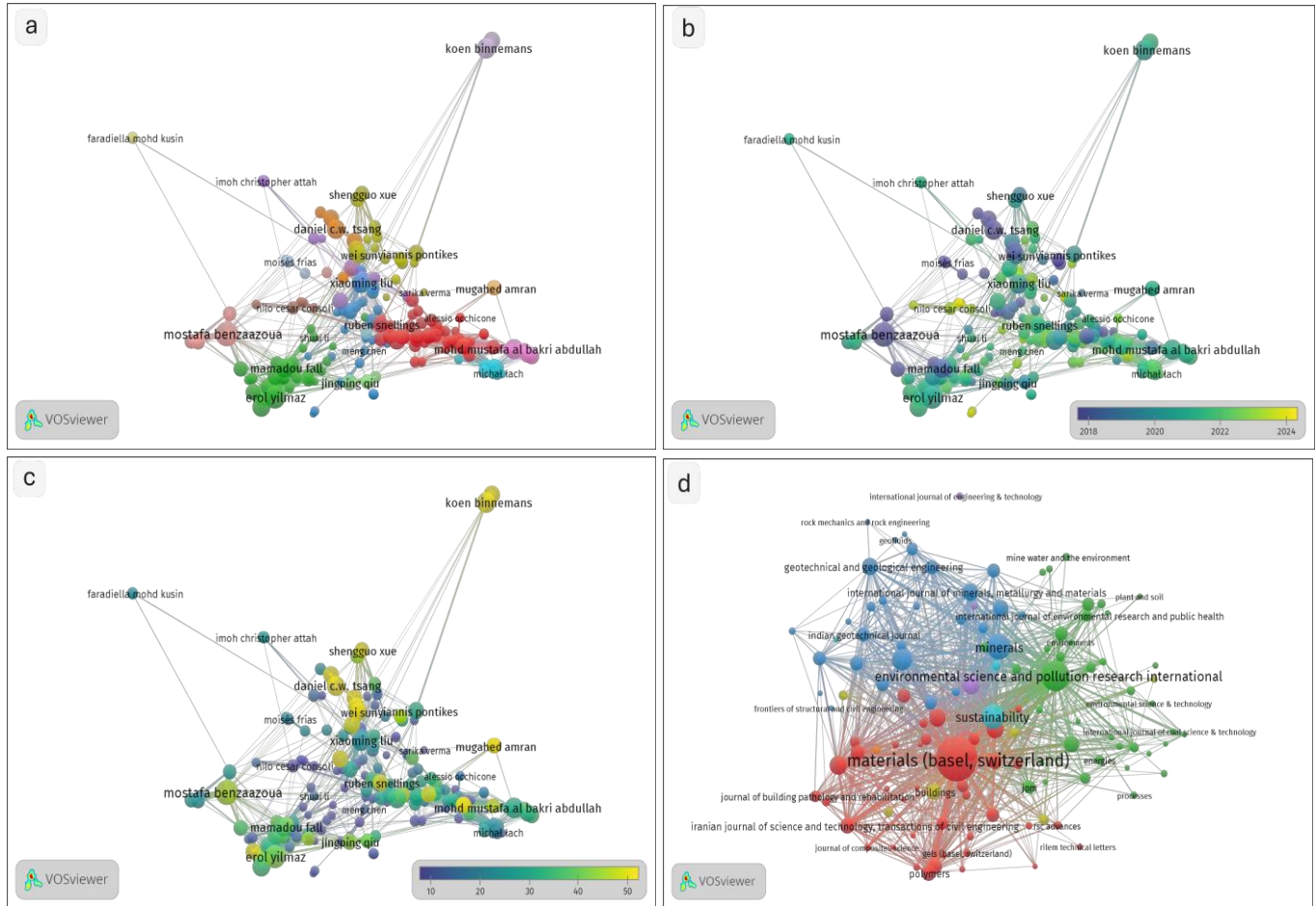


Fig. 6 Bibliographic Coupling Analysis

c. Author-Level Bibliographic Coupling b. Overlay Visualization With Time c. Overlay Visualization With Citations
d. Bibliographic Coupling of Sources

F. Implications for Future Research

Bibliometric analysis indicates that the tailings based SCM research community is now advancing towards standardized approaches for determination of strength, transport characteristics, and environmental safety. Long-term durability research under realistic exposure conditions-specifically the carbonation effect [82], [83], sulfate, and chloride ingress etc. are gaining high attention [84], [85], [86]. More and more people are using digital techniques, like mix optimization based on machine learning and artificial intelligence [87], [88]. These alliances can speed up the process of moving technology from the laboratory environment to the real world, in line with the Sustainable Development Goals set up by the United Nations for climate action and infrastructure growth.

V. CONCLUSION

The extensive bibliometric mapping, encompassing keyword, authorship, co-citation, and coupling analyses, accomplished that mine-tailings-based SCM research has shifted from environmental studies to a sustainable materials discipline. World-wide publishing data helps us understand this shift by indicating where innovation is strongest in different countries of the world. The condensing cross-references support a shift in developing from waste management to resource engineering. This makes SCM based on tailings necessary for building. Based on the research work carried out the following conclusions can be drawn:

1. Bibliometric analysis shows that research across the world on tailings-based SCMs has grown a lot since 2015. Which represents that the world is moving toward more sustainable and low-carbon binder alternatives.
2. Keyword and co-citation analyses validated the transition of the field from initial feasibility and stabilization approach to



advanced research works focused on the internal structure, durability, and life-cycle performance of alkali-activated and geopolymeric binder composites.

3. The mapping of the intellectual framework described four principal thematic domains namely alkali activation, microstructural characterization of concrete, heavy-metal immobilization, and sustainability analysis, that combined makes the scientific foundation of tailings utilization research.
4. Bibliographic coupling analysis showed that materials scientists, environmental engineers, and industrial ecologists are working together more and more across domains. This results in the merging of goals for environmental remediation with structural performance and resource optimization.
5. In the concept of circular economy, tailings based SCMs are very valuable for making carbon-neutral construction materials.

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