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Review

Global Research Trends on Mining Activities and Environmental Impacts

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Abstract

This study utilized the Scopus database to examine 2,626 publications published between 2014 and 2024, involving 7,712 authors from 797 different sources, with an annual growth rate of 11.48%, focusing on the environmental impacts of mining activities. The analysis revealed the evolution of scientific research over time by identifying the most influential journals, as well as the most active countries, while highlighting the core concepts that define this research field. Keyword co-occurrence analysis and thematic mapping indicate a shift in research focus toward sustainability, particularly through life cycle assessment (LCA), reclamation strategies, and circular economy principles, rather than primarily concentrating on acid mine drainage, heavy metal contamination, and tailings management. Thematic evolution analysis further shows that "tailings", "risk assessment", and "sustainable development" function as central research themes in recent studies. Despite this progress, the mining industry continues to face challenges in integrating environmental, social, and health dimensions, as well as in establishing standardized frameworks for impact assessment and post-mining restoration. This bibliometric study provides a quantitative evaluation of global scientific output and highlights the need for interdisciplinary collaboration, improved risk assessment methodologies, and coordinated international policies to achieve sustainable mining practices.

Keywords: bibliometric analysis, mining impacts, research hotspots

Introduction

Mineral resources form the foundation of the manufacturing, construction, technology, and energy sectors that underpin modern society. The strategic importance of these resources in today's economy has facilitated the rapid expansion of the extraction industry [1]. However, this expansion has resulted in serious environmental issues, such as land degradation, water contamination, biodiversity loss, increased greenhouse gas emissions, and subsequent impacts on community health. In the face of growing social awareness and increasingly stringent regulations, balancing economic growth, environmental protection,

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and socially responsible mining has become more challenging, particularly in developing economies where institutional and regulatory capacities are weak.

Many scholars have responded to the challenges faced by the mining industry by examining its environmental impacts. Some have analyzed the environmental effects of mining and proposed various sustainability approaches, such as Good Mining Practices (GMPs), environmental impact assessment (EIA), life cycle assessment (LCA), and the circular economy [2-4]. Although substantial research has been conducted on acid mine drainage, heavy metal pollution, tailings management, land rehabilitation, and biodiversity protection, the recently documented integration of sustainability principles with the United Nations Sustainable Development Goals (SDGs) represents a shift away from purely "reactive" pollution control toward more "proactive" and systematic environmental management [5, 6]. A more systemic, proactive, and preventive approach to pollution control has increasingly become the focus of research in the mining sector. Compliance with social responsibility standards, transparency, and a commitment to long-term environmental protection are rapidly becoming industry norms. Nevertheless, fragmentation in mining-environment research persists, with more pronounced divides in developing nations, especially where economic priorities dominate, and regulatory frameworks remain weak.

Mining companies must reposition themselves economically while transforming their operational practices to mitigate environmental impacts and meet evolving social expectations [7, 8]. This transformation involves not only changes in operational models but also a cultural shift within the mining industry toward integrated and self-sustaining practices that combine environmental protection, social equity, and economic sustainability. There has been rapid growth in the literature on mining and the environment; however, the global body of knowledge remains insufficiently synthesized. Most review articles tend to focus on specific themes, such as tailings management, acid mine remediation, or LCA, without integrating analyses of publication growth, collaboration networks, thematic evolution, and knowledge development over time. As a result, the dominant structure and trajectory of research on mining and the environment remain unclear. This gap highlights the need for a large-scale bibliometric and science-mapping study to articulate the integrated structure of this interdisciplinary field.

This study aims to provide the first comprehensive bibliometric analysis of global literature on mining and its environmental impacts from 2014 to 2024. The objectives are to (i) examine publication growth trends, leading publishers, and disciplinary distribution; (ii) identify key contributors, including authors, institutions, and countries, in mining and environmental research; and (iii) analyze thematic evolution, major research focus areas, and emerging sustainability trends. This study offers a systematic overview of the development and current state of research, contributing to models and policy frameworks that advance sustainable mining practices. Bibliometric data were obtained from the Scopus database and analyzed using Biblioshiny (R) and VOSviewer to generate research and policy insights for sustainable mining.

Materials and Methods

This study applied a bibliometric analysis, a quantitative research design, to analyze the scholarly literature on the topic. It provides an overview of research trends by applying statistical and mathematical techniques to the dataset [9, 10]. The bibliometric analysis procedures were divided into several key stages: (i) dataset extraction and construction of the bibliographic database; (ii) data processing through preprocessing; and (iii) tabulation and framework development for knowledge domain analysis using the R package Biblioshiny.

Data Sources and Search Strategy

The present study employed bibliometric analysis by combining measures of research activity growth with science-mapping techniques to provide both quantitative and qualitative insights into the field of study. The dataset was obtained from Scopus, which is uniquely positioned to address this topic due to its extensive coverage. In addition to journals, Scopus includes other types of publications such as articles, books, and conference papers. Alongside its broad coverage, Scopus offers structured and reliable metadata, as well as a comprehensive index, enabling robust bibliometric analyses. Compared with other databases such as PubMed, Web of Science (WoS), and Google Scholar, Scopus is considered one of the most comprehensive and representative databases for international scientific research. For these reasons, Scopus was selected as the data source for this bibliometric analysis. The search strategy included titles, abstracts, and author keywords retrieved from Scopus (www.scopus.com) using the following keyword query: "mine" OR "mining" OR "mining activity" AND "environmental impact" OR "environmental impacts." The search was conducted within the title, abstract, and author keyword fields. A total of 13,347 articles were initially identified. Following the PRISMA 2020 framework, non-article documents, non-English publications, and non-journal documents were excluded. Documents that did not meet the relevance criteria based on subject area and keywords were also removed. After applying the inclusion and exclusion criteria, the final dataset consisted of 2,626 publications. The data were exported in CSV format (see Fig. 1) and subsequently analyzed using VOSviewer software. Only articles written in English were included, as English is the predominant language used in international scientific publications.

Statistical Analysis

This phase of the research aims to provide an analysis of growth patterns, research trends, and collaborations, particularly those connected to mining and environmental impacts within the global research nexus. Relevant literature was harvested from the Scopus database by refining the search based on research topics, publication types, and article language. For the analysis, the datasets were processed using R and Biblioshiny to conduct an in-depth bibliometric analysis. Prior to analysis, the datasets were cleaned of duplicate records, standardized for consistency, and author and institutional names were normalized to a common format. A series of descriptive statistical analyses was conducted, including frequency distributions, annual growth rates, and citation counts, in accordance with general bibliometric protocols. The analysis measured productivity and scientific influence using three indicators: total citations (TC), average citations per publication (TC/P), and the Hirsch index (h-index), to evaluate the relationship between research output and academic impact. In addition, Lotka's Law and Bradford's Law were applied to evaluate author productivity distribution and core journal concentration patterns, respectively, ensuring that publication dispersion followed established bibliometric regularities. Citation analysis employed the full counting method, and impact indicators were interpreted comparatively rather than absolutely to avoid citation bias across publication years.

Social network analysis was also conducted to understand patterns of relationships and collaborations among authors, institutions, and countries in mining-related research. For network construction, the minimum document occurrence threshold was set at five for authors and institutions, and ten for keywords, to ensure statistical reliability and minimize noise from low-frequency nodes. Regarding the co-occurrence matrix, normalization based on association strength was applied, as recommended in bibliometric mapping studies. The VOS (Visualization of Similarities) clustering method was used to group nodes based on modularity and similarity optimization. Total link strength (TLS), centrality, and network cluster density metrics were used to describe thematic cohesion and collaboration intensity. This approach also enabled the mapping of interrelationships among research themes to better understand the dynamics and progression of knowledge in the fields of mining and the environment. Emerging themes were identified through centrality–density

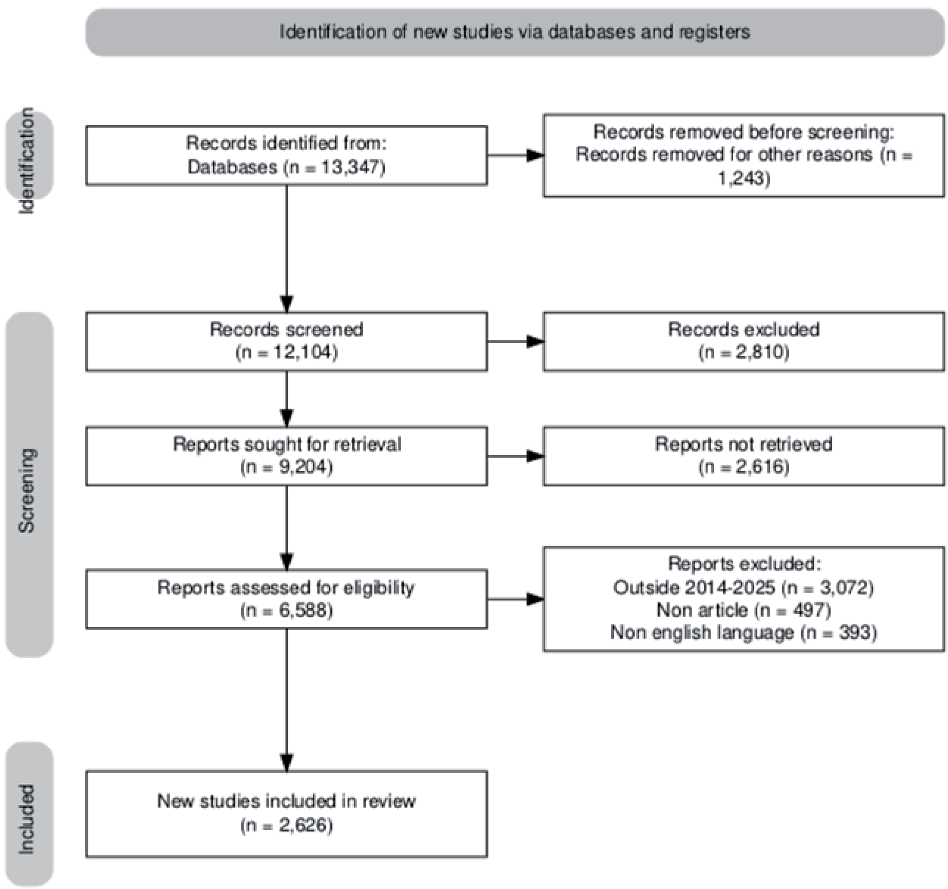

Fig. 1. PRISMA analysis of the study inclusion criteria.

analysis, in which centrality indicates the extent of a theme's interaction with other themes in the network, while density reflects the internal development of a cluster. Following standard science-mapping protocols, themes located in the lower-right quadrant were characterized as emerging themes, whereas those in the upper-right quadrant were classified as motor themes. By integrating the quantitative analytical capabilities of Biblioshiny (R) with the visual mapping functionality of VOSviewer, a holistic view of research impact, co-authorship patterns, and global research trends related to mining and its environmental impacts was obtained for the period 2014-2024. This comprehensive bibliometric analysis was conducted on 2,626 published items that met the inclusion criteria, after which the records were organized for further processing (see Fig. 1).

Results and Discussion

Main Statistics

A bibliometric analysis of 2,626 articles published from 2014 to 2024 shows that research related to mining and its environmental impacts has increased significantly over the past decade. The dataset represents 100% of the analyzed scientific output (n = 2,626), allowing for proportional interpretation of annual contributions. Fig. 2 illustrates continuous growth in publication numbers since 2016, reaching the highest point of 420 articles in 2024, which accounts for approximately 16.0% of the total publications over the ten-year period (420/2,626). This figure represents substantial year-on-year growth compared to the initial years of observation, indicating an accelerating research trajectory rather than linear expansion. Academic experts from various fields have increased their research focus on mining sustainability through interdisciplinary studies. The upward trend suggests a growing concentration of publications in the later years of the study period, reflecting heightened global concern regarding environmental governance, social responsibility, and energy efficiency in extractive industries after 2017.

Conceptual Structure

The diameter of each bubble represents the frequency of term occurrences. During this period, three topics consistently appeared with high frequency: Environmental Impact, Environmental Impact Assessment, and Mining. For instance, "environmental impact" appeared 971 times (approximately 37.0% of total publications), "mining" appeared 531 times (20.2%), and "environmental impact assessment" appeared 317 times (12.1%). These proportional values confirm that regulatory and impact-based approaches dominate the conceptual structure of the field. The high co-occurrence strength among these keywords indicates strong thematic centrality within the knowledge network. The main evolutionary trends in this area are marked by issues associated with Sustainable Development, Sustainability, and LCA. Global movements have also influenced these developments, particularly the SDGs. Currently, recent studies focus on performance, iron ore tailings, compressive strength, and other technical aspects. The keywords "tailings" and "risk assessment" have shown increasing co-occurrence intensity in recent years, indicating their growing importance within the thematic network. Increased recognition of iron ore tailings reflects a scientific response to large-scale dam failures that have drawn global attention to tailings management and associated risks. The collapse of tailings dams represents one of the most serious environmental and humanitarian crises. Materials released during such incidents can travel hundreds of kilometres, flooding areas with toxic mud that contaminates and devastates entire ecosystems [11, 12]. The rise of the "performance" topic indicates progress in assessing environmental management systems and reclamation practices.

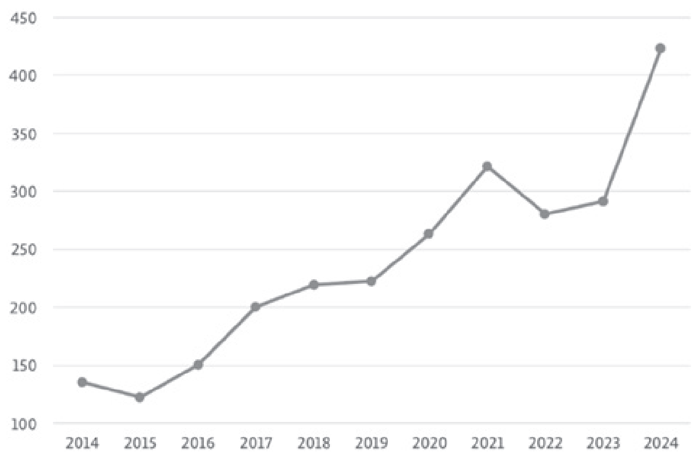

Fig. 2. Annual publication trend.

Hotspots and Future Research Needs in Mining–Environment Studies

Fig. 3 presents a strategic diagram of the research field, as it organizes all thematic clusters into four regions according to their centrality, meaning their relevance to the overall field, and density, referring to their internal development [13]. The upper right quadrant encompasses topics that are integral and foundational to the structural framework of the field. The themes of "tailings", "risk assessment", and "heavy metals" significantly influence current and future research directions. The prominence of these concerns underscores the substantial challenges within the industry, particularly regarding waste management and environmental disasters. Fundamental themes are highly important but exhibit relatively low density. Consequently, they represent essential transversal issues. "Mining" and "environmental impact assessment" relate to environmental considerations that are central to nearly all research in the discipline; however, they may not constitute the most innovative areas of inquiry.

Niche topics in the upper left quadrant demonstrate high density but low centrality. These themes are well developed but relatively isolated, showing limited connections to other areas of the discipline. "Sustainable development", "life cycle", and "sustainability" fall into this category. This suggests that they have evolved into advanced sub-disciplines, potentially with distinct research communities; nevertheless, these concepts remain insufficiently integrated across broader research domains. Emerging or declining themes in the lower left quadrant are characterized by low centrality and low density. "Waste management" appears in this quadrant, suggesting that it may represent an older and more general term that is being replaced by more specific and pressing topics such as "tailings". Conversely, "compressive strength" may indicate an emerging technical challenge related to the stability of backfill and tailings structures.

This diagram illustrates the developmental stages of research topics within the field. The foundational concept of "environmental impact" likely originated as a motor theme before evolving into a core component of the discipline. The shift from "waste management" as a broad concept to the more specific motor theme of "tailings" reflects an increasing research focus on clearly defined and technically specific problem areas. The positioning of "sustainable development" as a niche theme presents both a challenge and an opportunity. The key question is how this critical theme can be moved from the periphery to the core through stronger integration with fundamental and motor themes. Future research that bridges these quadrants may significantly advance the field toward its sustainability objectives. For example, applying "life cycle assessment" as a niche theme to "tailings management" as a motor theme may create stronger conceptual integration.

Emerging Research Themes

In recent years, environmental research in the mining sector has shifted from primarily addressing environmental damage to emphasizing mitigation strategies, rehabilitation initiatives, and sustainability-oriented practices. Temporal keyword analysis indicates that sustainability-related terms such as "sustainable development", "sustainability", and "life cycle assessment" have increased markedly in frequency after 2018 compared to the 2014 to 2017 period, reflecting a structural thematic shift within the dataset of 2,626 publications. This transition is also evident in the co-occurrence network, where sustainability-related clusters show increasing centrality and link

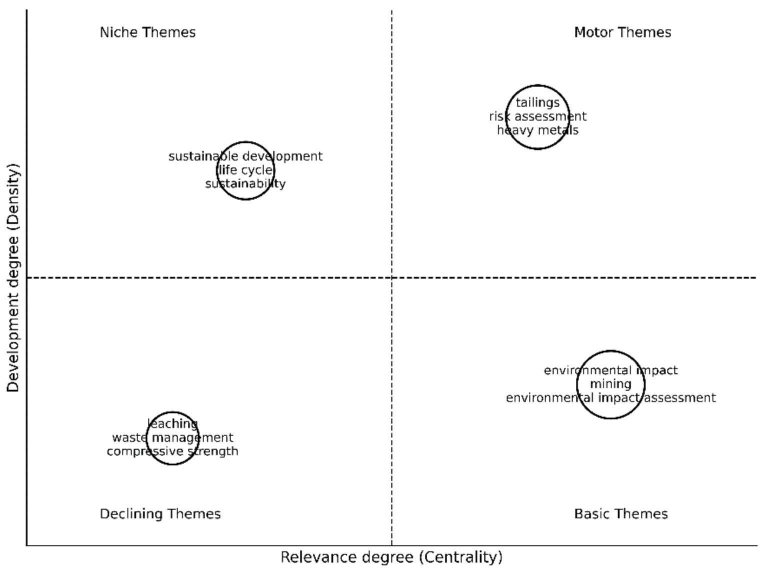

Fig. 3. Keyword analysis.

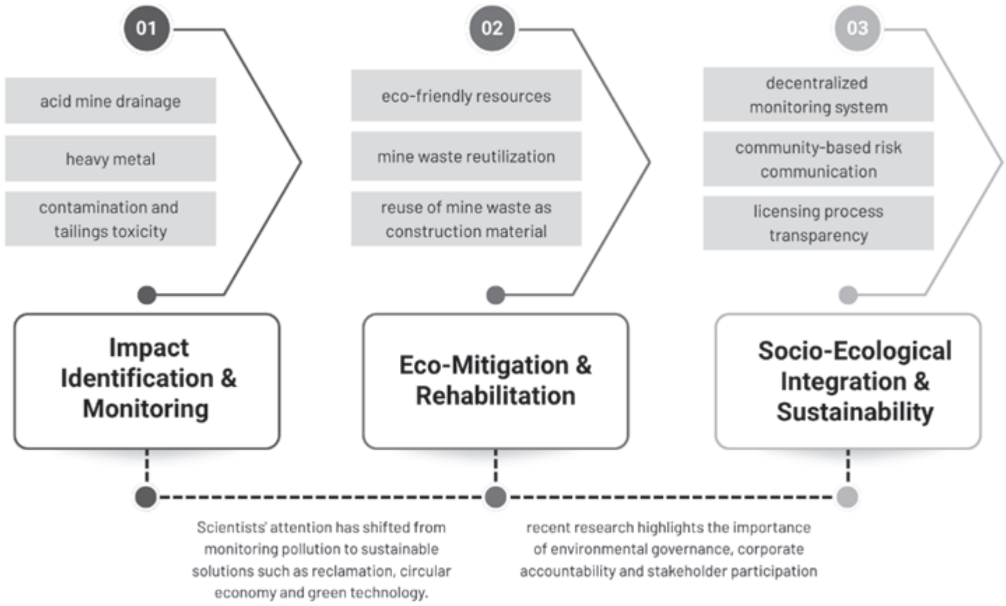

Fig. 4. Illustration patterns of pollution diagnosis.

strength, as illustrated in Fig. 4. These patterns suggest a redistribution of thematic emphasis from pollution diagnosis topics toward integrated management approaches and solution-oriented research domains.

For the first phase, the focus was on the themes of tailings toxicity, heavy metal contamination, and acid mine drainage. "Heavy metals" and "acid mine drainage" had high frequency and strong intra-cluster density in the earlier sub-period (2014-2017), which indicates the leading role of these keywords in the structure of the research network. The focus of this sub-period was to assess the environmental harm caused by extensive mining activities conducted without adequate control or regulation, or under poor regulatory frameworks [14]. Numerous studies were undertaken in this regard, focusing on pollution levels in soil and water, the mapping of pollutant movement pathways, and the evaluation of toxicity in local biota [15].

Research on small-scale gold mining in the Amazon has shown elevated levels of mercury and arsenic, with significant effects on public health and ecosystems [16]. The reduced emphasis on contamination-specific terms in the late 2010s indicates a shift in focus from purely contamination-related concepts toward themes of remediation, resilience, and governance. This shift is largely driven by the growing influence of global frameworks such as the SDGs and the European Green Deal, which emphasize risk-based assessment, sustainable remediation, and social-ecological resilience. Recently, phytoremediation using hyperaccumulator plants has been recognized as a cost-effective and environmentally friendly method for managing toxic tailings [17]. Beyond mere physical restoration of post-mining sites, the rehabilitation framework has increasingly incorporated ecosystem restoration, biodiversity protection, and community empowerment [18].

The principles of the circular economy are now beginning to be reflected in mining studies. Academic research on the repositioning and valorization of mine waste has emerged, including the recovery of rare earth elements from tailings and the use of mine waste as raw material in construction [19]. This development creates new economic opportunities beyond the mining sector. A more in-depth sustainability assessment may be warranted through a combination of LCA and Material Flow Analysis (MFA) methods. Recent studies have also highlighted the importance of environmental governance, corporate accountability, and stakeholder engagement in public policy processes. It is suggested that achieving more sustainable mining practices will require community-based decentralized monitoring, effective risk communication, and transparent permitting systems [20]. In mining-dependent regions, a transition paradigm has been formulated to reconcile ecological integrity, economic sustainability, and social equity. Recent strands of environmental mining research indicate a shift in the traditional view of the "environment" from a reactive perspective to a more proactive, integrated, and sustainability-oriented approach. Some possible future research directions include:

i. Unraveling the processes involved in the transfer of heavy metals through various trophic levels and examining their bioaccumulation in apex organisms.
ii. Assessing the consequences of chronic low-dose exposures to improve long-term public health risk estimation.
iii. Developing unified interdisciplinary frameworks integrating toxicology, environmental engineering, geochemistry, epidemiology, and policy science

to support evidence-based risk governance in the mining sector.

Risk Assessment and Impact Evaluation Methodology of Mining

The principal methodological approaches used to evaluate mining-related environmental risks are presented in Table 1. The bibliometric results show that contamination-oriented keywords such as "heavy metals" and "acid mine drainage" appear with substantial frequency, indicating that pollution diagnostics remain a foundational research domain. For example, terms related to heavy metal contamination constitute a significant proportion of environmental-impact-focused publications among the 2,626 analyzed articles, highlighting their persistent prominence throughout the study period. Empirical research consistently reports deterioration in environmental quality in ecosystems exposed to mining operations, including metal mobilization, soil structure alteration, reduced water quality, and biodiversity decline [21]. One of the main causes is the presence of tailings and acid mine drainage [22], which contain toxic heavy metal compounds such as Pb, As, Cd, and Hg. According to [23], acid mine drainage from gold mining in Peru lowers the pH of water to below 3, which kills many plankton and other aquatic invertebrates. The accumulation of these heavy metals in organisms causes growth, reproductive, immune, and neurotoxicological disorders [24]. Various methods have been employed to evaluate the risks associated with mining impacts. These include LCA, which is used as a long-term indicator of environmental footprints, EIA, and Geographic Information System (GIS)-based spatial modeling to identify areas under ecological disturbance. In addition, laboratory methods are applied, primarily through acute toxicity tests on bioindicator species such as *Daphnia magna*, *Danio rerio*, and *Eisenia fetida*, which are highly sensitive to heavy metals [25].

There is no conclusive evidence of permanent human injury resulting directly from mining waste; however, some studies suggest that long-term effects may occur. For instance, drinking water contaminated by arsenic in regions surrounding mining sites has been associated with higher incidences of skin and lung cancer, as well as cardiovascular damage and kidney failure [26]. Furthermore, Badakhshan et al. (2023) demonstrated that human kidney cells (HK-2) exposed to Pb and Hg exhibit increased production of reactive oxygen species (ROS), which induces DNA damage and cellular apoptosis [27]. According to Imaduddin et al. (2021), experiments on laboratory rats that consumed water containing tailings revealed weight loss, decreased liver enzyme activity, and thickening of the small intestine wall [28].

Mining waste demonstrates complexity in its physicochemical characteristics as well as in its interactions with environmental components, including water, soil, living organisms, and other anthropogenic contaminants [29], as illustrated in Fig. 5 and described in the narratives and data below. The interactions of mine waste leads to increased mobility of heavy metals [30], heightened ecosystem toxicity [31], and alterations in ecosystems' biogeochemical functions. Typically, mine waste contains materials such as tailings, acid mine drainage (AMD) [22], and mine dust, each of which can have direct and indirect effects on surrounding ecosystems [32]. Chemically, the primary process that occurs is the oxidation of sulfide minerals, which generates sulfuric acid and initiates the development of AMD. A study by Singh et al. (2024) suggests that when pH levels drop below 5, heavy metals such as arsenic (As), lead (Pb), cadmium (Cd), and mercury (Hg) become more soluble, leading to contamination of groundwater and surface water systems [33].

Mobile heavy metal contamination in the environment is influenced by soil pH, salinity, and the presence of competing ions and dissolved organic matter (e.g., Na, Ca, and others) [35]. Microorganisms

Table 1. Methodology for risk assessment of environmental impacts of mining activities.

Methodology	Evaluation Approach	Example of Application
Life Cycle Assessment (LCA)	Analysis of emissions, waste generation, and energy consumption throughout the production process	Assessment of the environmental footprint of copper mining in Chile and coal mining in Indonesia
Environmental Impact Assessment (EIA)	Assessment of biophysical and socio-environmental components and their potential impacts prior to project implementation	Preliminary environmental evaluation of mining activities in Australia and gold mining projects in West Africa
Risk-Based Corrective Action (RBCA)	Risk assessment using exposure pathway modeling and ecotoxicological analysis	Risk evaluation of arsenic-contaminated soils in mining regions of Brazil
Ecotoxicological Testing	Toxicity assessment using selected indicator organisms, including fish, insects, and microorganisms	Bioaccumulation studies of lead (Pb) and cadmium (Cd) in *Daphnia magna* and *Danio rerio*
Remote Sensing and GIS Analysis	Spatial assessment of ecological changes and land-use dynamics	Evaluation of vegetation changes caused by coal mining activities in China and Mongolia

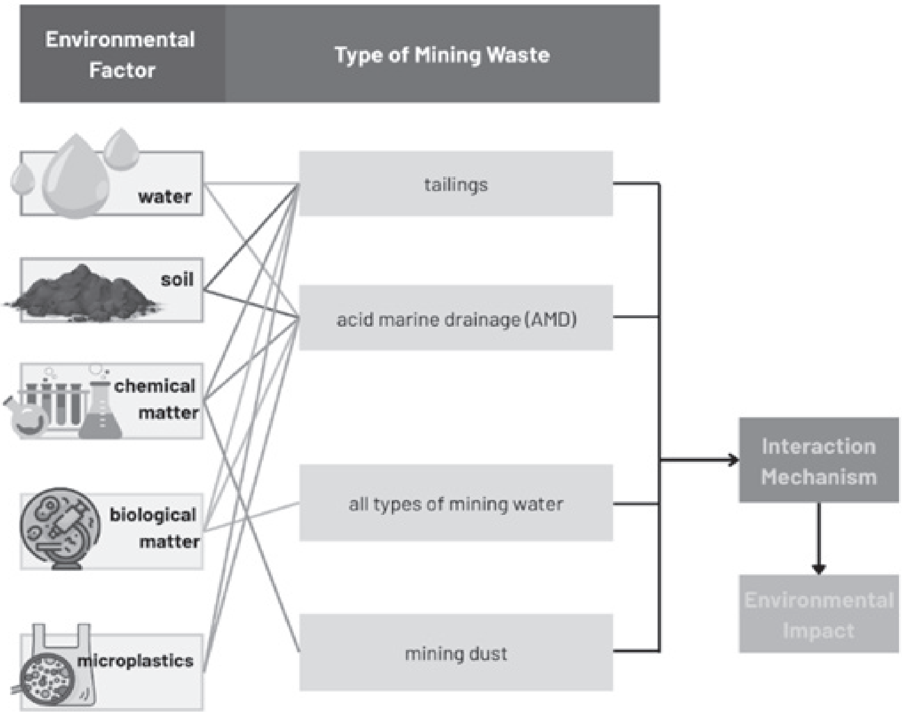

Fig. 5. Mining waste interaction patterns.

act as biological agents that interact with mine effluents; some are capable of detoxifying and/or immobilizing heavy metals [36]. Bacteria, such as *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans,* have been shown to accelerate sulfide oxidation and exacerbate AMD formation. Other microorganisms, such as *Pseudomonas* sp. and *Bacillus* sp., are able to biosorb heavy metals and thereby precipitate these contaminants [37]. The concentrations of these microorganisms vary depending on environmental conditions, including acidity and the presence of dissolved oxygen and metals. Mine waste can also interact with external contaminants such as pesticides, agricultural nitrates, industrial surfactants, and microplastics [38]. The combined effects of these contaminants can significantly increase the toxicity of affected ecosystems. Agricultural fertilizer nitrates may increase the rate of pyrite oxidation in tailings and worsen AMD formation. Microplastics can adsorb heavy metals and facilitate the transport of contaminants across biogeochemical boundaries when ingested by animals. The complexity of environmental factors and mining effluents creates systems that remain insufficiently understood. Table 2 outlines previously documented environmental systems and their ramifications. The examination of mining effluents and their contaminants requires assessment

Table 2. Types of interaction between mining waste and environmental factors.

Environmental Factor	Type of Mining Waste	Interaction Mechanism	Environmental Impact
Rainfall	Tailings; AMD	Increased dissolution and leaching of heavy metals	Groundwater and surface water contamination; increased water acidity
Soil and Water pH	Tailings; AMD	Regulation of sorption–desorption processes of metal ions	Altered bioavailability of heavy metals for plankton
Salinity (Na^+, Ca^{2+})	AMD; Tailings	Ionic competition and modification of metal mobility	Changes in metal bioaccumulation in marine and estuarine organisms
Naturally Occurring Organic Matter	All types of mining waste	Complexation between humic substances and heavy metals	Reduced immediate toxicity but increased contaminant persistence
Microorganisms	AMD; Tailings	Sulfide oxidation and metal bioprecipitation processes	Enhanced AMD formation or potential for heavy metal bioremediation
Pesticides and Nitrates	Mining dust; Tailings	Oxidative reactions and co-adsorption onto tailings particles	Increased soil and water toxicity

beyond metals, as these waste streams generate environmental interactions and systemic boundaries that are not yet fully defined. Future studies should aim to synthesize geochemical, microbiological, toxicological, and climate-related analyses within a systematic framework. Advances in structured, multidimensional modeling of field data will provide a robust foundation for assessing the cumulative impacts of these parameters. Technologies such as constructed wetlands, biochar applications, and the use of metal-tolerant microorganisms offer viable approaches to addressing the synergistic impacts of mining wastes and other environmental factors.

Mineral waste should not only be viewed in terms of its metal content, but also regarded as a complex system that responds to mechanisms such as climate change, geochemical interactions, and anthropogenic activities. Accordingly, it should be approached from an integrated perspective. Future research should integrate disciplines such as geochemistry, microbiology, toxicology, and climate science, as interdisciplinary approaches are likely to provide more comprehensive solutions to these challenges. The long-term environmental impacts of cross-factor interactions between mineral waste and other waste types should be modeled and assessed through integrated, multi-parameter predictive field studies. Ecological approaches, such as constructed wetlands, MeriBiochar, and metal-tolerant microorganisms, show strong potential for mitigating the synergistic impacts of mining waste and environmental factors.

Conclusions

From a bibliometric standpoint, research on mining and its environmental impacts spans a decade and multiple disciplines, resulting in 2,626 publications from 2014 to 2024. Due to global interest in enhancing resource management and minimizing environmental risks, there has been a steep increase in eco-centric publications in recent years, and this trend is expected to continue as these interests grow. Based on prior studies, the primary structure and function of the mining industry have centered on acid mine drainage, tailings, and heavy metal toxicity. Currently, there is a shift toward focusing on LCA, circular economy models, environmental governance frameworks, and risk management frameworks. A transition from a reactive approach addressing environmental damage after it occurs to proactive, integrated, and comprehensive sustainable environmental protection is evident, as reflected in the emergence and prominence of sustainability-related themes on thematic maps. Interdisciplinary risk management approaches are increasingly prevalent, and sustainable mining practices are expected to continue evolving in the future. However, this study has several limitations, including its restriction to English-language publications, the 2014-2024 time frame, and exclusive reliance on the Scopus database. Consequently, regionally based research that may not have been published in indexed journals could have been overlooked. Bibliometric approaches identify structural patterns but do not assess the technical merit or practical impact of individual studies. Therefore, future research should integrate bibliometric mapping with systematic content analysis and empirical testing to more effectively support evidence-based policy formulation. The field of mining-environment research indicates that future progress will require deeper integration across environmental science, public health, socioeconomics, and technological innovation.

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AI Usage Disclosure Statement

During the preparation of this work, the author(s) used Chat GPT-3.0 to improve readability and language understanding. After utilizing this AI technology, the author(s) meticulously reviewed and amended the content as required, ensuring its accuracy and completeness. The author(s) assume(s) complete accountability for the content of the publication.

Conflict of Interest

The authors declare no conflict of interest.

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