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Recent Advances in Mining and Metallurgy: A Systematic Literature Review and Bibliometric Mapping of Research Trends

Zanescaya Wirasangka
Mineral and Coal – Ministry of Energy and Mineral Resources, Indonesia
Email: zanescayawirasangka@gmail.com

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ABSTRACT

Mining and metallurgy are increasingly influenced by growing demand for critical metals, digitalization, and the transition toward sustainable and circular production systems. This study aimed to map recent advances, dominant research themes, methodological trends, and knowledge gaps across the interconnected fields of mining and metallurgy. A systematic literature review following the PRISMA 2020 framework was combined with bibliometric analysis and keyword mapping using VOSviewer. The review analyzed 55 Scopus-indexed open-access articles published between 2025 and 2026 across three journals. Five thematic clusters were identified: physical metallurgy, alloy engineering, and manufacturing; extractive metallurgy and hydrometallurgy; mineral processing, geochemistry, and deposit exploration; mining engineering, geotechnics, and safety; and artificial intelligence, automation, and process digitalization. Experimental characterization integrated with modelling emerged as the dominant research approach, while waste valorization, critical metal recovery, continuous monitoring, and artificial intelligence represented prominent research trends. However, the literature remained fragmented, with limited integration among extraction processes, materials design, environmental assessment, and industrial process control. Many automation and machine-learning applications were also validated primarily through laboratory-scale experiments or simulations. This study concludes that future development requires industrial-scale validation, life-cycle sustainability assessment, interoperable datasets, and cross-disciplinary digital twin frameworks that connect mineral extraction, metallurgical processing, and intelligent control systems to support more sustainable, efficient, and resilient resource production worldwide.

INTRODUCTION

Mining and metallurgy form the backbone of the global raw material supply chain, linking resource exploration and extraction with mineral processing, refining, and the production of functional metals. Over the past decade, this supply chain has faced increasing pressure from the energy transition and electrification, which have substantially increased demand for critical metals such as nickel, copper, tungsten, tin, vanadium, antimony, and rare earth elements. Research in both fields has responded by becoming increasingly dynamic and interdisciplinary, integrating knowledge from geoscience, materials engineering, computational methods, and environmental engineering (Boustila et al., 2026; Guillen & Iriarte, 2026; Hoa et al., 2026; Lee, 2026; Lotsu et al., 2026; Rostami & Pour, 2026).

The challenges within this supply chain become more apparent when upstream and downstream processes are considered together. On the supply side, critical metals are unevenly distributed and require different extraction and processing strategies depending on deposit characteristics, while downstream industries increasingly demand materials with improved properties, including lower weight, higher thermal resistance, and enhanced corrosion resistance (Abdukodirov & Benndorf, 2026; Bulgurcu & Ozturk, 2026; Jiao et al., 2026; Miranda Ordóñez et al., 2026; Urolov et al., 2026). Consequently, challenges at the mining stage, such as determining the economic recovery potential of low-grade ore deposits, are closely connected with metallurgical requirements related to achieving desired material properties and microstructures. Environmental assessments further emphasize this interdependence, as life-cycle studies demonstrate that the environmental impacts associated with metal production vary considerably among commodities and are influenced by both ore characteristics and processing pathways (Afanassieff et al., 2026; H. Li et al., 2026; Öztürk & Altay, 2026; Sun et al., 2026; Xu et al., 2026). Therefore, improvements at one stage of the supply chain may be limited if the entire production system is not considered holistically, supporting the need for a broad cross-domain review.

Digitalization represents another major factor reshaping mining and metallurgy, evolving from basic process monitoring into integrated technological approaches commonly associated with Mining 4.0 and smart mining (Çetinkaya et al., 2026; Wang et al., 2026). These approaches combine sensing technologies, connectivity, simulation, data analytics, and machine learning to improve decision-making and operational efficiency. Industry-wide reviews indicate that the Internet of Things (IoT) and artificial intelligence (AI) have become dominant themes in applied research, with applications spanning exploration, extraction, mineral processing, and mine closure (Macchiarella et al., 2026; Putri et al., 2026; Su et al., 2026; Wu et al., 2026). Studies focusing on machine learning in mineral processing have organized research around data-driven modelling, fault detection, and machine vision while emphasizing the importance of distinguishing between synthetic datasets, laboratory experiments, and industrial-scale validation. Recent reviews have further classified this research area based on mining life-cycle stages and mineralogical data applications, consistently highlighting that real-world validation remains a major challenge despite rapid algorithmic development (Chen et al., 2026; X. Li et al., 2026; Zubair et al., 2026). Therefore, artificial intelligence should be considered both a cross-cutting technological enabler and a distinct research theme within mining and metallurgy.

Sustainability considerations represent a third major force transforming the field, particularly through the adoption of circular economy principles in mining waste management. Mining tailings in mature mining regions have been identified as potential secondary resources containing valuable critical metals, although challenges remain regarding economic feasibility, regulatory frameworks, and accurate characterization of waste composition. Due to the scale and complexity of mining waste, effective strategies require combinations of waste reduction, reprocessing, recycling, upcycling, downcycling, and future resource recovery planning, with digital technologies supporting the identification of high-value opportunities. Rare earth elements demonstrate this transition, as research has explored recovery opportunities from industrial waste streams, mining residues, and electronic waste. In addition, biotechnological recovery approaches, traditionally applied to metals such as copper, uranium, and gold, have expanded toward polymetallic resources and rare earth recovery. These developments increasingly connect extractive metallurgy with recycling and secondary resource processing, reducing the distinction between primary extraction and resource recovery.

Despite the extensive volume of individual studies, comprehensive systematic synthesis that examines mining and metallurgy as an interconnected research domain remains limited. Existing reviews generally focus on specific topics, such as flotation processes, particular hydrometallurgical methods, or mining automation, rather than characterizing publication trends across the broader mining–metallurgy interface. This research gap motivated the present study, which combined a Systematic Literature Review (SLR) based on the PRISMA 2020 framework with bibliometric mapping. The SLR component established transparent search strategies, eligibility criteria, and screening procedures to develop a reproducible research corpus, while bibliometric analysis was used to identify publication patterns, thematic clusters, and dominant keywords. These approaches were considered complementary, as bibliometric analysis without controlled selection criteria may reflect database retrieval bias, whereas an SLR without bibliometric analysis may provide limited insight into broader research structures and emerging trends.

This study was guided by four research questions: the characteristics and distribution of recent mining and metallurgy publications based on journal, publication year, quartile ranking, and publisher; the dominant research clusters and themes within the recent literature; the methods, technologies, and approaches most frequently applied or emerging in the field; and the research gaps and future directions identified from existing studies. The overall objective was to systematically map recent advances and research trends in mining and metallurgy, providing a foundation for academics, researchers, and practitioners in developing future research agendas.

The contribution of this study was threefold. First, it provided an integrated characterization of mining and metallurgy research trends rather than focusing on a single specialized topic, enabling observation of relationships and interactions between the two domains. Second, by limiting the corpus to Scopus-indexed open-access journal articles within a recent publication period, the study provided a transparent and verifiable research snapshot while maintaining methodological consistency. Third, by comparing identified thematic patterns with findings from previous domain-specific reviews, the study distinguished emerging research directions from recurring themes and provided a clearer basis for future research development.

METHOD

Review Design and Protocol

This study used a Systematic Literature Review (SLR) design following the PRISMA 2020 reporting framework and established SLR procedures. The bibliometric analysis was conducted using standard methods, and keyword co-occurrence networks were mapped using VOSviewer. PRISMA 2020 was applied to ensure a transparent and reproducible review process through the stages of identification, screening, eligibility assessment, and inclusion.

Research Questions

The four research questions (RQ1-RQ4) stated in the Introduction guided the entire extraction and synthesis process. RQ1 was answered through descriptive bibliometric analysis, RQ2 through thematic clustering, RQ3 through an analysis of methods and technologies, and RQ4 through a narrative synthesis of research gaps and future agendas.

Data Sources and Search Strategy

Literature was searched across Scopus, Web of Science, and the Directory of Open Access Journals (DOAJ), with a deliberate focus on Scopus-indexed open-access journals so that every article could be retrieved and verified in full. The search window was limited to the most recent issues (2025-2026) to capture the current state of the art, using a search string combining terms such as mining, mineral processing, metallurgy, hydrometallurgy, pyrometallurgy, extractive metallurgy, and alloy with terms such as recovery, leaching, microstructure, flotation, characterization, and process, restricted to open-access, Scopus-indexed sources.

Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were set to safeguard the relevance and quality of the studies retained, as summarised in Table 1.

Table 1. Study Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles indexed in Scopus	Conference proceedings, book chapters, abstracts, editorials, and the like
Open-access journals (full text retrievable)	Paywalled articles or full text unobtainable
Published within 2025-2026	Published outside the defined window
Focused on mining and/or metallurgy	Outside the mining/metallurgy scope
Empirical studies or scholarly reviews	Opinion/non-scholarly items, or not in English/Indonesian

Study Selection (PRISMA 2020 Flow)

Study selection followed the four PRISMA 2020 stages. During identification, a set of records was gathered from the databases and indexes, after which duplicates were removed. Screening then examined titles and abstracts before full texts were retrieved. The eligibility stage checked each full text against the inclusion and exclusion criteria. In the end, 55 primary studies were retained as the review corpus.

Data Extraction and Bibliometric Analysis

Data were extracted into a structured worksheet capturing author, title, journal, volume/issue/year, DOI, access link, publisher, indexing/quartile, and theme. Descriptive bibliometric analysis covered the distribution by journal, year, quartile, and publisher (addressing RQ1). Thematic clustering was performed by coding keywords and title topics (addressing RQ2), and a keyword co-occurrence network was mapped in VOSviewer to reveal themes that sit close to one another.

RESULT AND DISCUSSION

RQ1: Publication Characteristics and Distribution

Fifty-five primary articles were analysed. Most came from the Journal of Mining and Metallurgy, Section B: Metallurgy (n = 35), followed by Mining (n = 10) and Minerals (n = 10). Thirty articles appeared in 2026 and 25 in 2025, making the corpus decidedly current. By quartile, there were 10 Q1 articles (Minerals), 10 Q2 articles (Mining), and 35 Q3 articles (JMMB); by publisher, MDPI accounted for 20 articles and the University of Belgrade for 35, as summarised in Table 2.

Table 2. Bibliometric Distribution of the 55 Primary Articles

Journal (Publisher)	Count	Quartile	Year
Journal of Mining & Metallurgy B: Metallurgy (Univ. of Belgrade)	35	Q3	2025-2026
Mining (MDPI)	10	Q2	2026
Minerals (MDPI)	10	Q1	2026
Total	55	-	2025-2026

This distribution shows that physical and extractive metallurgy drive the corpus, consistent with the broad remit of JMMB, while the MDPI titles reinforce the mining side through mineral processing and geosciences. The quartile profile and thematic profile are not independent of one another, since the Q3 title contributes most physical-metallurgy work while the two Q1-Q2 titles supply the mining-side material; cluster counts should therefore be read as a description of this literature rather than as an estimate of the field's true composition. With most articles carrying a 2026 imprint, the corpus captures the research front rather than the settled canon, which is why the analysis relies on keyword co-occurrence and thematic coding rather than citation-based indicators that recent papers have not yet had time to accumulate.

RQ2: Dominant Research Themes

Thematic coding sorted the 55 articles into five main clusters, listed in Table 3: physical metallurgy, alloy engineering and manufacturing (n = 23); extractive metallurgy and hydrometallurgy (n = 11); mineral processing, geochemistry and deposit exploration (n = 10); mining engineering, geotechnics and safety (n = 6); and artificial intelligence, automation and process digitalization (n = 5).

Table 3. Thematic Clusters and Study Counts

Thematic Cluster	Count	Share
Physical metallurgy, alloy engineering & manufacturing	23	42%
Extractive metallurgy & hydrometallurgy	11	20%
Mineral processing, geochemistry & deposit exploration	10	18%
Mining engineering, geotechnics & safety	6	11%
Artificial intelligence, automation & process digitalization	5	9%

The physical-metallurgy cluster dominates and centres on the process-microstructure-property relationship, spanning heat treatment and deformation of steels and superalloys, additive manufacturing, advanced and high-entropy alloys, and surface/corrosion behaviour. Beneath this variety lies a common design problem: how to place a desired microstructure into a component through thermal and mechanical history. What is largely absent from this cluster is sustained engagement with where the constituent metals actually come from, an absence the extractive-metallurgy cluster is actively working to close.

The extractive-metallurgy and hydrometallurgy cluster shows a clear pull toward recovering valuable and critical metals from waste streams that conventional accounting would classify as refuse, blast-furnace dust, fly ash, steel slag, copper cake, pet-coke cinder, and secondary sulphide concentrate, effectively treating them as ores. This is the technical half of the circular-economy programme that the wider literature has been arguing for, though it does not yet supply the environmental accounting (energy and reagent burden) needed to confirm the recovery is genuinely favourable.

The mineral processing, geochemistry, and deposit exploration cluster is where mining meets the geosciences, covering flotation innovations, advanced analytical instrumentation (LIBS-EPMA, online XRF), and ore-deposit characterisation across tungsten-tin, Fe-Mn, and Pb-Zn systems. Some studies in this cluster, such as saltworks-byproduct characterisation, already frame their subject in circular-economy terms, showing the boundary with the extractive cluster is thinner than the raw counts suggest. The analytical instrumentation reported here also functions as the sensing layer that any future smart-processing agenda would depend on.

The mining-engineering, geotechnics, and safety cluster, though the smallest alongside AI, covers ventilation modelling, dust mitigation, slope and stope stability monitoring, and environmental-footprint modelling, sharing a common preference for direct measurement over estimation. Notably, this cluster carries a disproportionately small share of the corpus relative to the practical weight of safety and environmental-incident risks it addresses.

The artificial-intelligence, automation, and digitalization cluster is the smallest by explicit count but is judged to be growing fastest and cutting across every other cluster, since many studies elsewhere in the corpus already use machine-learning-adjacent methods (multivariate statistics, response-surface optimisation, constitutive modelling) without being thematically filed as AI. The count of five articles should therefore be read as a floor rather than a full measurement of the theme's reach. The corpus also reproduces a validation gap flagged by earlier reviews of machine learning in this domain: most AI and automation studies here are still evaluated in simulated or laboratory settings rather than on operating plant, a pattern that appears structural rather than a temporary lag.

RQ3: Methods, Technologies, and Emerging Approaches

Experimental characterisation paired with modelling is the dominant approach across the corpus. Techniques such as XRD, SEM-EDS, EPMA, LIBS, and XRF are used widely to connect process with microstructure and composition, while additive manufacturing, severe plastic deformation, and equal channel angular pressing stand out as advanced processing routes. Statistical and experimental-optimisation methods, including Response Surface Methodology and multivariate statistics (PCA, HCA), are also on the rise, and the clearest emerging trend is the entry of artificial intelligence and machine learning into mining and metallurgical processes, from mineral-alteration mapping to smelting and thermodynamic optimisation, complemented by remote-monitoring technologies such as radar and InSAR on the safety front.

Characterisation techniques render an internal state observable, while modelling and statistical methods render an observed state predictable; the corpus's dominant move is to pair the two, which is what distinguishes contemporary work from purely empirical tradition. This has an important implication: the constitutive equations, phase diagrams, and response surfaces produced throughout the corpus are exactly the kind of extrapolable descriptions that digital-twin architectures require, yet the corpus never connects this technical substrate to the AI and automation cluster that would need it, arguably the single most consequential observation the mapping yields. A further underlying trend is the movement of measurement toward the process stream itself, evidenced by online XRF on conveyor belts, LIBS-based characterisation, and radar/InSAR slope monitoring, a shift from periodic sampling toward continuous observation that every downstream ambition in automation and digital twins presupposes.

RQ4: Research Gaps and Future Directions

Several gaps emerged from the synthesis. First, much of the automation and modelling work still rests on simulation or laboratory-scale evidence and needs validation under real operating conditions. Second, although recovering metals from waste is clearly growing, full integration of circular-economy principles with life-cycle sustainability assessment remains limited. Third, machine-learning applications remain fragmented across subtopics, with few studies linking predictive models to process-control systems end to end. Fourth, the two halves of a potential digital-twin programme, constitutive/thermodynamic modelling and process sensing on one side, machine-learning and automation studies on the other, are both present in the corpus but never composed together. Fifth, the evidence base is geographically and institutionally narrow, with technological prescriptions calibrated to particular ore types and regulatory settings that limit generalisation.

From these gaps, four future directions stand out: field validation and scale-up for new automation and hydrometallurgical processes; deeper cross-disciplinary integration linking mineral processing, extractive metallurgy, and data analytics toward a genuine smart-mining and smart-metallurgy vision; a stronger push on recovering critical metals and rare earth elements from secondary sources backed by measurable sustainability indicators; and development of digital-twin frameworks and AI-based process control. Turning these into concrete priorities, the study recommends treating field validation as a publishable contribution in its own right, embedding environmental accounting directly into process-development papers, reporting feedstock grade/volume/variability with the same rigour as primary-deposit studies, and operationalising cross-disciplinary integration as shared data and models between the extraction and materials communities rather than as an aspirational closing remark.

Cross-Cutting Synthesis

Reading the four research questions together reveals three patterns. First, the definition of an orebody is being redefined: roughly a quarter of the corpus, once boundary cases are included, treats waste streams such as blast-furnace dust, fly ash, steel slag, copper cake, and pet-coke cinder as feedstocks, directly matching the circular-economy and secondary-REE-supply literature. Second, the corpus is technically strong but systemically silent: individual studies establish mechanisms and optimise parameters to a high standard, but almost none situates its result within its wider supply or environmental chain, despite established tools for that accounting already existing. Third, there is a validation asymmetry: physical metallurgy validates on real material with a clear pass/fail outcome, while automation and modelling work still defers to simulated or laboratory-scale evidence, meaning the fastest-growing cluster also rests on the weakest evidential footing.

Together these patterns suggest the field is not short of technique but short of connective tissue, between upstream extraction and downstream materials design, between technical performance and environmental accounting, and between the model and the plant. This reframes the identified gaps as a single structural problem rather than four separate ones. One caveat applies throughout: a corpus of 55 articles from three journals over two years is a sample of a research front, not a census of a discipline, so the apparent lack of integration may partly reflect the sampling frame rather than the field itself, a question that broader replication could settle.

CONCLUSION

This study systematically reviewed and bibliometrically mapped 55 Scopus-indexed, open-access articles published between 2025 and 2026 to identify recent developments in mining and metallurgy. The findings revealed five major research clusters: physical metallurgy, alloy engineering, and manufacturing; extractive metallurgy and hydrometallurgy; mineral processing, geochemistry, and deposit exploration; mining engineering, geotechnics, and safety; and artificial intelligence, automation, and process digitalization. Experimental characterization combined with modelling emerged as the dominant methodological approach, while waste valorization, critical-metal recovery, continuous process monitoring, and artificial intelligence represented prominent emerging trends. Nevertheless, the literature remains fragmented across the mining–metallurgy value chain. Many studies demonstrate strong technical performance but provide limited integration between upstream extraction and downstream material design, environmental assessment, and industrial-scale process control. Moreover, automation and machine-learning applications are still predominantly validated through laboratory experiments or simulations rather than under actual operating conditions.

Future research should prioritize industrial-scale validation of automation, machine-learning, hydrometallurgical, and waste-recovery technologies across diverse geological, operational, and regulatory contexts. Researchers should integrate life-cycle assessment, energy and reagent consumption, feedstock variability, and measurable sustainability indicators directly into process-development studies to establish whether technical improvements also produce environmental and economic benefits. Greater collaboration among mineral processing, extractive metallurgy, materials engineering, and data science is also needed to develop interoperable datasets, digital-twin frameworks, and end-to-end AI-based process-control systems. In addition, subsequent reviews should expand the database coverage, publication period, journal selection, and geographic representation beyond the present corpus of 55 articles from three journals. Such expansion would allow the identified thematic patterns and integration gaps to be verified and would provide a more representative basis for developing a connected, sustainable, and digitally enabled mining and metallurgy research agenda.

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