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Review

From Mine Waste to Construction Materials: A Bibliometric Analysis of Mining Waste Recovery and Tailing Utilization in Construction

Vicente Zetola [1], Brian F. Keith [2], Elizabeth J. Lam [3,*], Ítalo L. Montofré [4,5], Rodrigo J. Rojas [3], Juan Marín [3] and Mathias Becerra [3]

1 Construction Management Department, Universidad Católica del Norte, Antofagasta 1270709, Chile; vzetola@ucn.cl
2 Department of Computing & Systems Engineering, Universidad Católica del Norte, Antofagasta 1270709, Chile; brian.keith@ucn.cl
3 Department of Chemical and Environmental Engineering, Universidad Católica del Norte, Antofagasta 1270709, Chile; rrojas02@ucn.cl (R.J.R.); juan.marin@ce.ucn.cl (J.M.); mathias.becerra@ce.ucn.cl (M.B.)
4 Mining Business School, ENM, Universidad Católica del Norte, Antofagasta 1270709, Chile; imontofre@ucn.cl
5 Mining and Metallurgical Engineering Department, Universidad Católica del Norte, Antofagasta 1270709, Chile
* Correspondence: elam@ucn.cl

Abstract: This article presents a comprehensive scientometric analysis of mining waste valorization, focusing on tailings utilization in construction materials from 2010 to 2024. Through examination of 1096 Web of Science publications and utilizing CiteSpace mapping and network analyses, we analyze the intellectual structure of this field. Subject category analysis reveals materials science, construction technology, and environmental engineering as the dominant disciplines, interconnected through 168 links across 64 thematic nodes. Our co-citation analysis identifies 12 major research clusters, with materials science and environmental engineering serving as primary disciplinary pillars. Keyword co-occurrence analysis of 532 nodes connected by 1181 links highlights the field's emphasis on fly ash, concrete applications, and mechanical properties. Recent citation bursts indicate growing research focus on thermal stability, heavy metal treatment, and innovative processing methods. Through synthesizing these scientometric indicators, this review provides strategic insights for advancing sustainable construction practices through mining waste utilization. Research gaps identified include long-term durability assessment, standardization needs, and scalability challenges. By synthesizing these diverse scientometric indicators, this review provides strategic insights for researchers, industry practitioners, and policymakers, contributing to the advancement of sustainable construction practices through mining waste utilization.

Keywords: mine waste; mine tailings; construction materials; bibliometrics; CiteSpace

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1. Introduction

The mining industry, crucial for global economic development, grapples with significant environmental challenges, particularly in managing tailings. These fine-grained ore processing residues, if mishandled, can lead to soil and water contamination through acid mine drainage and heavy metal leaching, threatening local ecosystems and water resources [1–4].

Chile, as the world's largest copper producer and a significant source of lithium, molybdenum, rhenium, and silver [5], exemplifies both the economic benefits and environmental concerns of mining. The sector contributes 10% to Chile's GDP and over half of its exports [6]. However, the country grapples with over 764 tailings deposits, totaling more than 10 billion cubic meters. These deposits risk soil and water contamination, dust emissions, and potential dam failures [3,7,8].

In this context, the growing emphasis on sustainable practices and increasing raw material demand has spurred research into mining waste recovery and utilization. The construction industry, a major consumer of raw materials, offers a promising avenue for repurposing mining waste [9]. As research in this field proliferates, systematic analysis of the literature becomes crucial. Bibliometric and scientometric analyses provide powerful tools for mapping the scientific landscape, revealing key trends, research hotspots, and knowledge gaps [10].

In particular, this study aims to present a comprehensive scientometric analysis of the literature on mining waste recovery and tailing utilization in construction materials published since 2010. Our analysis is based on a dataset of 1096 publications indexed in the Web of Science database using the CiteSpace scientometric tool [11]. In particular, we seek to: (a) map the intellectual structure and evolution of the field over the past decade; (b) identify key research themes, methodologies, and applications; (c) highlight influential works, authors, and institutions shaping the discourse; and (d) detect emerging trends and potential future research directions.

Mining waste has been successfully incorporated into a diverse range of construction materials, as evidenced by our analysis of more than 1000 research publications. The primary applications include cemented paste backfill for ground support [12], eco-friendly bricks [13], and geopolymer concrete [14]. These range from relatively simple applications like using processed tailings as fine aggregate replacements in concrete [15], to more sophisticated approaches such as alkali-activated materials [16]. Research has particularly focused on improving the cementitious properties of mining wastes through mechanical and chemical activation methods [17,18].

Furthermore, this study provides an overview of the field and aligns with several United Nations Sustainable Development Goals (SDGs). Specifically, our research contributes to SDG 9 (Industry, Innovation, and Infrastructure) by promoting innovative use of mining waste in construction, SDG 11 (Sustainable Cities and Communities) through the development of sustainable building materials, SDG 12 (Responsible Consumption and Production) by encouraging the reuse of industrial waste, and SDG 13 (Climate Action) by highlighting studies that could potentially aid in reducing the carbon footprint of both mining and construction industries. This focus on sustainability and innovation underscores the scientific and societal relevance of our scientometric analysis, providing a solid foundation for future research and practical applications in the field of mining waste recovery and utilization in construction.

2. Materials and Methods

2.1. Data Collection and Processing

This study employed the Web of Science (WoS) Core Collection as the primary bibliometric database, selected for its comprehensive coverage and established reputation in scientific research [19–21]. The following query string was used to perform the search:

(“Ag” OR “Au” OR “Cu” OR “Fe” OR “Li” OR “Mo” OR “Zn” OR “Copper” OR “Gold” OR “Iron” OR “Lithium” OR “Molybdenum” OR “Silver” OR “Zinc”) AND (“tailing*” OR “mine dump*” OR “mining dump*”) AND (“construction material” OR “building material” OR “geopolymer” OR “brick” OR “concrete aggregate*” OR “concrete” OR “portland cement” OR “ceramsite*” OR “lightweight aggregate*” OR “supplementary cementitious material*”).

The asterisk in our query terms (e.g., “tailing”) serves as a wildcard operator to capture variations such as “tailings” and “tailing”. Note that the query focuses on specific metals due to their importance and prevalence as mining waste. We further restricted our search to articles published since 2010 to focus on research from the current and past decades. The results were retrieved on 23 October 2024 and include all journal articles indexed by Web of Science up to this date. We discarded non-journal articles from the analysis. Following this approach, the search retrieved 1096 documents in total. Out of these, there are 1039 research articles and 57 reviews (including early access articles).

2.2. Scientometrics Analysis Methods and Tools

This study employs scientometric techniques, leveraging social network analysis to systematically investigate the intricate web of scholarly relationships and interactions. By mapping the complex connections among publications and authors, we gain profound insights into the structure of academic communities [22,23]. These methods enable the processing of extensive datasets, facilitating the identification of knowledge gaps and emerging research frontiers [24,25], thus providing crucial guidance for future scientific endeavors.

Citation analysis serves as the basis of our methodology, revealing the underlying knowledge architecture and academic communities within the field [26,27]. This approach is complemented by bibliometric analyses, which are instrumental in illuminating research landscapes in nascent and rapidly evolving domains [28].

To enhance our understanding of the field's temporal evolution, we employ both popularity-based and network-based trend identification approaches [29]. The former focuses on conceptual shifts over time [30], while the latter examines citation and collaboration networks to highlight emerging themes and structural patterns [31]. Our study specifically adopts a network-based approach to systematically review research hotspots and trends in mining waste recovery and tailing utilization in construction materials.

The implementation of CiteSpace 6.3.R3 software enables scientometric mapping of the knowledge domain. Through co-citation analysis, we identify pivotal contributions, intellectual turning points, and research fronts [11,32]. We generate document co-citation network maps using citation data from the Web of Science Core Collection, visualizing the structure and evolution of research areas over time. Furthermore, we mapped a keyword co-occurrence network to elucidate conceptual subdomains and uncover disciplinary and temporal patterns.

CiteSpace's advanced capabilities in tracking citation bursts, rising trends, and betweenness centrality metrics facilitate the identification of high-impact publications, seminal discoveries, and emerging innovations that have shaped the scientific landscape of mining waste utilization in construction materials [11]. This multifaceted approach offers both retrospective understanding and prospective horizon scanning, providing contextual and forward-looking intelligence to guide ongoing research in this dynamic field.

Throughout this work, we rely on clustering analysis performed by CiteSpace, which automatically generates cluster labels using title terms extracted from highly cited documents within each group. This is based on three statistical labeling approaches: Log-Likelihood Ratio (LLR), Latent Semantic Indexing (LSI), and Mutual Information (MI) tests [11]. These methods identify salient phrases characteristic of each cluster by determining term frequency differences between the focal group and the overall background domain, capturing the essence and themes of that segment of literature [33].

3. Results

3.1. Subject Categories Co-Occurrence Analysis

The scientific landscape of mining waste recovery and tailings utilization in construction materials was explored through an in-depth analysis of WoS subject categories. This examination provides crucial insights into the field's thematic diversity and interdisciplinary nature. There are several research domains contributing to this area of study. Table 1 enumerates the top 10 WoS categories most prevalent in our dataset, offering a concise overview of the primary research fields involved.

Table 1. Top 10 most frequent WoS categories in the retrieved documents.

Rank	Frequency	WoS Category
1	480	Materials Science, Multidisciplinary
2	454	Construction and Building Technology
3	434	Engineering, Civil
4	199	Environmental Sciences
5	112	Engineering, Environmental
6	99	Green and Sustainable Science and Technology
7	92	Metallurgy and Metallurgical Engineering
8	71	Mining And Mineral Processing
9	70	Physics, Applied
10	60	Chemistry, Physical

To elucidate the relationships between these fields, we employed a co-occurrence analysis of subject categories [33]. This approach revealed a knowledge network comprising 64 distinct thematic nodes, interconnected through 168 links. Figure 1 provides a graphical representation of this knowledge structure. In this visualization, circular nodes denote individual Web of Science subject categories identified in our document set. The interconnecting lines signify publications bridging multiple categories, thus illustrating cross-disciplinary integration. The visual weight of each node correlates with the category's frequency of occurrence, while the thickness of connecting lines represents the strength of inter-category relationships based on co-assignment patterns. This visualization underscores the field's multidisciplinary character, encompassing contributions from environmental sciences, multiple engineering branches, materials science, geochemistry, mineralogy, and sustainable technology research. The temporal dynamics of subject category prominence, as indicated by citation bursts, illuminate the field's evolutionary trajectory. We observed a shift from an initial focus on environmental considerations to more targeted engineering applications, ultimately progressing towards holistic, integrated approaches. This development pathway reflects the field's increasing sophistication and its growing relevance in addressing concurrent challenges in waste management and sustainable construction.

The CiteSpace analysis of subject category co-occurrence in research on mining waste valorization for construction applications since 2010 reveals a rich interdisciplinary landscape. At the nexus of this knowledge network lies materials science, serving as a central hub connecting various fields [14]. This centrality underscores the multifaceted nature of waste upcycling in construction contexts.

Construction and building technology emerge as another pivotal category, emphasizing the critical role of understanding material properties and their performance in built environments [13,34,35]. The significant presence of green and sustainable science/technology [36], metallurgical engineering [16], and mining engineering [37] illustrates a growing focus on sustainability and the synergistic integration of mining waste management with innovative construction material development. The involvement of specialized fields such as physical chemistry [38], applied physics [39], and mineralogy [37] further accentuates the multidisciplinary character of this research domain. This diverse scientific landscape, captured by our co-occurrence analysis, highlights how the collective efforts across various disciplines have propelled advancements in the environmental application and efficacy of mining waste utilization for sustainable construction materials.

Table 2 ranks the top 10 categories based on network centrality criteria. Notably, the high centrality of environmental sciences [36,40,41]. The table highlights the complexity inherent in mining waste recovery and utilization for construction, necessitating expertise from diverse fields to tackle technical, environmental, and sustainability challenges. The interconnected nature of these subject categories also points to fertile ground for future cross-disciplinary collaborations and innovations.

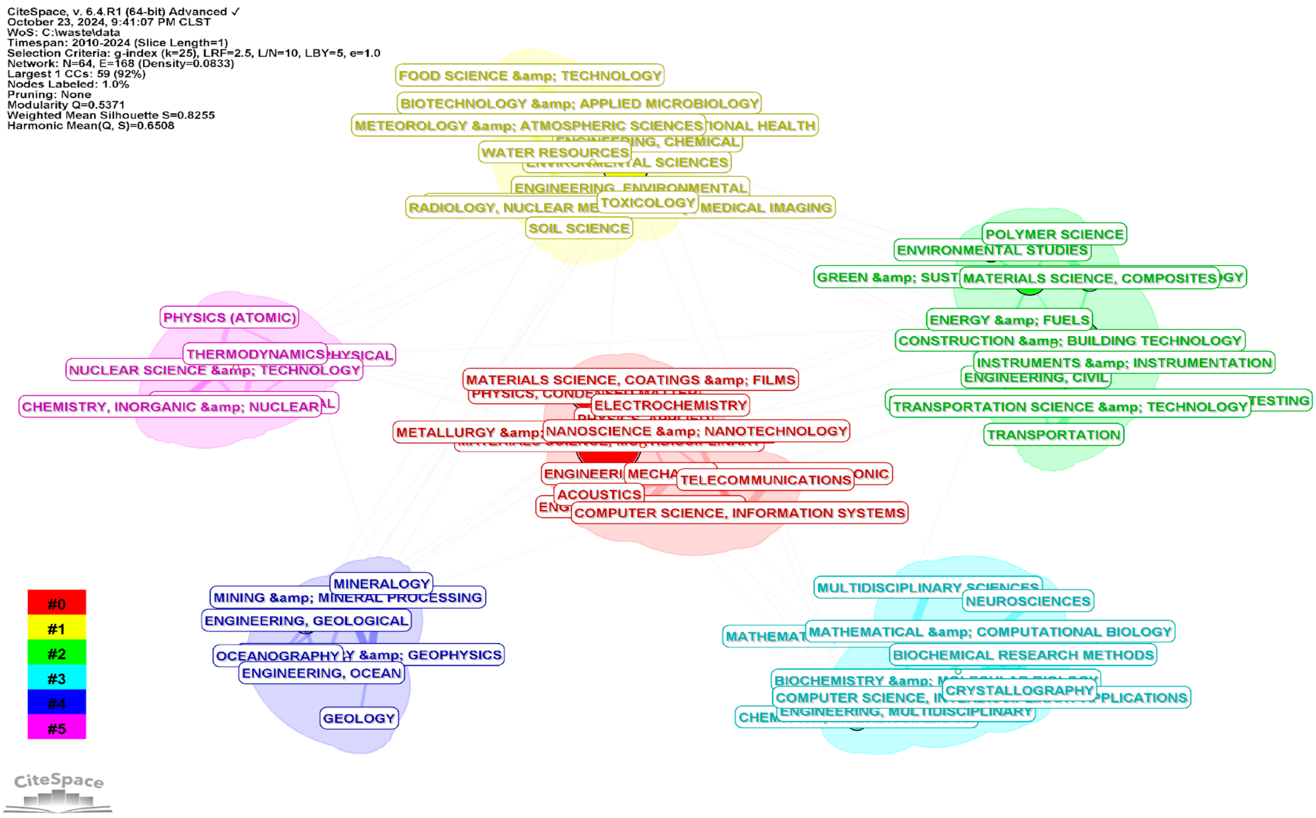

Figure 1. Interdisciplinary knowledge network: visualization of 64 subject categories and their 168 interconnections in mining waste valorization research (high−resolution image available in Supplementary Materials).

Table 2. The top 10 subject categories extracted from the co-occurrence network based on betweenness centrality, a measure reflecting connections bridging across the broader network.

Rank	Centrality	Node Name
1	0.51	Environmental Sciences
2	0.39	Materials Science, Multidisciplinary
3	0.31	Chemistry, Multidisciplinary
4	0.23	Engineering, Civil
5	0.20	Engineering, Multidisciplinary
6	0.19	Mining and Mineral Processing
7	0.17	Physics, Applied
8	0.17	Biochemistry and Molecular Biology
9	0.16	Green and Sustainable Science and Technology
10	0.12	Chemistry, Physical

Table 3 presents the top 10 subject categories exhibiting the most significant bursts of activity over time in our analyzed literature set. These categories demonstrated marked increases in annual assignments, signifying areas of intensifying research focus within the knowledge domain.

Table 3. The top 10 subject categories found through burst analysis from the co-occurrence network in the period since 2010.

WoS Category	First Appearance	Burst Strength	Burst Begin	Burst End
Geochemistry and Geophysics	2017	5.10	2018	2021
Engineering, Environmental	2010	3.83	2010	2011
Mining and Mineral Processing	2012	3.79	2019	2020
Environmental Sciences	2010	3.72	2010	2011
Mineralogy	2012	3.33	2019	2020
Engineering, Multidisciplinary	2012	2.45	2020	2021
Engineering, Chemical	2012	2.41	2012	2013
Geosciences, Multidisciplinary	2010	1.99	2016	2018
Engineering, Electrical and Electronic	2020	1.22	2020	2021
Engineering, Geological	2010	1.12	2013	2015

The citation burst analysis reveals the progression in research priorities for mining waste recovery and tailings utilization in construction over the past decade. The early 2010s demonstrated a strong environmental focus, exemplified by foundational work on heavy metal contamination in river sediments [42]. This research established critical assessment methodologies for environmental risks that would later become fundamental for the safe development of construction materials. The emphasis on environmental sciences during this period (2010–2011) laid the groundwork for subsequent technological developments.

The field then evolved towards more specialized processing and mineralogical studies from 2012 to 2016, with made significant contributions by investigating alkali-activated blast furnace slag in cemented paste backfill, demonstrating superior performance compared to conventional Portland cement for high-sulphide tailings [37]. Concurrently, innovative methodologies were developed for manufacturing geopolymer bricks using iron ore tailings, establishing optimal processing parameters and demonstrating economic viability [43]. These works marked a shift towards more practical applications while maintaining environmental considerations.

The mid-decade period (2016–2018) saw an expansion into broader geoscientific perspectives, with an investigation of durability and strength in fiber-reinforced compacted gold tailings–cement blends established crucial relationships between porosity/cement indices and mass loss [44]. This work was complemented by a characterization of copper and gold mine tailings for geopolymeric applications, providing guidelines for their safe utilization in construction materials [45]. These studies demonstrated increasing sophistication in understanding material behavior and environmental implications.

The period of 2019–2020 showed intensified focus on advanced mineral processing and material optimization. Detailed investigations were conducted into the rheological properties of cemented paste backfill with alkali-activated slag, providing crucial insights for practical applications [46]. The field was advanced through innovative mechanical activation methods to enhance the pozzolanic properties of iron ore tailings, demonstrating new possibilities for material improvement [17].

The most recent period (2020–2021) has emphasized multidisciplinary integration and technological advancement. Hybrid artificial intelligence models were introduced for predicting foam-cemented paste backfill strength, representing a significant technological leap in material design and optimization [47]. Similarly, studies were conducted on leaching risks associated with fly ash-slag-based binders [48], maintaining the field's commitment to environmental safety while advancing technical capabilities.

This evolution demonstrates the field's progression from basic environmental concerns to sophisticated technical solutions integrating multiple disciplines. Recent works indicate a trend toward process optimization and advanced technology integration while maintaining fundamental environmental considerations, suggesting a maturing field that retains its core sustainability principles. The emergence of electrical and electronic engineering applications, though still exploratory, signals potential new directions for technological innovation in the field.

The chronological analysis reveals how the field has maintained its environmental and engineering foundations while continuously adapting to address new challenges in mining waste management and sustainable construction. This progression suggests a dynamic research area that successfully balances practical applications with environmental responsibility, increasingly incorporating advanced technologies and interdisciplinary approaches to solve complex challenges in sustainable construction materials development.

3.2. Keywords Co-Occurring Analysis

Keywords serve as concise indicators of a publication's core content and concepts [49]. Our analysis of keyword co-occurrence revealed a network of 532 nodes connected by 1181 links, providing insights into the field's key topics and trends, which we show in Figure 2.

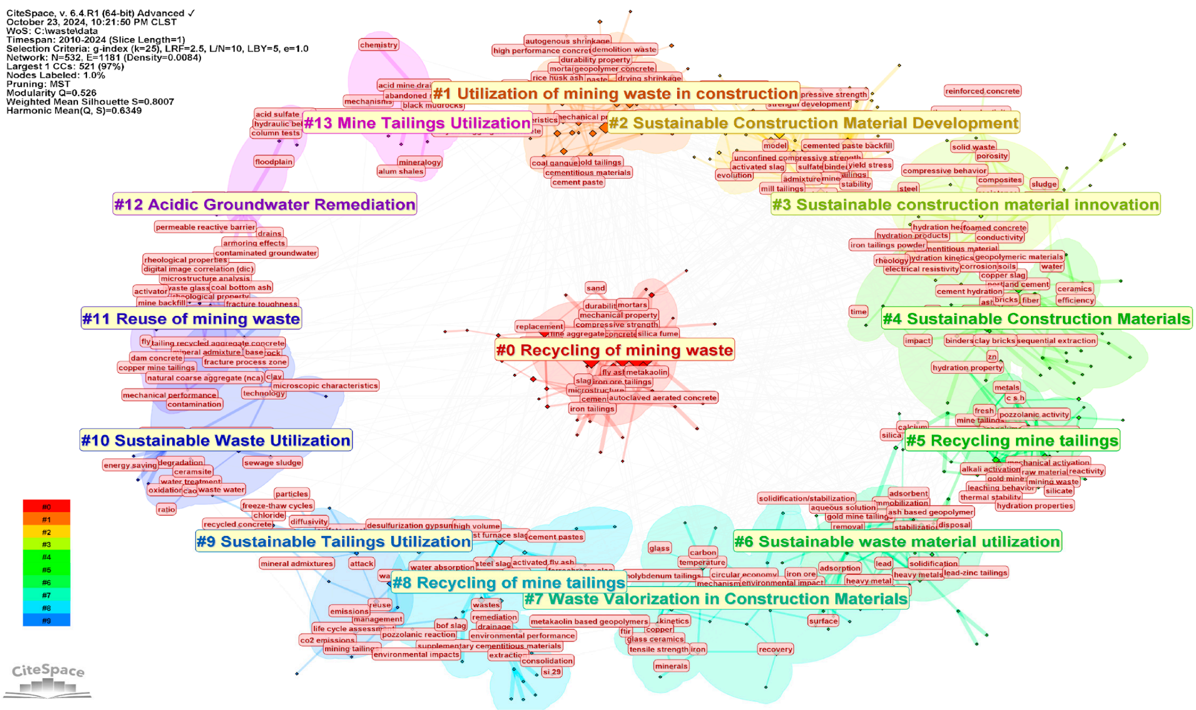

Figure 2. Circular network visualization of the 14 topical clusters identified in the keyword co-occurrence analysis. This network delineates the major research areas that have developed over time in the field. A higher-resolution version of this figure is included in the Supplementary Materials. Cluster labels were defined using the GPT option of CiteSpace.

Table 4 lists the top 10 most frequent keywords in the network. "Fly ash" and "concrete" share the highest frequency with 293 occurrences each, closely followed by "concrete" (279) and then "strength" (273). This highlights the field's focus on using mining waste, particularly fly ash, as a supplementary material in concrete production. The prominence of "strength" and "compressive strength" underscores the importance of mechanical properties in evaluating these waste-derived materials. "Mine tailings" and "iron ore tailings" indicate the specific types of mining waste under extensive study. The inclusion of "performance", "behavior", "mechanical property", and "microstructure" suggests a focus on developing an understanding of these materials.

Table 4. The 10 most common keywords assigned across the set of reviewed publications, ranked by frequency of articles featuring the term.

Rank	Frequency	Keyword
1	293	fly ash
2	279	concrete
3	272	strength
4	197	compressive strength
5	173	performance
6	164	behavior
7	152	mine tailings
8	150	mechanical property
9	146	iron ore tailings
10	127	microstructure

Table 5 presents the 10 keywords with the highest betweenness centrality, indicating terms that bridge different areas of research. "Cemented paste backfill" shows the highest centrality (0.16), suggesting its role in connecting diverse research areas; "behavior" (0.15), "copper tailings" (0.13), "fly ash" (0.11), and "bricks" (0.11) are next in terms of centrality, indicating their importance in linking various aspects of the field. The presence of "durability" and "activation" (both 0.10), followed by "aggregate" and "drainage" (both 0.09), and "cement" (0.08) in the high-centrality list emphasizes the importance of understanding both material properties and processing techniques.

Table 5. The top 10 keywords in the co-occurrence network by centrality across the set of reviewed publications.

Rank	Centrality	Keyword
1	0.16	cemented paste backfill
2	0.15	behavior
3	0.13	copper tailings
4	0.11	fly ash
5	0.11	bricks
6	0.1	durability
7	0.1	activation
8	0.09	aggregate
9	0.09	drainage
10	0.08	cement

Our burst analysis identified 20 significant keywords, shown in Table 6, revealing shifts in research focus over time. The early 2010s saw "wastes" emerge as a key term with the highest burst strength (6.55) from 2011–2017. Environmental concerns were prominent, with "drainage" (3.15, 2011–2016) and "acid mine drainage" (3.08, 2012–2019) gaining attention, alongside "mine" (3.0, 2012–2019) and "sequential extraction" (2.9, 2012–2018).

Table 6. List of the 20 keywords that had occurrence bursts since 2010. The keywords are listed by the burst strength.

Keywords	First Appearance	Burst Strength	Burst Begin	Burst End
wastes	2011	6.55	2011	2017
drainage	2011	3.15	2011	2016
acid mine drainage	2012	3.08	2012	2019
mine	2012	3	2012	2019
sequential extraction	2012	2.9	2012	2018
bricks	2015	5.98	2015	2019
technology	2015	3.25	2015	2021
tailings	2012	2.86	2017	2020
unconfined compressive strength	2013	5.72	2018	2020
stability	2018	3.82	2018	2021
management	2018	3.33	2018	2021
paste backfill	2018	3.3	2018	2020
microstructural property	2019	4.95	2019	2021
gold mine tailings	2019	3.28	2019	2021
yield stress	2019	3.16	2019	2020
mining waste	2020	3.35	2020	2021
curing temperature	2012	3.19	2020	2021
model	2019	2.84	2020	2021
heavy metal	2011	3.64	2021	2022
thermal stability	2021	2.89	2021	2022

Mid-decade, the focus shifted to construction applications, with “bricks” showing a strong burst (5.98, 2015–2019) and “technology” demonstrating sustained interest (3.25, 2015–2021). “Tailings” emerged as a significant term (2.86, 2017–2020), while “unconfined compressive strength” showed a notable burst (5.72, 2018–2020).

The latter period of the decade emphasized material properties and management aspects. “Stability” (3.82), “management” (3.33), and “paste backfill” (3.30) all showed significant bursts from 2018–2021. “Microstructural property” (4.95) and “gold mine tailings” (3.28) gained prominence from 2019–2021, alongside “yield stress” (3.16, 2019–2020).

Most recently (2020–2022), research has focused on “mining waste” (3.35, 2020–2021), “curing temperature” (3.19, 2020–2021), “model” (2.84, 2020–2021), “heavy metal” (3.64, 2021–2022), and “thermal stability” (2.89, 2021–2022), indicating a trend toward process optimization and environmental considerations.

From 2018, research expanded to include management and stability concerns. “Stability” (burst strength 3.82, 2018–2021), “management” (3.33, 2018–2021), and “paste backfill” (3.30, 2018–2020) all showed significant bursts. Recent trends show growing interest in material properties, with “microstructural property” demonstrating a strong burst (4.95, 2019–2021) alongside “gold mine tailings” (3.28, 2019–2021). Process parameters gained attention with “yield stress” (3.16, 2019–2020), while more recent research has focused on “mining waste” (3.35, 2020–2021), “curing temperature” (3.19, 2020–2021), and “model” (2.84, 2020–2021). The most recent trends (2021–2022) emphasize environmental and stability concerns, with bursts in “heavy metal” (3.64) and “thermal stability” (2.89).

Applying cluster analysis to the keyword co-occurrence network offers valuable insights into the thematic distribution and developmental paths of research on mining waste recovery and tailing utilization in construction materials. Figure 3 illustrates the network's division into 12 distinct clusters, each automatically labeled by CiteSpace using the format "# + number + label" based on prominent keywords.

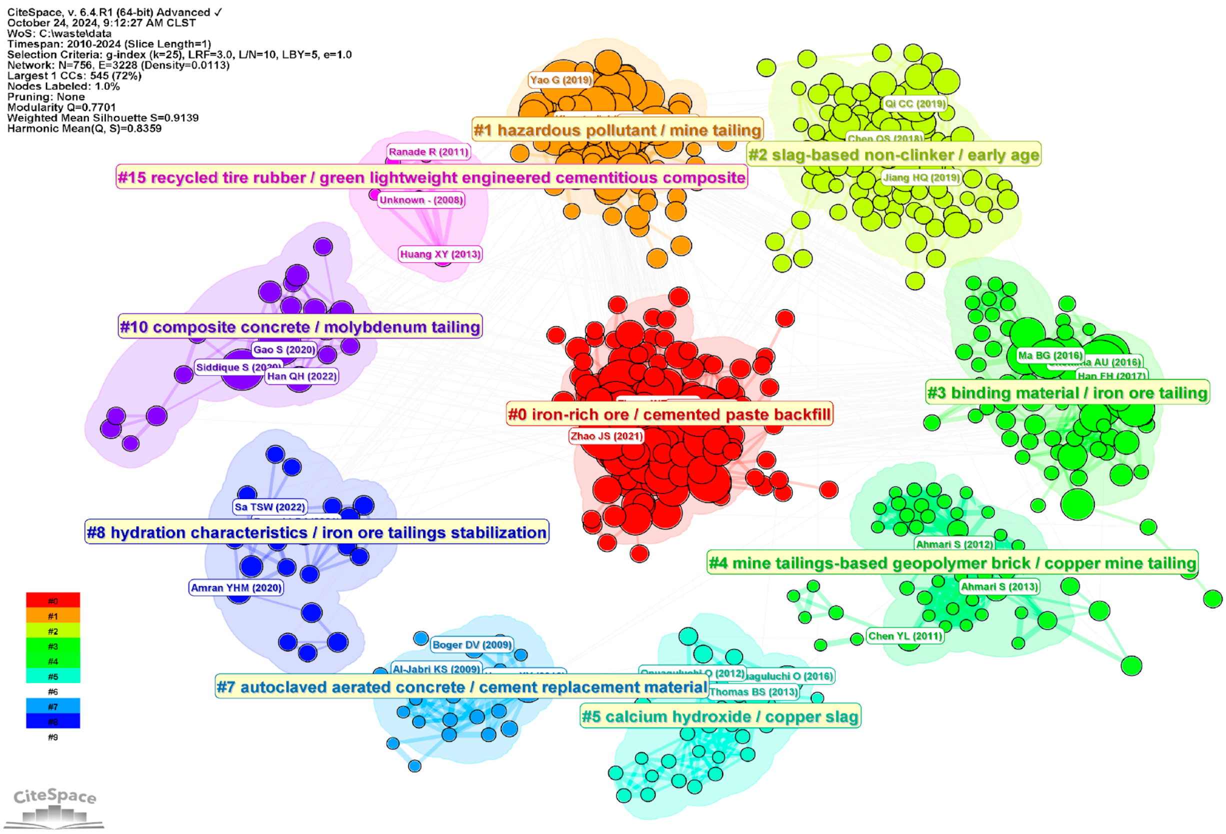

Figure 3. Co−citation landscape in mining waste utilization research. This network diagram illustrates 756 interconnected reference nodes with 3228 co-citation links, representing key influences in the field. Node size correlates with citation frequency. Labels identify significant clusters and their most impactful publications. This visualization offers insights into the intellectual structure and influential works shaping research on mining waste recovery for sustainable construction materials.

By examining the temporal emergence of these clusters, we can trace the evolution of research focus and themes that have gained prominence throughout the field's history. The labeled cluster network and timeline visualization reveal a clear progression in the field's focus. Initial research concentrated on waste characterization and environmental concerns, gradually shifting towards advanced material applications and sustainable construction practices.

This trajectory demonstrates the field's maturation from foundational utilization concepts to more sophisticated, performance-oriented solutions, as evidenced by the progression from basic recycling (Cluster #0, focusing on sustainable tailings utilization in construction) to advanced applications (Cluster #1, exploring utilization techniques) and specialized developments (Cluster #2, addressing sustainable construction material development). These advanced approaches simultaneously address the challenges of waste management and meet the evolving needs of the construction industry, as shown in Clusters #3 through #5, which focus on sustainable construction material innovation and mine tailings recycling. The cluster analysis thus provides a general overview of how the field has expanded and diversified over time, from basic waste management (Clusters #6–#8) to sophisticated applications (Clusters #9–#21), including specialized areas such as acidic groundwater remediation and sustainable cementitious materials. This progression reflects the growing complexity and interdisciplinary nature of research in this domain, as demonstrated by the evolution from simple recycling concepts to integrated approaches in sustainable material development.

To assess the quality of the co-occurrence network's clustering, we examined the evaluation metrics reported by CiteSpace. The mean Q value of 0.5260 indicates a moderate level of community structure within the network and the mean S value of 0.8007 indicates that the clusters demonstrate internal consistency [50]. These metrics support the robustness of our cluster analysis for examining the keyword co-occurrence network, which revealed 14 major topical clusters related to mining waste recovery for sustainable construction materials.

The largest cluster (#0) has 64 members with a silhouette score of 0.867 and focuses on the recycling of mining waste, particularly highlighted by Lazorenko et al.'s [51] work on mine tailings-based geopolymers and their industrial applications (63 citations). This cluster explores various applications, from cement–iron tailings powder composite materials to the effects of fly and coal bottom ash in backfill materials [52]. It also includes recent investigations into geopolymer composites using industrial by-products [53] and the utilization of molybdenum tailings as fine aggregate in recycled aggregate concrete [54].

Cluster #1, the second largest with 94 members and a silhouette value of 0.953, focuses on the utilization of mine tailings in construction materials, as evidenced by high-impact studies on geopolymer production [55] (111 citations) and on industrial applications of mine tailings-based geopolymers [56] (63 citations). The research examines comprehensive aspects through reviews on geopolymer applications [57] (53 citations) and on physicochemical and environmental considerations [51] (49 citations). Recent work [58] (34 citations) provides insights into methods and challenges for using mine tailings as cementitious binders.

The third largest cluster (#2) has 60 members with a silhouette score of 0.831, focusing on Sustainable Construction Material Development. This cluster examines diverse aspects of cemented backfill materials, evidenced by highly cited research on strength development and microstructural investigation of lead-zinc mill tailings-based paste backfill [59] (98 citations), and another highly cited study on mineral admixtures' effects on flow properties [12] (124 citations). The cluster also includes significant research on leaching risks in fly ash-slag-based binders [48] (114 citations) and investigations into phosphogypsum-based applications, including slurry preparation and durability evaluation through drying–wetting cycles [60].

The fourth largest cluster (#3) has 47 members with a silhouette score of 0.711, focusing on sustainable construction material innovation. This cluster is characterized by highly cited reviews and innovative methodologies, such as a review of mine tailings as raw materials in alkali activation [16] (61 citations) and pioneering work on iron ore tailings utilization for cementitious materials [40] (113 citations). The research scope includes durability studies of copper tailings in cement mixtures [61] (36 citations) and more recent investigations into recycling processes, as shown in work on slag utilization [62] and research on unburned brick production using waste-stream binders [63]. The cluster demonstrates significant evolution in sustainable construction materials, emphasizing both mechanical performance enhancement and environmental benefits. Key themes include the development of eco-friendly building solutions using various mining and industrial wastes, while addressing concerns about long-term performance reliability and environmental impacts in large-scale applications.

The fifth largest cluster (#4) has 46 members with a silhouette score of 0.858, focusing on sustainable construction materials with an emphasis on environmental safety and performance optimization. The research encompasses both historical and contemporary approaches, as evidenced by highly cited works [64] (46 citations) on thermal treatment effects in lightweight aggregates and on the practical applications of base-metal tailings in mortars [65] (45 citations). Recent developments in this cluster highlight evolving priorities in sustainability and safety, including work on heavy metal stabilization in lead-zinc tailings [66], research on zero-carbon inertization processes for hazardous mine tailings [51], and investigation of enhanced pozzolanic activity in modified nickel slag [67]. The cluster demonstrates how sustainable construction materials must balance three key aspects: the replacement of traditional materials with mining waste products, environmental safety considerations, particularly regarding heavy metal leaching, and performance optimization through chemical activation and admixture incorporation.

Beyond these primary clusters, our analysis reveals a rich diversity of research directions in the field. Cluster #5 (44 members, silhouette score 0.732) demonstrates approaches to mine tailings recycling, particularly highlighted by significant review papers [51,55] (63 and 111 citations, respectively). This cluster emphasizes geopolymer development and alkali activation methods, as evidenced by its most cited keywords, mine tailings (152), geopolymer (28), and pozzolanic activity (26), suggesting a strong focus on innovative material processing techniques.

Cluster #6 (42 members, silhouette score 0.763) focuses on sustainable waste material utilization, with particular emphasis on heavy metal immobilization. The highly cited work [68] (155 citations) on porous geopolymers exemplifies the cluster's innovative approach to environmental challenges. The cluster's most cited terms—heavy metals (63), red mud (46), and immobilization (39)—reflect its strong environmental focus and practical applications in waste management.

The research direction shifts slightly in Cluster #7 (36 members, silhouette score 0.824), which examines waste valorization in construction materials. This cluster spans a broader range of applications, from geotechnical implementations to environmental assessments. The emphasis on temperature (62 citations), recovery (25), and mechanisms (22) suggests a more technical approach to material development and performance optimization.

Clusters #8 and #9 (34 and 29 members with high silhouette scores of 0.882 and 0.787, respectively) represent more specialized research areas. Cluster #8 concentrates on the recycling of mine tailings with particular attention to heavy metal immobilization and solidification techniques, while Cluster #9 extends into sustainable tailings utilization with a broader focus on life cycle assessment and waste management strategies.

The smaller clusters (#10–#13) represent emerging or highly specialized research directions. Cluster #10 (25 members, silhouette 0.793) focuses on sustainable waste utilization with an emphasis on life cycle analysis. Cluster #11 (14 members) examines specific applications of mining waste in construction, while Clusters #12 and #13 (10 members each) address specialized areas such as acidic groundwater remediation and environmental risk assessment in tailings utilization.

This cluster analysis reveals a field that has evolved from basic recycling concepts to sophisticated, application-specific research. This progression demonstrates increasing emphasis on environmental safety, sustainable practices, and innovative material processing techniques. The high silhouette scores across clusters (ranging from 0.732 to 0.993) indicate well-defined research communities with distinct focuses, while the interconnected themes suggest a field that maintains strong collaborative links across various specializations.

These diverse research directions collectively contribute to advancing sustainable construction practices while addressing critical environmental challenges in mining waste management. The emphasis on both fundamental research and practical applications suggests a mature field that continues to evolve through innovative approaches to waste utilization and environmental protection.

In general, this diverse range of research topics illustrates the field's evolution towards more specialized and application-oriented studies, reflecting the growing importance of sustainable practices in both the mining and construction industries.

3.3. Reference Co-Citation Overview

The advancement of scientific knowledge is a cumulative process, with new research typically building upon and referencing previous work. This practice of citation not only contextualizes new contributions, but also creates a web of interconnected studies. By analyzing patterns of co-citation—instances where multiple papers are cited together—we can uncover intrinsic connections and underlying structures within a field of study.

Figure 3 presents the co-citation network derived from our literature survey. This visualization serves as a map of scholarly influences, highlighting key publications, research groups, and concepts that have been instrumental in shaping the field of mining waste recovery and its application in sustainable construction materials.

By examining the patterns of citation across the timeline of this research area, we can trace its genesis and evolution. This analysis provides valuable insights into the driving forces behind scientific progress in this domain, revealing how ideas have spread, merged, and evolved over time.

The co-citation network not only showcases the most influential works, but also illustrates how different subfields and research themes are interconnected. This holistic view of the literature landscape helps identify pivotal studies that have bridged different areas of research, as well as emerging trends that may signal future directions in the field.

Our co-citation analysis has uncovered a set of highly influential publications that have significantly shaped the research domain of mining waste recovery and its application in construction materials. Table 7 presents these seminal works ranked by their citation frequency. The identified publications cover a diverse spectrum of research areas within the field. They range from foundational studies that characterize the properties of various mining wastes to cutting-edge research exploring innovative applications of these materials in construction. These highly cited works serve as cornerstones in the field, providing crucial insights and methodologies that have guided subsequent research efforts. By examining these influential publications, we can trace the evolution of key concepts and approaches that have driven progress in the utilization of mining waste for sustainable construction materials. The breadth of topics covered by these seminal works underscores the multidisciplinary nature of this research area, highlighting how advances in waste characterization, materials science, and construction technology have converged to create new possibilities for sustainable resource utilization.

Table 7. The top 10 references from the co-citation network ranked by total citations. The frequent appearance of these works highlights the foundational ideas, methods, and discoveries.

Citation Counts	Node Name	DOI
57	[69] Zhang WF, 2020, Constr Build Mater, V260, P0	https://doi.org/10.1016/j.conbuildmat.2020.119917
53	[15] Shettima AU, 2016, Constr Build Mater, V120, P72	https://doi.org/10.1016/j.conbuildmat.2016.05.095
51	[70] Zhao JS, 2021, Constr Build Mater, V286, P0	https://doi.org/10.1016/j.conbuildmat.2021.122968
49	[71] Lv XD, 2019, J Clean Prod, V211, P704	https://doi.org/10.1016/j.jclepro.2018.11.107
47	[18] Zhang N, 2021b, Constr Build Mater, V288, P0	https://doi.org/10.1016/j.conbuildmat.2021.123022
47	[17] Yao G, 2020, Powder Technol, V360, P863	https://doi.org/10.1016/j.powtec.2019.11.002
44	[72] Gou MF, 2019, Sci Eng Compos Mater, V26, P449	https://doi.org/10.1515/secm-2019-0029
42	[73] Han FH, 2019, Powder Technol, V345, P292	https://doi.org/10.1016/j.powtec.2019.01.007
40	[74] Protasio FNM, 2021, J Clean Prod, V278, P0	https://doi.org/10.1016/j.jclepro.2020.123929
40	[48] Li T, 2020, J Clean Prod, V259, P0	https://doi.org/10.1016/j.jclepro.2020.120923

The most cited paper in Table 7 [69] (57 citations), examines concrete properties incorporating mining waste materials, particularly focusing on compressive strength and permeability in ultra-high-performance concrete. In general, this research established a fundamental understanding of material performance optimization. The second article [15] (53 citations) provided crucial insights into iron ore tailings utilization in concrete, establishing key parameters for aggregate replacement strategies.

Other key studies further expanded our understanding of mining waste applications, including evaluations of iron ore tailings characteristics and their effects on concrete properties [70] (51 citations) and the practical utilization of iron tailings as complete aggregate replacement in dam concrete [71] (49 citations). Other works [17,18] (both with 47 citations) advanced the field through innovative approaches to materials processing and characterization. Particularly significant was the work on tailings utilization in cement and concrete, providing a systematic framework for applications [72] (44 citations).

Recent high-impact research has focused on optimization and practical implementation. Notable contributions include powder technology applications [73] (42 citations), and works addressing sustainability and cleaner production aspects [48,74] (both with 40 citations). These studies collectively demonstrate the field's maturation from basic utilization concepts to sophisticated performance-oriented solutions.

This analysis of highly cited works reveals the field's primary research priorities: material performance optimization, innovative processing techniques, and sustainability considerations. The chronological progression of citations indicates an evolution from fundamental characterization studies to advanced applications and environmental impact assessments, reflecting the growing emphasis on sustainable practices in both mining and construction sectors.

3.4. Citation Clusters Analysis

Our analysis initially identified 21 potential clusters. However, the CiteSpace analysis omitted several of these clusters, specifically cluster #6, #9, #11 through #14, and #16 through #19 from the network diagrams and output data. This exclusion occurred due to the cluster's lack of connections with the primary co-citation network. Consequently, our final analysis focuses on 12 relevant clusters.

The reliability of the co-citation network clustering is supported by the evaluation metrics provided by CiteSpace. The analysis yielded a mean Q value of 0.7701 and a mean S value of 0.9139. These high values are indicative of well-defined and internally consistent clusters within the network. Such metrics provide confidence in the robustness of the identified clusters and their ability to represent distinct research themes or subfields within the broader domain of mining waste utilization in construction materials. The 12 major clusters focus on different aspects of mining waste recovery and utilization in construction materials:

Cluster #0, the largest identified cluster with 125 members and a silhouette value of 0.794, represents a significant research focus on sustainable tailings utilization in construction materials. This cluster demonstrates the field's evolution toward comprehensive sustainability approaches, particularly evident in recent high-impact reviews and research papers. The cluster's temporal development is notable, with highly cited foundational works [69,70] (64 citations and 63 citations, respectively)establishing core concepts in construction materials development. These works are complemented by contributions to composite materials science [72] (59 citations) and advances in powder technology applications [17] (56 citations).

Recent developments in this cluster [75], demonstrate an increasing focus on specific applications such as low-carbon concrete and ultra-high-performance concrete. Particularly significant is the work on cementitious activity of iron ore tailings [76] (103 citations), which bridges fundamental research with practical applications. The cluster exhibits three distinct research priorities, including material performance optimization, focusing on mechanical properties and durability, environmental sustainability, particularly in developing low-carbon alternatives, and innovation in material processing, especially through geopolymer development and alkali-activation.

A notable characteristic of this cluster is its high coverage values (ranging from 27 to 37) for recent review papers, suggesting a field that is actively consolidating knowledge while continuing to advance. The cluster's silhouette score (0.794) indicates a well-defined research community with clear thematic boundaries. This cluster demonstrates the field's maturation from basic utilization concepts to sophisticated, performance-oriented solutions that balance technical requirements with environmental considerations.

Cluster #1, the second largest cluster with 94 members and a notably high silhouette score of 0.953, represents a focused research direction on mine tailings utilization, particularly in geopolymer applications. The cluster demonstrates strong contemporary relevance through several highly-cited review papers published between 2021 and 2022. The most impactful contribution [55] offered a systematic review of mine tailings in geopolymer production. This is complemented by other works [51,57] (63 and 53 citations, respectively), that expanded the understanding of geopolymer applications and industrial prospects.

The research evolution within this cluster is particularly noteworthy, as evidenced by its most cited foundational works that established fundamental principles in clean production approaches [77] (38 citations), while more recent works [18] (35 citations) advance these concepts with contemporary applications. The cluster exhibits three primary research themes, including geopolymer synthesis and characterization (demonstrated by high coverage values in review papers), physicochemical and environmental considerations [51], and industrial application potential [56].

A distinctive feature of this cluster is its strong focus on environmental and sustainability aspects, evidenced by the predominance of publications in the Journal of Cleaner Production among its most cited members. Furthermore, this cluster demonstrates the field's progression toward more sophisticated applications of mine tailings, particularly in geopolymer technology, while maintaining a strong focus on environmental sustainability and practical industrial implementation. The balance between fundamental research and application-oriented studies suggests a mature research area with significant potential for continued development.

Cluster #2 (91 members, silhouette score 0.931) represents a significant research focus on mine tailings recycling, particularly in cemented paste backfill applications. The cluster is characterized by highly cited works focusing on material properties and performance optimization, notably work on mineral admixtures effects [12] (124 citations) and on strength behavior [78] (109 citations). A distinctive feature is the emphasis on advanced characterization methods, including ultrasonic pulse velocity measurements and rheological assessments. The most cited foundational work (41 citations) established key principles in mineral engineering applications.

Cluster #3 (76 members, silhouette score 0.908) demonstrates a broader approach to mine tailings utilization, particularly in cement and concrete applications. The cluster features the highly influential work [34] (349 citations) on innovative 3D printing applications, representing a significant technological advancement. Other notable contributions include a highly cited review [72] (118 citations) and a study on cementitious activities [18]. The cluster's evolution is evidenced through foundational works [15] (55 citations) and subsequent developments in powder technology [79] (36 citations).

Cluster #4 (48 members, silhouette value 0.992) is anchored by two highly cited works: The first on geopolymer concrete properties (2015, 345 citations) and Ahmari et al. on eco-friendly brick production [13] (322 citations). The research progression demonstrates increasing sophistication in understanding activation mechanisms and curing conditions, particularly evident in Ahmari's subsequent works [80,81] (90 citations and 57 citations respectively).

Clusters #2, #3, and #4 collectively reveal three distinct but complementary research directions: advanced material processing and characterization (Cluster #2), innovative applications and sustainability optimization (Cluster #3), and fundamental understanding of geopolymerization processes (Cluster #4). The chronological development across these clusters (2012–2024) demonstrates the field's evolution from basic material understanding to sophisticated applications and optimization techniques. The high citation counts for recent works suggest continuing innovation and practical relevance in the field.

Cluster #5, with 32 members, represents a well-defined research community focused on mining byproduct utilization. The most influential work in this cluster [36] is a study on sustainable copper slag utilization in self-compacting concrete, garnering 167 citations. This research demonstrated the successful incorporation of copper slag as fine aggregates in combination with supplementary cementitious materials, establishing both technical viability and environmental benefits. The study's high citation count indicates its significant impact on subsequent research directions in sustainable construction materials. A complementary study by the same authors, focusing on durability assessment (83 citations), extended the understanding of long-term performance implications. This work addressed critical concerns regarding the stability and longevity of copper slag-incorporated concrete, providing essential validation for practical applications. The sequential nature of these publications demonstrates a systematic approach to establishing copper slag as a viable construction material.

A key contribution is a series of studies examining various applications of copper slag [82], including its use as concrete sand, cementitious material, and in road pavement applications. Although these works show lower citation counts individually, their collective contribution provides a broad framework for copper slag utilization across different construction applications. This approach has been instrumental in establishing the versatility of copper slag as a construction material. The cluster demonstrates strong thematic coherence across three main areas: material performance, environmental sustainability, and economic viability.

Cluster #7 represents a highly focused research community dedicated to recycling industrial waste in concrete applications. This cluster demonstrates a clear progression in understanding and implementing mining waste materials in construction applications. The research is anchored by Onuaguluchi's studies [61,83], which systematically investigated copper tailings utilization in cement-based materials. Their most cited work (85 citations) established fundamental principles for recycling copper tailings as cement mortar additives. This systematic approach was complemented by a study [84] (145 citations) on autoclaved aerated concrete using combined coal gangue and iron ore tailings, marking a shift toward more complex waste utilization strategies.

The cluster's research exhibits three interconnected themes: material properties and performance optimization, waste incorporation strategies, and environmental-economic considerations. The progression from foundational work [85] to more recent studies demonstrates increasing sophistication in combining different waste materials and optimizing their performance in concrete applications. This evolution reflects a growing understanding of material behavior and practical implementation requirements.

A significant focus within this cluster is addressing practical challenges while maintaining environmental safety, particularly regarding toxic metal immobilization. This has driven research toward advanced characterization methods and improved processing techniques. The research impact extends beyond academic findings to practical implementation guidelines and quality control protocols, suggesting a mature field ready for industrial application.

Cluster #8 represents a contemporary research focus on mining waste utilization. This cluster is particularly noteworthy for its recent publications, with most major works appearing in 2023–2024, suggesting an active and evolving research area. The research demonstrates a clear focus on iron ore tailings utilization, as evidenced by work on alkali-activated cement for dry stacking [58] and the investigation of iron ore tailings in pavement applications [86]. These studies represent advances in practical applications while addressing environmental concerns. The cluster builds upon foundational work [87], which established key principles for mining waste incorporation in civil engineering applications.

A significant shift toward sustainability is evident in the cluster's recent publications, including an assessment of environmental, economic, and social sustainability [88], and work focusing on low-carbon stabilization techniques [89], demonstrating the field's evolution toward holistic sustainability approaches. This trend is supported by earlier work [90,91], which established fundamental principles for sustainable waste utilization.

The cluster addresses three critical aspects: sustainable construction techniques through geopolymer development, enhanced stabilization methods using alkali-activated binders, and environmental impact assessments. A key challenge emerging from this research is the balance between economic viability and environmental protection, particularly when dealing with potentially hazardous mining by-products. The recent nature of most publications suggests this field is actively developing solutions to these challenges while maintaining focus on practical implementation.

Cluster #10 represents a highly focused research area on mine tailings utilization, particularly molybdenum tailings. The cluster is notable for its very recent publications, with all major citing articles from 2024, indicating an emerging and rapidly developing research direction. The research demonstrates significant focus on molybdenum tailings applications across various construction contexts. Recent work investigates road performance using cement and fly ash stabilization [92] and explores innovative egg-structured ceramsite preparation [93]. These studies build upon foundational work [94,95], which established fundamental principles for tailings utilization in construction materials, both receiving 39 citations.

A clear progression in research sophistication is evident, moving from basic material applications to specialized performance aspects. Previous works, such as a study on frost resistance [88] and an investigation of bond behavior in concrete-filled steel tubes [96], demonstrate increasing technical complexity. This evolution is supported by earlier work [54,97], which established key principles for sustainable waste utilization in construction.

The cluster addresses three main research themes: mechanical property enhancement through innovative material combinations, environmental benefits from industrial byproduct recycling, and sustainable construction material development. A significant challenge emerging from this research is balancing material performance with environmental safety, particularly regarding toxicity concerns and long-term durability under various environmental conditions. The cluster's recent nature suggests active development in addressing these challenges while maintaining focus on practical implementations.

Cluster #15 represents a specialized research focus on sustainable cementitious materials. Despite its small size (6 members), the cluster demonstrates significant impact through highly cited works, particularly in the development of innovative sustainable construction materials. The research is anchored by influential papers [85,98], which collectively garnered 280 citations. The first study, focusing on recycled tire rubber for concrete repairs (100 citations), and the second, investigating green lightweight engineered cementitious composites (180 citations), established fundamental principles for incorporating waste materials in high-performance construction applications.

The cluster addresses key sustainability challenges through three main approaches: the incorporation of industrial by-products, optimization of mechanical and thermal properties, and enhancement of durability characteristics. A significant recurring challenge is the balance between sustainability goals and performance requirements, particularly when incorporating waste materials that may affect structural integrity or require additional processing. The high citation counts of the key papers suggest that the research has successfully addressed many of these challenges while maintaining practical applicability.

Cluster #20 represents a highly focused research area on sustainable concrete materials. Despite its small size (four members), the cluster demonstrates significant impact through influential publications focusing on iron ore tailings utilization in concrete. The research is led by an evaluation of iron ore tailings characteristics and concrete properties [70] (104 citations), establishing a fundamental understanding of these materials in construction applications. This work is complemented by a study on sustainable concrete production using Germano dam tailings [74] (62 citations), and an investigation of workability enhancement using HPMC [99]. These studies build upon earlier work [100], which provided foundational principles for sustainable concrete development.

The cluster addresses two critical challenges in sustainable concrete development: optimizing mechanical properties while incorporating mining by-products, and ensuring long-term durability and safety. The research demonstrates clear progression from basic material characterization to practical applications, with increasing focus on workability and performance optimization. The recent nature of the major publications (all from 2021) suggests an active field responding to growing demands for sustainable construction solutions.

Cluster #21 represents an emerging research area focused on sustainable mine tailings utilization. Though small in size (three members), this cluster demonstrates cutting-edge research directions in sustainable construction materials, particularly noteworthy for its very recent publications, all from 2024. The research is characterized by innovative approaches, as evidenced by work on ultra-high-performance geopolymer concrete using iron ore tailings [101], and an investigation of 3D printing applications with coal fly ash and superfine iron tailings [10]. These studies build upon recent foundational work [102,103], demonstrating rapid advancement in processing techniques and applications.

The cluster reveals three emerging research directions: advanced geopolymer development incorporating mine tailings, innovative manufacturing processes including 3D printing technologies, and fundamental understanding of chemical interactions in tailings-based materials. A key focus is optimizing material performance while addressing environmental concerns, particularly regarding toxicity and leaching behavior. The recent nature of all publications indicates an active research front responding to increasing demands for sustainable construction solutions.

3.5. Centrality Co-Citation Analysis

Centrality metrics identify publications that play crucial connecting roles across research domains due to their diverse co-citation links. Analyzing these influential works reveals key knowledge integrators promoting broader synthesis in the field. Table 8 presents the top 10 references based on centrality.

Table 8. The top 10 most important references found in the co-citation network, ranked by betweenness centrality.

Centrality	Node Name	DOI
0.10	[85] Huang XY, 2012, Constr Build Mater, V27, P1	https://doi.org/10.1016/j.conbuildmat.2011.08.034
0.09	[68] Duan P, 2016, Constr Build Mater, V118, P76	https://doi.org/10.1016/j.conbuildmat.2016.05.059
0.09	[79] Han FH, 2017, Powder Technol, V315, P322	https://doi.org/10.1016/j.powtec.2017.04.022
0.09	[104] Yang CM, 2014, Constr Build Mater, V70, P36	https://doi.org/10.1016/j.conbuildmat.2014.07.075
0.08	[80] Ahmari S, 2013a, Constr Build Mater, V40, P1002	https://doi.org/10.1016/j.conbuildmat.2012.11.069
0.08	[105] Osinubi KJ, 2015, Transp Geotech, V5, P35	https://doi.org/10.1016/j.trgeo.2015.10.001
0.07	[106] Young G, 2019, Constr Build Mater, V197, P152	https://doi.org/10.1016/j.conbuildmat.2018.11.236
0.07	[81] Ahmari S, 2013b, Constr Build Mater, V44, P743	https://doi.org/10.1016/j.conbuildmat.2013.03.075
0.06	[107] Wei B, 2017, Constr Build Mater, V145, P236	https://doi.org/10.1016/j.conbuildmat.2017.03.234
0.06	[108] Thomas BS, 2013, Constr Build Mater, V48, P894	https://doi.org/10.1016/j.conbuildmat.2013.07.075

These high-centrality references play crucial connecting roles across different research domains in mining waste recovery and construction materials utilization. The article [85] with the highest betweenness centrality (0.10) establishes a fundamental connections between waste characterization and concrete applications. Three papers share the second-highest centrality (0.09), with works on bridging geopolymer research with iron ore tailings applications [68]; linking powder technology with cementitious materials [79]; and connecting material properties with performance assessment [104].

The first article (with centrality 0.08 demonstrates a significant influence in connecting geopolymer research with broader construction applications [80], while the second article with centrality 0.08 bridges mining waste utilization with geotechnical engineering [105].

Next, there are two papers with 0.07 centrality, that link environmental considerations with material performance [81,106].

The network analysis is completed by the final works on the table [107,108], both with centrality 0.06, connecting studies on mechanical activation and supplementary cementitious materials, respectively. These references collectively demonstrate the field's integration of materials science, environmental engineering, and construction technology, facilitating knowledge transfer across different research domains.

This high-centrality network reveals the crucial role these papers play in bridging different aspects of the field, from fundamental materials characterization to practical applications, while maintaining focus on both technical performance and environmental considerations. Their influence extends beyond their immediate research areas, facilitating the development of a more comprehensive and integrated approach to sustainable construction materials.

The referenced works serve as crucial connectors in the research landscape, enabling the exchange of knowledge across various specializations and thematic areas. Their elevated centrality metrics highlight their significance in bridging disparate research domains, thus promoting a more comprehensive and interdisciplinary approach to the study of mining waste utilization in construction materials. These publications play a pivotal role in synthesizing insights from different subfields, ultimately contributing to a more holistic understanding of the challenges and opportunities in this area of study.

3.6. Co-Citation Burst Analysis

To identify key references and emerging research trends, we performed a burst detection analysis on the reference co-citation network. This method highlights publications that have experienced a rapid increase in citations over a specific time period, indicating growing influence and impact in the field. Burst detection reveals articles that have gained significant attention within a short timeframe, suggesting that they represent important developments or new directions in the research area. Tables 9 and 10 present the top references exhibiting strong citation bursts, ranked by the duration and strength of their burst activity. Table 9 lists the top 10 references with the longest-lasting citation bursts, indicating sustained impact on the field of mining waste recovery and tailings utilization in construction materials. Table 10 lists the top 10 references with the highest burst strength, indicating works with a high impact on the field, but not necessarily as long-lasting as those shown in Table 9. These bursting references provide insights into the evolving focus of research in this domain, highlighting topics and approaches that have gained particular traction among researchers over time.

Table 9. Top 10 references with strong bursts listed by burst duration.

Reference	Year	Burst Strength	Burst Begin	Burst End
[84] Wang CL, 2016, Constr Build Mater, V104, P109, https://doi.org/10.1016/j.conbuildmat.2015.12.041,	2016	9.35	2016	2021
[109] Fontes WC, 2016, Constr Build Mater, V112, P988, https://doi.org/10.1016/j.conbuildmat.2016.03.027	2016	8.65	2016	2021
[85] Huang XY, 2012, Constr Build Mater, V27, P1, https://doi.org/10.1016/j.conbuildmat.2011.08.034	2012	8.52	2012	2017
[15] Shettima AU, 2016, Constr Build Mater, V120, P72, https://doi.org/10.1016/j.conbuildmat.2016.05.095	2016	20.54	2017	2021
[41] Ma BG, 2016, J Clean Prod, V127, P162, https://doi.org/10.1016/j.jclepro.2016.03.172	2016	12.25	2017	2021
[13] Ahmari S, 2012, Constr Build Mater, V29, P323, https://doi.org/10.1016/j.conbuildmat.2011.10.048	2012	10.13	2012	2016

Table 9. *Cont.*

Reference	Year	Burst Strength	Burst Begin	Burst End
[68] Duan P, 2016, Constr Build Mater, V118, P76, https://doi.org/10.1016/j.conbuildmat.2016.05.059	2016	9.63	2017	2021
[83] Onuaguluchi O, 2016, J Clean Prod, V112, P420, https://doi.org/10.1016/j.jclepro.2015.09.036	2016	5.91	2017	2021
[101] Huang XY, 2013, Constr Build Mater, V44, P757, https://doi.org/10.1016/j.conbuildmat.2013.03.088	2013	3.73	2013	2017
[35] Zhao SJ, 2014, Constr Build Mater, V50, P540, https://doi.org/10.1016/j.conbuildmat.2013.10.019	2014	15.43	2016	2019

Table 10. Top 10 references with strong bursts listed by burst strength.

Reference	Year	Burst Strength	Burst Begin	Burst End
[15] Shettima AU, 2016, Constr Build Mater, V120, P72, https://doi.org/10.1016/j.conbuildmat.2016.05.095	2016	20.54	2017	2021
[35] Zhao SJ, 2014, Constr Build Mater, V50, P540, https://doi.org/10.1016/j.conbuildmat.2013.10.019	2014	15.43	2016	2019
[41] Ma BG, 2016, J Clean Prod, V127, P162, https://doi.org/10.1016/j.jclepro.2016.03.172	2016	12.25	2017	2021
[13] Ahmari S, 2012, Constr Build Mater, V29, P323, https://doi.org/10.1016/j.conbuildmat.2011.10.048	2012	10.13	2012	2016
[109] Cheng YH, 2016, Constr Build Mater, V118, P164, https://doi.org/10.1016/j.conbuildmat.2016.05.020	2016	9.65	2019	2021
[68] Duan P, 2016, Constr Build Mater, V118, P76, https://doi.org/10.1016/j.conbuildmat.2016.05.059	2016	9.63	2017	2021
[84] Wang CL, 2016, Constr Build Mater, V104, P109, https://doi.org/10.1016/j.conbuildmat.2015.12.041	2016	9.35	2016	2021
[110] Kiventerä J, 2016, Int J Miner Process, V149, P104, https://doi.org/10.1016/j.minpro.2016.02.012	2016	9.23	2019	2021
[111] Cai LX, 2016, Constr Build Mater, V128, P361, https://doi.org/10.1016/j.conbuildmat.2016.10.031	2016	8.68	2018	2021
[109] Fontes WC, 2016, Constr Build Mater, V112, P988, https://doi.org/10.1016/j.conbuildmat.2016.03.027	2016	8.65	2016	2021

Our initial burst analysis focused on the duration of citation bursts, with results presented in Table 9. This analysis identified key papers, reviews, and articles that introduced significant new approaches in mining waste utilization for construction materials.

The citation burst analysis reveals significant temporal patterns in the influence of key publications in mining waste utilization for construction materials. The analysis identified several works with prolonged impact periods, particularly from 2016 to 2021, demonstrating the field's maturation and increasing sophistication.

The work that shows the highest burst strength (20.54) and a sustained impact from 2017 to 2021 focuses on iron ore tailings as concrete aggregate [15]. This is complemented by a study on utilizing iron ore tailings in ultra-high-performance concrete [35] (burst strength 15.43, 2016–2019). Another highly relevant work addressing clean production aspects of tailings utilization [41] demonstrates significant influence (burst strength 12.25, 2017–2021).

Early foundational works [13,85] established fundamental approaches to waste utilization, with bursts starting from 2012 up to 2017 with strengths of 10.13 and 8.52, respectively. These works maintained extended influence periods, indicating their role in shaping subsequent research directions.

A cluster of 2016 publications [68,84,109] shows particularly strong and sustained impact through 2021, with burst strengths of 9.35, 9.63, and 8.65, respectively. This convergence of influential works in 2016 marks a significant advancement in research approaches and applications, particularly in sustainable construction materials development.

Several 2016 publications appear in both tables, indicating their significant impact in terms of duration and strength of influence. These include studies that explore different aspects of mining waste utilization in construction materials [68,84,112]. The work of Ahmari and Zhang [13] is notable for its presence in both tables, showing a strong burst (10.54) from 2012 to 2016. This study on eco-friendly bricks from copper mine tailings represents an early influential work that influenced subsequent research directions. The analysis also reveals emerging trends indicating growing interest in mine tailings for alkali activation applications [110] (strong burst from 2019 to 2021). Similarly, a recent burst (2019–2020) suggests increased attention to iron recovery from tailings for construction use [113].

This burst analysis illustrates the field's evolution from initial explorations of mining waste in concrete to more diverse and sophisticated applications, including geopolymers, alkali-activated materials, and specialized construction products. The sustained impact of papers on iron ore tailings suggests this remains a key research area. The analysis also indicates a trend towards more sustainable and eco-friendly approaches in mining waste utilization for construction materials.

4. Discussion

Our scientometric analysis reveals a rapidly growing body of literature on mining waste recovery and tailings utilization in construction materials since 2010. Environmental sciences and engineering form the core of this interdisciplinary field, with significant contributions from materials science [18], geochemistry [17], and sustainable technologies [72]. The prominence of green technologies and sustainable construction themes underscores the positioning of mining waste utilization as an eco-friendly strategy in construction.

The research focus has evolved from initial waste characterization to optimization for field implementation and commercial adoption. Early efforts centered on understanding waste properties have given way to more sophisticated recycling methods. These include mechanical activation techniques [39], alkali activation processes [110], thermal treatment methods [84], and hybrid approaches combining multiple activation strategies [68]. Selection criteria and performance enhancement studies have become increasingly important [15,41]. Innovative solutions through alkali activation and geopolymerization have gained particular traction [110], while increased field testing signals a move toward practical applications [35].

Keyword analysis highlights the focus on strength development, microstructure, and durability of mining waste-incorporated materials [68,84]. Cluster analysis reveals efforts in waste activation methods [1], geopolymer applications [57], material variability [72], and long-term performance [18]. Highly cited works include seminal reviews on tailings utilization in cement and concrete [72] and innovative waste recovery approaches [51]. Sustained citation bursts for studies on iron ore tailings [15] and geopolymers [13] confirm their enduring impact. Bridging publications link waste characterization [85] with performance assessments [35] and practical applications [68], facilitating knowledge exchange across the field.

The research landscape highlights studies on waste–binder interactions [114] and in situ demonstrations [59]. A temporal analysis shows an early focus on basic properties [13,85]), followed by diversification into variable conditions [35], incremental solutions [41], and performance evaluations [18].

In general, the field demonstrates increasing sophistication and interdisciplinarity, recognizing systemic interactions between waste properties, activation methods, and construction environments [51,57]. The trajectory indicates a shift from conceptual proofs to translational testing, moving towards integrated, sustainable construction solutions [54].

Finally, we summarize some key technologies and developments in Figure 4, showcasing the evolution of mining waste recycling methods in construction through time.

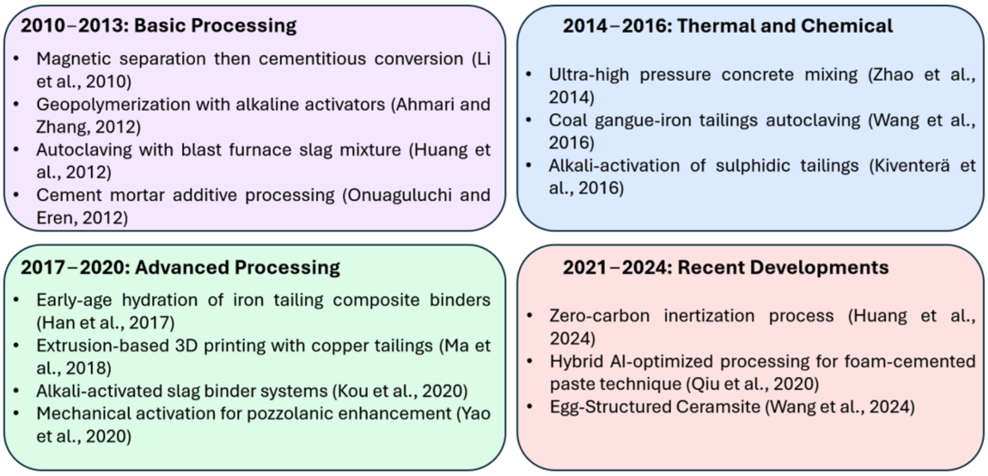

Figure 4. Technologies and developments of waste mining recycling methods in construction, presenting four general stages from 2010 to 2013 (basic processing) [13,40,61,85], 2014 to 2016 (thermal and chemical methods) [35,84,110], 2017 to 2020 (advanced processing) [17,34,46,79], and 2021 to 2024 (recent developments) [47,93,101].

4.1. Limitations

This scientometric analysis has certain constraints. Reliance on a single bibliographic database may have excluded relevant research published in non-indexed sources. Despite efforts to maximize diversity, regional, linguistic, and accessibility biases may persist. Resource limitations precluded a detailed manual review of abstracts, which could have further refined our study selection. The inherent complexity of network visualization may obscure specialized subdomains containing important nuances [115]. Additionally, algorithmic clustering, while efficient, may not fully capture the field's heterogeneity [116].

Our focus on English-language publications may have underrepresented valuable research from non-Anglophone countries. The dynamic nature of the field means that the most recent developments might not be fully reflected in the published literature. Lastly, while citation metrics provide valuable insights into research impact, they do not always directly correlate with work quality or practical significance. Factors such as self-citation and the Matthew effect in science can influence these metrics [117].

4.2. Significance and Contributions

This scientometric analysis contributes to the field of mining waste recovery and tailings utilization for construction materials in several ways. It provides a systematic review of the literature using advanced bibliometric techniques, offering a comprehensive view of the field's evolution. The cluster analysis identified 12 thematic clusters, illustrating the diversity of research areas and potential future directions. The temporal analysis revealed a progression from basic waste characterization to more advanced applications, indicating the field's maturation.

Our analysis reveals significant research gaps in the current literature. Long-term durability studies extending beyond 10 years of exposure remain notably scarce, limiting our understanding of material performance over extended periods. The field also lacks sufficient research on scalable activation methods suitable for industrial implementation, creating a gap between laboratory findings and practical applications. The absence of standardized testing protocols and quality control measures has emerged as a significant limitation, particularly for commercial adoption. Current research inadequately addresses material behavior under extreme environmental conditions, leaving uncertainty about performance in challenging settings. Additionally, the long-term environmental impacts and leaching behavior of mining waste in construction materials remain incompletely understood, necessitating more comprehensive studies. Economic feasibility studies for large-scale applications are also insufficient, creating uncertainty about commercial viability.

These research gaps indicate promising directions for future investigations while highlighting the need for more comprehensive approaches to sustainable construction materials development. This study underscores the importance of bridging laboratory research with industrial applications through systematic investigation of scaling effects, standardization requirements, and economic viability.

Finally, we highlight that this research aligns with several United Nations Sustainable Development Goals, particularly SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). By examining the connections between academic research and practical applications, this study aims to contribute to the advancement of sustainable solutions in both the mining and construction industries.

5. Conclusions

This scientometric analysis offers a comprehensive view of the evolution in mining waste recovery and tailings utilization for construction materials since 2010. Our analysis reveals key patterns in the growth and diversification of this emerging research area. The field has experienced rapid expansion, evolving from fundamental studies on waste properties to practical applications and sustainability assessments. Environmental sciences, materials engineering, and sustainable technologies have converged to drive significant innovations in waste processing and utilization methods.

Our analysis highlights the field's maturation towards integrated, sustainable solutions, particularly in developing advanced waste activation mechanisms and innovative manufacturing processes. The research community has successfully moved from basic characterization studies to sophisticated performance-oriented applications, demonstrating an increasing capability in creating high-performance construction materials from mining waste. The establishment of standardized testing protocols and the integration of environmental safety considerations with technical performance requirements mark significant achievements in the field's development.

Emerging research directions identified through our analysis include the exploration of advanced characterization techniques for waste activation mechanisms, comprehensive life cycle assessments, and techno-economic analyses of mining waste-based construction materials. Field demonstrations of integrated systems incorporating various types of mining waste have become increasingly important, alongside the development of novel manufacturing processes such as 3D printing applications. These advancements are supported by growing interdisciplinary collaborations addressing the complex challenges associated with large-scale implementation.

The cluster analysis revealed distinct thematic areas demonstrating the field's diversity and evolution, while temporal analysis showcased a clear progression toward more sophisticated applications. By identifying specific research gaps and emerging trends, such as the need for more research on waste activation mechanisms and life cycle assessments, we provide guidance for future research investigations. The strong alignment with sustainable development goals indicates the broader societal impact of these research efforts.

Looking forward, the field appears well-positioned for continued growth through the integration of emerging technologies, development of standardized practices, and enhancement of industrial scalability. The emphasis on environmental performance and academic–industry partnerships suggests a promising trajectory for future innovations. These developments carry significant practical implications for industry practitioners seeking sustainable waste management solutions, researchers exploring new directions in construction materials, and policy makers developing regulations for waste utilization.

Our findings contribute significantly to advancing sustainable practices in both mining and construction industries. This research establishes a solid foundation for future innovations in waste utilization and environmental protection, while demonstrating the field's capacity for continued evolution and practical impact. The convergence of environmental sciences, materials engineering, geochemistry, and sustainable technologies has fostered collaborative and innovative approaches that promise to drive further advancements in sustainable construction practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su162310314/s1, File S1: High-resolution version of the Co-citation Analysis Network; File S2: High-resolution version of the Keyword Analysis Network; File S3: High-resolution version of the Subject Categories Network; File S4: Raw Publication Lists (part 1 of two files, as generated by Web of Science); File S5: Raw Publication Lists (part 2 of two files, as generated by Web of Science); File S6: Compressed file with CiteSpace Processed Data.

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