Global Trend of Innovation in the Mining Industry: A Comprehensive Bibliometric Analysis

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Abstract. This bibliometric analysis examines innovation trends and gaps in the mining sector, focusing on resource depletion, environmental sustainability, and operational efficiency. Using Scopus to gather articles, Microsoft Excel for frequency analysis, VOSviewer for data visualization, and Publish or Perish for citation metrics, the study identifies key publication patterns, influential authors, and primary research themes. Since the early 2000s, publications and citations have surged, highlighting increasing academic interest. China leads in research output, followed by South Africa and Australia. The study offers recommendations for stakeholders to boost innovation strategies, enhancing operational efficiency and sustainability. Network and cluster analyses reveal four key themes driving new ideas in the mining sector.

Keywords: Bibliometric Analysis, Innovation, Mining Industry, Publish or Perish, VOSviewer

1. Introduction

The mining sector has been instrumental in propelling worldwide economic expansion by providing vital raw materials for diverse sectors. Over the past decades, the demand for minerals and metals has significantly increased, driven by technological advancements and the growing needs of emerging economies. Innovations in mining processes and technologies have become crucial to meet these demands efficiently and sustainably. For instance, the adoption of automation and digitalization in mining operations has revolutionized productivity and safety standards [1]. These advancements have also contributed to reducing environmental impacts, making mining more sustainable.

Despite these progressions, the mining industry continues to face numerous challenges, including resource depletion, regulatory pressures, and environmental concerns. Innovations are not only pivotal in addressing these issues but also in enhancing operational efficiency and competitiveness. Modern technological advancements include the Internet of Things (IoT), big data analytics, and artificial intelligence, are revolutionizing conventional mining methods [2]. These technological innovations are enabling more precise exploration, efficient resource extraction, and improved safety measures, thereby reshaping the industry's landscape.

While the benefits of the innovations in the mining business are highly recognized, the sector still grapples with several persistent problems [3]. One major issue is the slow pace of technological adoption among many mining companies. According to recent studies, a significant number of firms remain reluctant to invest in new technologies due to high costs and uncertain returns on investment [3]. This hesitation hinders the industry's overall progress and limits its ability to respond effectively to emerging challenges.

AICOBPA 2023, November 01, Malang, Indonesia

DOI 10.4108/eai.1-11-2023.2359822

Additionally, the mining industry is under constant scrutiny for its environmental and social impacts [4]. The extraction processes often lead to habitat destruction, water pollution, and significant carbon emissions, prompting calls for more sustainable practices. Despite the development of eco-friendly technologies, their implementation is still not widespread. To tackle these issues, it is necessary to have a thorough comprehension of the elements that impact innovation in the mining industry, as well as effective strategies to overcome the barriers to technological advancement [5].

Although there is extensive investigation into advancements in the mining sector, significant gaps remain in the literature. First, there are few studies that systematically analyze publication trends and identify key patterns in mining innovation. Second, previous studies tend to focus on specific aspects without considering a more holistic approach such as research conducted by [6] that reviews about sustainability in the long run as it relates to mining safety of the mining industry. This study elicits further apprehensions, encompassing the subsequent: (i) There are direct and indirect consequences of coal dust contamination on ecosystems. (ii) The majority of investigation initiatives have prioritized technological advancement over adherence to safety standards. Another bibliometric analysis by [7] examined the most highly cited articles on mining injuries, both in terms of annual and lifetime citations. The researchers discovered that the topic most commonly mentioned was the use of lost-time injury as a measure of outcome. Third, there is a lack of studies linking innovation to tangible outcomes in the industry, such as increased productivity and reduced environmental impact. Bibliometric analysis can help fill these gaps by offering a more extensive and detailed analysis of the present landscape of mining innovation studies.

This study is significant since it offers profound insights into the developments and research trends in innovation in the mining industry. By using bibliometric analysis, this study can identify underexplored areas, uncover collaboration patterns, and assess the impact of various innovations that have been implemented. The results of this study can guide researchers, practitioners, and policymakers in directing subsequent investigations and development efforts. Additionally, this study can help improve the effectiveness and efficiency of investments in innovation in the mining industry.

Bibliometric analysis, as emphasized by [8], [9], is a suitable approach for conducting systematic science mapping. It enables a thorough examination of certain areas, offering a full review and visual analysis. Additionally, it facilitates the identification of research clusters from earlier studies. Unlike traditional trend analysis, this method merely requires creating a list of variables and theories and doing a simple analysis. Bibliometric analysis enables researchers to use title and keyword network analysis, facilitating the identification and development of clusters of research within a specific field. With the use of scientific mapping and analysis of networks, the researcher may provide a thorough synopsis of the previous study's authors, sources, and citations. This study seeks to investigate the subsequent research questions:

RQ1. What is the state of the art and publishing pattern on innovation research in the mining industry research?

RQ2. Who are the contributors, countries, and sources that have made the most impact and achieved the highest level of productivity in innovation research within the mining industry?

RQ3. What are the most impactful articles on innovation research in the mining industry?

RQ4. Which are the main research themes of innovation research in the mining industry?

The paper is structured as follows. In the following section, we shall outline the bibliometric approach employed in this study. Publish or Perish, VOSviewer, and Excel are the tools for bibliometric analysis that are detailed in this section, along with a number of flowcharts

and references. The result and discussion section aims to answer specific research questions, followed by a conclusion and suggestions for further research.

2. Methods

[10] states that the bibliometric method effectively tracks and reports statistical insights on specific terminology or notions disseminated within a specific discipline. This strategy is essential for precisely comprehending the existing information in the topic using a scientific approach. Bibliometric analysis offers an advantage over traditional narrative reviews by relying on objective data rather than subjective perceptions, thus overcoming biases and providing more informative results. It enables researchers to systematically analyze and record metadata, facilitating the dissemination of knowledge and enabling well-grounded conclusions.

The use of bibliometric analysis has become prevalent as it provides a scientific mapping of the publication database, enhancing the researcher's understanding of the field. Such reviews, as supported by [11], usually make use of niche online resources like WoS or Scopus (Web of Science), enabling them to have comprehensive access to pertinent publications and articles. Furthermore, as pointed out, services like Scopus allow users to search across many bibliographic areas [12].

2.1. Identification of Sources

A bibliographic analysis of publications was performed as of April 04, 2024. Scopus was utilized for this study because of its extensive compilation of citations and abstracts from academic papers across several disciplines [13]. As of now, there are more than 39,743 titles in the Scopus database. Out of these, more than 25,000 are active titles, while 14,558 are inactive, primarily consisting of older versions of the active titles. Furthermore, it encompasses around 210,000 books. An all-encompassing view of the results of scientific studies across the world may be provided by this sort of database. Researchers all around the world rely on the Scopus database for up-to-date information [14]. Because of its status as the preeminent online database for citations and abstracts in the domains of technology, social science, business, and management, this study made use of Scopus. In addition, [15] highlighted the utilization of data from the Scopus database owing to its comprehensive compilation of esteemed and high-caliber articles. Figure 1 illustrates the detailed methodology for the search strategy utilized in this study, along with the complex procedures required for conducting bibliometric analysis.

2.2. Search Strategy

In order to obtain more relevant documents, we utilized a combination of keywords based on research questions. A keyword is a particular type of search expression that is employed to locate datasets that are associated with the technology acceptability model and public service field [16]. For this purpose, the following query for the Scopus database consists of three main keywords: innovation and mining industry. Specifically, we performed a comprehensive search by using TITLE-ABS-KEY by adding some various terms of keywords and the boolean operator (AND, OR). Thus, we finalized the search by using the following query: (TITLE-ABS-KEY (innovation) AND TITLE-ABS-KEY ("mining industry" OR "mining company" OR "mining sector" OR "mining enterprise")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (LANGUAGE , "English")).

Table 1. Selection criteria

No	Inclusion Criteria	Exlusion Criteria
1	IC1: Peer review journal articles	EC1: Conference papers, Books, Book Chapters, Book Series
2	IC2: English	EC2: Non-English

Table 1 presents the complete criteria for the inclusion and exclusion of gathered datasets. We do not restrict our search in terms of timeframes. Initially, 1,040 papers were acquired from Scopus, spanning from 1948 to 2024. To get high-quality information, we will exclusively select journal articles as our sources, excluding other document categories such as conference proceedings, books, book chapters, and book series. This is because journal articles, unlike other forms such as conference papers and book chapters, undergo a more rigorous scientific peer review procedure. Consequently, they were our preferred option over alternative formats. Consequently, utilizing the IC1 and EC1 in the Scopus query yielded 883 documents published as journal articles.

Subsequently, we only limited articles written in English. After implementing the IC2 inclusion criteria and EC2 exclusion criteria, the number of remaining articles was reduced to a mere 433 items. Lastly, the 433 articles will undergo further analysis in the following part. Figure 1 depicts the comprehensive process for the research technique utilized in this research and the rigorous methodologies for conducting bibliometric analysis.

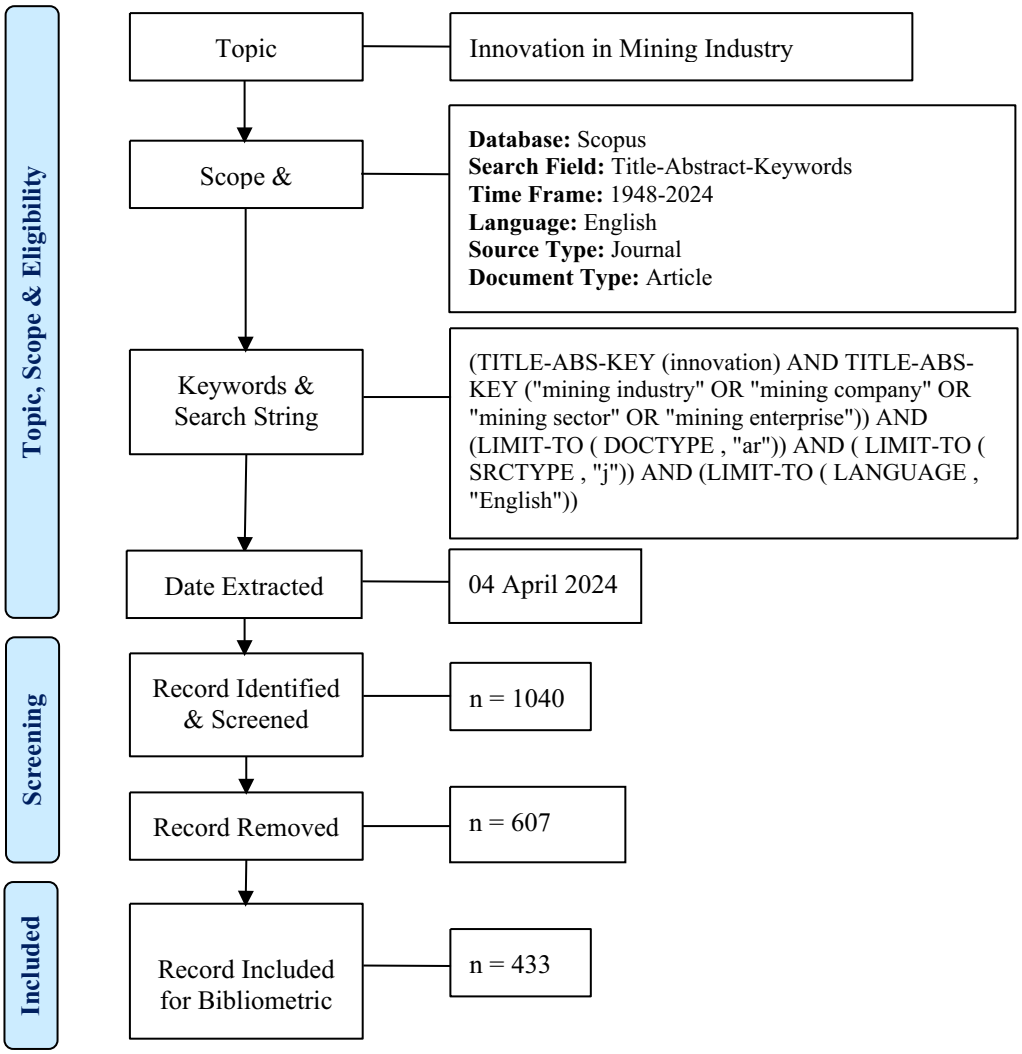

Figure 1. Flow diagram of the search strategy
Source: [17]

2.3. Data Analysis

To accomplish this, we utilize a wide range of technologies to accomplish the research objective and answer the research questions put forward in this study: 1) Microsoft Excel is used so that appropriate visual representations may be generated and publishing frequencies and percentages can be calculated. 2) Publish or Perish is utilized to determine the impact and performance of publications based on specific metrics. 3) Bibliometric networks are created and visualized using VOSviewer (version 1.6.20). Both descriptive and network analyses were used to classify the papers included in this investigation. To answer the research questions (RQs) stated at the beginning of this article, these analyses are primarily carried out. Microsoft Excel

and Publish or Perish were employed for conducting the descriptive analysis, while VOSviewer was utilized for performing the network analysis.

We refer to the [18] who recommended that two main approaches may be used to provide comprehensive bibliometric analysis: performance analysis and science mapping. Performance analysis examines the individual contributions of research components in a particular subject, whereas Science mapping explores the relationships and linkages between different areas of research. Hence, a total of 433 documents were analysed following the [19] studies: the first analysis covered the analysis of publications and impacts by year to answer RQ1. The second analysis was conducted by presenting the contribution of authors, countries and source titles to answer RQ2. The third analysis of top 20 highly cited documents was revealed to answer the RQ3. Lastly, we analyzed the author's keywords in the network visualization map to answer RQ4.

Before we conducted the examination, the data cleaning and harmonisation were performed. According to [20], these stages are crucial in bibliometric analysis to guarantee the precision and dependability of the findings. To achieve this objective, a VOSviewer thesaurus file can serve as an excellent tool, enabling us to effectively standardize data and enhance its accuracy. Put simply, A thesaurus file is a textual document that facilitates data purification while generating a map using bibliographic data. In this study, we have consolidated various variations of keywords found in the dataset by grouping together synonyms, accounting for spelling discrepancies, and combining abbreviated phrases with their corresponding full terms. Examples of such consolidation include merging "innovations" and "innovation," "investments" and "invest-ment," and "patent families" and "patents," among others. A thesaurus file consists of two columns: a column for labels and another for "replace by" functions. A thesaurus file begins with a header line that contains the headers for each column. Every line in a thesaurus file, with the exception of the first, includes two columns: one for the label and another for the alternative label. What this means is that the current label has to be replaced with the new one. Once we have completed the data cleaning process, we proceed with the analysis.

3. Results and Discussion

This section summarizes the findings obtained from the study questions specified in the introduction.

3.1. Descriptive Analysis

The profile and research history are covered in this section with an analysis of innovation research in the mining industry. [18] referred to this approach as performance analysis, which evaluates the contributions of diverse research entities (including authors, institutions, nations, and publications) to a particular subject. This analysis is the hallmark of bibliometric studies. Consequently, this includes all information on the subject areas, languages, publication trends, prolific authors, countries and institutions, source titles and highly cited papers. The primary indicators are the number of articles published and cited each year or for each part of the research, where the former measures impact and the latter measures productivity. Supplementary metrics, including citation per publication, h-index, and g-index, utilize both citations and publications for assessment the research output of individuals or groups. The analysis, although descriptive, acknowledges the significance of several components within a research subject. For this purpose, the descriptive analysis was conducted to answer RQ1 – RQ3 in this paper.

3.2. Subject Areas

The issue of innovation in the mining industry attracts considerable attention from various scientific disciplines, but with a strong dominance in three main fields: ecology, sociology, and planetary science (Table 2). Environmental Science dominates with a total of 175 publications, which comprise 40.42% of the total. This is closely followed by Social Sciences with 173 publications or 39.95%. Earth and Planetary Sciences also show significant contributions with 128 publications, accounting for 29.56% of the total.

Table 2. Subject area

Subject Area	Total Publications (TP)	Percentage (%)
Environmental Science	175	40.42%
Social Sciences	173	39.95%
Earth and Planetary Sciences	128	29.56%
Engineering	106	24.48%
Economics. Econometrics and Finance	104	24.02%
Business. Management and Accounting	79	18.24%
Energy	50	11.55%
Computer Science	30	6.93%
Materials Science	27	6.24%
Arts and Humanities	17	3.93%
Decision Sciences	12	2.77%
Agricultural and Biological Sciences	10	2.31%
Mathematics	8	1.85%
Chemical Engineering	7	1.62%
Chemistry	7	1.62%
Psychology	7	1.62%
Medicine	5	1.15%
Physics and Astronomy	4	0.92%
Multidisciplinary	3	0.69%
Biochemistry. Genetics and Molecular Biology	2	0.46%
Pharmacology. Toxicology and Pharmaceutics	2	0.46%
Health Professions	1	0.23%
Neuroscience	1	0.23%
Nursing	1	0.23%

3.3. Publication Trends

According to Table 3, the studies indicate a notable rise beginning in the early 2000s, in terms of both total publications and citations, reflecting a growing academic interest in this topic. Starting from the 2000s, there was a sharp rise in total citations, particularly in 2020, with 822 citations from just 28 publications, indicating a high citation per publication (C/P) rate of 29.36. This trend continued with publications in subsequent years maintaining relatively high citation rates per publication. Earlier periods, especially before 2000, exhibited much lower publication activity with negligible citations. Specifically, the period between 2020 and 2023

shows consistent increases in the number of cited publications (NCP), with a significant improvement in the publication-to-citation ratio. This indicates not just an increase in the volume of publications but also an enhancement in research quality, as reflected by the rising h-index (h-index) and g-index (g-index), reaching peak values in 2020 at 12 and 28, respectively.

Table 3. Publication trend

Year	TP	%	NCP	TC	C/P	C/CP	*h*	*g*
2024	30	6.93%	6	6	0.20	1.00	1	1
2023	56	12.93%	31	199	3.55	6.42	7	12
2022	51	11.78%	42	437	8.57	10.40	13	19
2021	48	11.09%	45	640	13.33	14.22	13	23
2020	28	6.47%	26	822	29.36	31.62	12	28
2019	16	3.70%	16	344	21.50	21.50	10	16
2018	32	7.39%	27	353	11.03	13.07	10	18
2017	27	6.24%	24	324	12.00	13.50	11	17
2016	17	3.93%	17	312	18.35	18.35	9	17
2015	17	3.93%	14	567	33.35	40.50	7	17
2014	12	2.77%	10	118	9.83	11.80	5	10
2013	6	1.39%	3	67	11.17	22.33	3	6
2012	10	2.31%	9	226	22.60	25.11	5	10
2011	7	1.62%	4	36	5.14	9.00	4	6
2010	6	1.39%	3	72	12.00	24.00	3	6
2009	7	1.62%	6	66	9.43	11.00	4	7
2008	6	1.39%	6	228	38.00	38.00	6	6
2007	4	0.92%	3	114	28.50	38.00	2	4
2006	4	0.92%	3	30	7.50	10.00	2	4
2004	2	0.46%	2	257	128.50	128.50	2	2
2003	1	0.23%	0	0	-	-	0	0
2002	2	0.46%	1	31	15.50	31.00	1	2
2001	3	0.69%	2	411	137.00	205.50	2	3
2000	6	1.39%	3	59	9.83	19.67	3	6
1998	3	0.69%	2	18	6.00	9.00	2	3
1997	2	0.46%	2	36	18.00	18.00	2	2
1996	2	0.46%	2	38	19.00	19.00	2	2
1995	5	1.15%	2	7	1.40	3.50	1	2
1994	1	0.23%	1	3	3.00	3.00	1	1
1993	3	0.69%	2	12	4.00	6.00	2	3
1992	3	0.69%	3	33	11.00	11.00	3	3
1991	1	0.23%	1	5	5.00	5.00	1	1
1990	1	0.23%	0	0	-	-	0	0
1989	1	0.23%	0	0	-	-	0	0
1988	2	0.46%	0	0	-	-	0	0
1987	2	0.46%	1	1	0.50	1.00	1	1
1986	2	0.46%	0	0	-	-	0	0
1985	3	0.69%	1	9	3.00	9.00	1	3
1984	1	0.23%	0	0	-	-	0	0
1982	2	0.46%	0	0	-	-	0	0
1948	1	0.23%	0	0	-	-	0	0
Total	**433**							

Notes: TP=total number of publications; TC=total citations; NCP=number of cited publications; C/CP=average citations per cited publication; C/P=average citations per publication; h=h-index; and g=g-index

3.4. Prominent Contributors

A bibliometric analysis in the mining industry's innovation field identifies many significant contributors from different countries. Table 4 displays the authors who have published at least three works in the field of innovation in the mining sector, indicating their popularity. Warhurst, A. from the United Kingdom has the highest number of publications, with 5 papers. Cheng, J. from China and Wiewiora, Australian contributors, have both made important contributions with 4 documents each. In terms of the overall number of citations by writers, Cheng, J. ranked top with 114 citations, followed by Figueiredo, P.N. with 99 citations and Warhurst, A with 84 citations.

Table 4. Most prominent contributors

Author's Name	**Affiliation**	**Country**	**TP**	**NCP**	**TC**	**C/P**	**C/CP**	***h***	***g***
Warhurst. A.	Warwick Business School	United Kingdom	5	4	84	16.80	21.00	4	5
Cheng. J.	China University of Geosciences	China	4	3	114	28.50	38.00	3	4
Wiewiora. A.	Queensland University of Technology	Australia	4	4	51	12.75	12.75	3	4
Cheng. L.	Chinese Academy of Geological Sciences	China	3	2	17	5.67	8.50	1	3
Fernandez. V.	Universidad Adolfo Ibáñez	Chile	3	3	28	9.33	9.33	3	3
Figueiredo. P.N.	Fundacao Getulio Vargas	Brazil	3	3	99	33.00	33.00	3	3
Golik. V.I.	Moscow Polytechnic University	Russian Federation	3	2	42	14.00	21.00	2	3
Gruenhagen. J.H.	Queensland University of Technology	Australia	3	3	75	25.00	25.00	3	3
He. M.	China University of Mining and Technology	China	3	3	170	56.67	56.67	1	3
Luo. D.	Chengdu University of Technology	China	3	2	17	5.67	8.50	1	3

Notes: TP=total number of publications; TC=total citations; NCP=number of cited publications; C/CP=average citations per cited publication; C/P=average citations per publication; h=h-index; and g=g-index

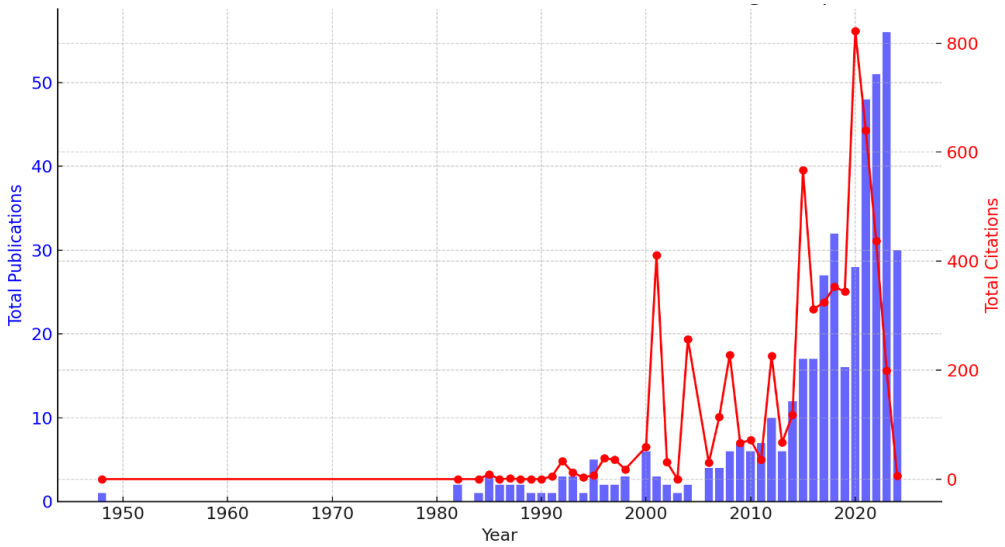

Figure 2. Number of publications and citations each year

3.5. Prolific Countries

The bibliometric data on innovation in the mining industry provides interesting facts about the global research scene and how it affects, with a particular emphasis on the leading countries that contribute to this field. Researchers from 65 nations have published scholarly papers sourced from the Scopus database in this particular domain. Based on Table 5, China emerges as the leader not only in the total number of publications (TP) with 79 papers, but also in total citations (TC) with 1,550 citations, indicating its central role in shaping research and discourse in mining innovation. South Africa and Australia also stand out as key contributors. South Africa, with 39 publications and 649 citations, demonstrates a strong research presence in Africa, while Australia's 36 publications have garnered an impressive 909 citations, reflecting high-quality research outputs that are frequently cited internationally. Both countries exhibit robust academic networks and are influential in advancing mining technology. Bibliometric data also shows significant global contributions from multiple continents. Asia is led by China with the most publications and citations. South Africa stands out in Africa. Australia represents Oceania with high quality research. Europe, North, and South America also show substantial involvement through countries such as Russia, United Kingdom, Canada, the United States, Chile, and Brazil.

Table 5. Most prolific countries

Country	TP	NCP	TC	C/P	C/CP	h	g	Continent
China	79	55	1550	19,62	28,18	20	39	Asia
South Africa	39	32	649	16,64	20,28	11	25	Africa
Australia	36	29	909	25,25	31,34	14	30	Oceania
Russian Federation	33	23	249	7,55	10,83	8	15	Europe
United Kingdom	26	23	592	22,77	25,74	12	24	Europe

Country	TP	NCP	TC	C/P	C/CP	h	g	Continent
Chile	25	21	372	14,88	17,71	10	19	South America
Canada	24	20	252	10,50	12,60	9	15	North America
United States	22	17	923	41,95	54,29	9	22	North America
Brazil	19	18	363	19,11	20,17	10	19	South America
Poland	19	17	146	7,68	8,59	8	11	Europe

Notes: TP=total number of publications; TC=total citations; NCP=number of cited publications; C/CP=average citations per cited publication; C/P=average citations per publication; h=h-index; and g=g-index

3.6. Prominent Source

According to the combined article count and citation count, Table 6 shows which main sources have contributed to mining industry innovation-related publications.

Table 6. Top ten source titles

Source Title	TP	NCP	TC	C/P	C/CP	h	g	Quartile
Resources Policy	73	55	1271	17,41	23,11	21	34	Q1
Sustainability Switzerland	12	10	41	3,42	4,10	4	6	Q1
Journal Of Cleaner Production	9	9	264	29,33	29,33	7	9	Q1
Journal of Mines Metals and Fuels	9	3	3	0,33	1,00	1	1	Q4
Eurasian Mining	8	6	58	7,25	9,67	3	7	Q2
Journal of The Southern African	8	6	25	3,13	4,17	3	4	Q3
Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu	8	4	24	3,00	6,00	2	4	Q3
Acta Montanistica Slovaca	7	6	64	9,14	10,67	5	7	Q2
Extractive Industries and Society	5	3	66	13,20	22,00	3	5	Q1
Metallurgical and Mining Industry	5	2	9	1,80	4,50	2	3	N/A

Notes: TP=total number of publications; TC=total citations; NCP=number of cited publications; C/CP=average citations per cited publication; C/P=average citations per publication; h=h-index; and g=g-index; Quartile=journal rank based on percentile

The "Resources Policy" stands out as the most prolific and influential source, with 73 total publications and 1,271 citations, showcasing an impressive average citation per publication of 17.41. This journal, which is positioned in the top quartile (Q1), highlights its premier status and significant impact in disseminating research on mining policy and innovation. Other notable journals contributing to the discourse include "Sustainability Switzerland" and "Journal of Cleaner Production," both also ranked in the first quartile, though with considerably fewer total publications at 12 and 9, respectively. The "Journal of Cleaner Production" in particular shows a high citation impact per publication, averaging 29.33, indicating the high relevance and quality of its articles. Lower quartile journals like "The Journal of Mines Metals and Fuels" in the fourth

quartile, despite similar publication counts to some second and third-quartile journals, have significantly lower citation impacts, highlighting the disparity in influence and recognition among journals in this field.

3.7. Highly Cited Documents

The landscape of innovation in the mining industry has been richly documented in the top-cited literature, revealing a diverse array of thematic and methodological approaches (Table 7). At the forefront, the work by [21] on the commercial applications of biohydrometallurgy stands out with a significant total citation count of 374. Conversely, [22] explored the integration of big data analytics within mining, boasting the highest citation rate per year at 8625, underscoring its critical impact on operational excellence and sustainable supply chain performance. In addition, [23] provided insights into driving Chinese mining companies' green innovation, reflecting the increasing importance of environmental concerns in mining operations with the second highest of 3200 citations per year. Further back, [24] analysis of collaborative innovation throughout the British Industrial Revolution, particularly around the Cornish pumping engine, resonates with a total of 205 citations. In addition, [25] addressed the current difficulties in mining by introducing the "cutting cantilever beam theory" in the specific setting of China's longwall mining. Their work has received significant scholarly attention with 168 citations.

Table 7. Top 20 highly cited papers

Author(s)	Title	TC	C/Y
[26]	“Present and future commercial applications of biohydrometallurgy”	374	1626
[22]	“Big data analytics as an operational excellence approach to enhance sustainable supply chain performance”	345	8625
[24]	“Collective invention during the British Industrial Revolution: The case of the Cornish pumping engine”	205	1025
[25]	“Longwall mining "cutting cantilever beam theory" and 110 mining method in China-The third mining science innovation”	168	1867
[21]	“How will biomining be applied in future?”	135	844
[27]	“Encore for the Enclave: The Changing Nature of the Industry Enclave with Illustrations from the Mining Industry in Chile”	116	1289
[28]	“Small-scale mining in Ghana: The government and the galamsey”	99	825
[23]	“How to drive green innovation in China's mining enterprises? Under the perspective of environmental legitimacy and green absorptive capacity”	96	3200
[29]	“Is progress in energy-efficient comminution doomed?”	96	1067
[30]	“Is mining a high-tech industry? Investigations into innovation and productivity advance”	96	565
[31]	“Addressing the CO2 emissions of the world's largest coal producer and consumer: Lessons from the Haishiwan Coalfield, China”	86	956

Author(s)	Title	TC	C/Y
[32]	"The good, the bad and the ugly: An overview of the sustainability of blockchain technology"	78	1950
[33]	"Evolution of flotation chemistry and chemicals: A century of innovations and the lingering challenges"	76	950
[34]	"The sources of green management innovation: Does internal efficiency demand pull or external knowledge supply push?"	71	1183
[35]	"Environmental management and the soft side of organisations: Discovering the most relevant behavioural factors in green supply chains"	68	1700
[36]	"Theoretical and technological exploration of deep in situ fluidized coal mining"	64	1280
[37]	"Innovations as a Factor in the Development of the Natural Resources Sector"	59	1180
[38]	"Are cleaner production innovations the solution for small mining operations in poor regions? the case of Padua in Brazil"	59	590
[39]	"Factors driving or impeding the diffusion and adoption of innovation in mining: A systematic review of the literature"	58	1450
[40]	"Coal mining and environmental development in southwest China"	54	771

Notes: TC = total citations; C/Y = total citations per year

3.8. Network Analysis

Network analysis is one of the most prevalent instruments in bibliometric analysis. Donthu (2019) termed this study as scientific mapping, which examines the relationships among research elements. The approach examines the intellectual interactions and organizational affiliations among research participants. [41] asserted that VOSviewer is extensively utilized for network analysis. The subsequent part analyzes the co-occurrence and cluster dynamics of innovative research within the mining sector.

The fundamental concept of keyword analysis is that the writer's selection of keywords adequately represent the article's content [42]. The co-occurrence of two terms in the article signifies a connection between the two themes. To examine the last research question (RQ4), we utilize co-occurrence and cluster analysis using the VOSviewer software. We employed VOSviewer, a software application for constructing and visualizing bibliometric networks, to analyze the provided keywords and generate a mapping of these keywords to each article. Figure 3 depicts a network visualization of authors' keywords created by VOSviewer. The visualization showcases the strength of the connections between keywords through the use of color, the size of the circles, and the font and thickness of the connecting lines. Keywords that are related are often grouped together based on their color. The significance of an item or keyword increases proportionally with its frequency, resulting in a larger circle.

The frequency of recurrence directly influences the dimensions of the items. Unsurprisingly, the mining industry and innovation are the most often researched topics, given their high occurrence rate. The analysis has resulted in the development of four clusters in innovative research within the mining industry, based on the author keywords (Table 8). The total unique author's keywords found in this study are 1422 words. Table 10 shows the most frequently used keywords that occur at least three times. There are four clusters indicates main

research topic in this field— Cluster 1 comprises a total of 17 articles. The predominant terms in this cluster pertain to the mining sector, innovation. investment, productivity and competitiveness. The theme label of this cluster is Competitiveness through Innovative Investments. This research theme focuses on how investment in innovation can increase productivity and competitiveness in the mining industry. In this context, innovation includes the development of new technologies, more efficient operating methods, as well as the implementation of sustainable practices that can reduce costs and increase output.

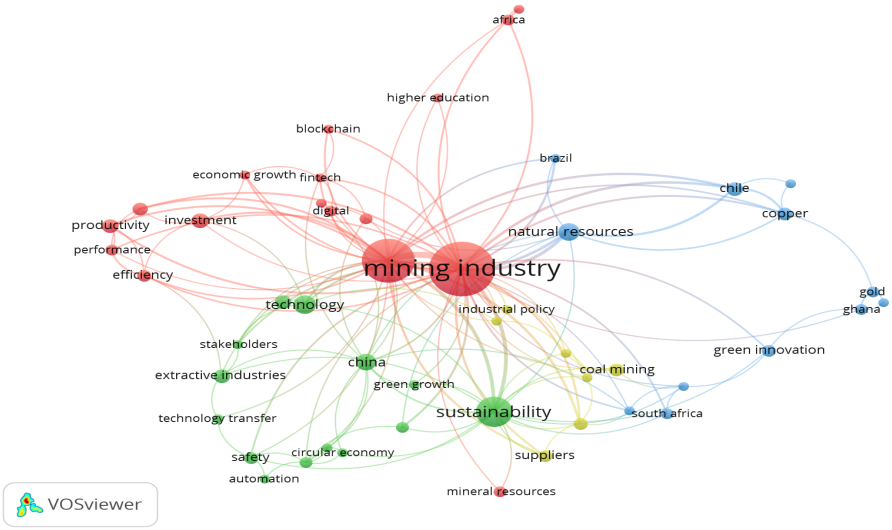

Figure 3. VOSViewer's network visualisation

Table 8. Cluster analysis

Most Frequent Keywords	Cluster	Occurrences	Total Link Strength	Total Keywords (Items)
Mining industry	1	104	110	17
Innovation	1	66	91	
Investment	1	8	8	
Productivity	1	7	9	
Competitiveness	1	6	9	
Sustainability	2	32	33	14
Technology	2	12	11	
Extractive industries	2	7	6	
Safety	2	5	7	
Environment	2	4	8	
Natural resources	3	11	23	12
Copper	3	6	12	
Green innovation	3	5	5	
Knowledge sharing	3	3	7	
Knowledge management	3	3	6	

Most Frequent Keywords	Cluster	Occurrences	Total Link Strength	Total Keywords (Items)
Coal Mining	4	6	5	7
Strategy	4	5	11	
Supplier	4	5	8	
Energy Security	4	3	6	
Open innovation	4	3	5	

Cluster 2 contains fourteen keywords The primary terms are sustainability, technology, extractive industries, safety and environment. The label of this cluster is Sustainable Mining Innovation. This research theme focuses on the intersection of sustainability and technology within the mining industry, emphasizing the development and implementation of innovative practices and technologies that enhance safety and minimize environmental impact. The theme explores how advancements in technology can contribute to more sustainable extractive processes, improve worker safety, and reduce the environmental footprint of mining activities. Cluster 3 consists of 12 items. Natural resources, copper, green innovation, knowledge sharing and knowledge management constitute the predominant keywords within this cluster. The designation of this cluster is Resource Management in the Mining Sector. This research theme focuses on the sustainable management of natural resources within the mining industry, with a particular emphasis on copper. It explores how green innovation practices are integrated into mining operations to minimize environmental impact. Additionally, the theme delves into the importance of knowledge sharing and knowledge management among stakeholders to foster sustainable practices and enhance operational efficiency. Cluster 4 has 7 keywords, with coal mining, strategy, supplier, energy security and open innovation as the most prevalent terms in this cluster. Coal Mining Strategic Innovation is the Overarching Theme of This Cluster. This research theme focuses on the strategic approaches and innovations in the coal mining industry aimed at enhancing energy security. The keywords suggest a comprehensive exploration of how coal mining operations are innovating their strategies and collaborating with suppliers through open innovation practices. The ultimate goal is to ensure a stable and secure energy supply.

4. Conclusion

The bibliometric analysis we conducted offers a thorough overview of innovative research in the mining industry. We identified significant publication trends, subject area, a detailed examination of the most prolific authors and countries, reflecting the model's global reach and interdisciplinary impact. The research has been predominantly published in the area of environmental science, suggesting that innovation in the mining sector is extensively examined from an environmental standpoint. The trend of the studies showed a significant increase in the aggregate count of publications (TP) and citations (TC) from the early 2000s, reflecting a growing academic interest in this topic. Our analysis reveals that innovation research in the mining industry is predominantly active in Asia, led by China, which has the most publications and citations, while South Africa stands out in Africa, and Australia represents Oceania with high-quality research. Our findings also highlighted the most prolific authors of innovation research in the mining industry. Warhust, A. from the United Kingdom leads among authors, followed by Cheng, Cheng, J. from China in second place, and Wiewiora, A. from Australia, who have notable contributions. The network and cluster analyses revealed four main themes in innovation within the mining sector. Despite significant advancements in innovation within the

mining industry, there remains a critical research gap, especially in the coal mining industry. It is important to understand the specific organizational innovations required to enhance business sustainability further. Existing studies often focus on technological improvements and external collaborations, but comprehensive research on internal organizational factors—such as leadership, culture, and learning and knowledge acquisition—is lacking. Furthermore, the interplay between these organizational innovations and external pressures like regulatory changes, market demands, and environmental concerns is not fully explored. Addressing this gap is crucial, as understanding these dynamics can lead to more effective strategies that not only boost operational efficiency but also ensure long-term sustainability and resilience of coal mining businesses in an increasingly volatile and environmentally-conscious market.

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