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Review

Harnessing Emerging Technologies in the Global Mining Sector from a Bibliometric Standpoint

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Abstract: The numerous challenges facing the global mining industry and the adverse impacts on the natural and human environment call for urgent action. In the present industry 4.0, the signature influx of emerging technologies (ETs) has seen various sectors of the economy embracing their application. To improve the safety, operational efficiency, and sustainability of the mining value chain, there has been a significant increase in the adoption, incorporation and application of ETs such as digital twins, artificial intelligence, the internet of things, and blockchain. Through a bibliometric analysis of scholarly publication outputs on ETs in the mining industry, this study visualises and ascertains the development and trends of these technologies from 1986 until now. Bibliometric datasets made up of 135 articles drawn from the popular Scopus database were employed. Dataset analysis revealed influential scholarly outputs, authors, and research clusters. The study provides relevant stakeholders in the sector with firsthand insight into the state of ET integration and use in the mining sector. Further studies are recommended to explore innovative technological interventions in other industries that can be adapted to enhance and optimise the activities and processes of the mining sector.

Keywords: artificial intelligence; digital technologies; health and safety; industry 4.0; mining industry; sustainable development goals

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1. Introduction

The mining sector globally is one of the core industries responsible for gross domestic product (GDP) growth, economic development, and employment generation avenues. Despite its linkage to large social impacts, environmental disturbances, and inequalities, the mining sector provides the majority of the minerals that we are dependent on to provide energy, infrastructure, and other core basic amenities [1]. With the widespread clamour for sustainable development in all sectors of the economy, the mining sector remains behind owing to the continued pressure it experiences. Such pressure arises from the fact that replacing fossil fuel-based technologies requires mined metals such as cobalt, lithium, indium, and neodymium to enable sustainable technologies like distributed transmission grids, solar panels, electric vehicles, and wind turbines, among others [2]. Also, most African countries depend on mining as a source of income and GDP growth. Sub-Saharan Africa is an important region for the global supply of precious and significant minerals. For example, the region accounts for over 10% of global mine production, a 37% share of world diamond productions, and more than a 10% market share in six minerals (such as uranium, rutile, manganese, cobalt, and bauxite) with mostly all African countries

known for one mineral or other [3]. Also, countries such as China, India, and Indonesia are regarded as top mining economies, with China widely known to be the leading mining country for most commodities. According to Statista [4], as shown in Figure 1, the top ten leading gold mining countries in the world based on production in metric tons are China, Australia, Russia, Canada, the United States, Kazakhstan, Mexico, Indonesia, South Africa, and Uzbekistan. Hence, the economic derivatives of the mining sector seem to overshadow the need to consider the various adverse impacts of the industry on the environment. To overcome these challenges, among numerous others, the mining sector will have to reinvent itself, embrace innovative approaches, and ensure minerals can be efficiently and sustainably exploited to support global development that leads to the people's welfare and quality of life [5]. As a result, voluntary initiatives are undertaken by major mining entities to meet their social and environmental responsibilities [6]. A major game changer and intervention is the influx and application of emerging technologies (ETs) to solve the various challenges experienced in the mining sector.

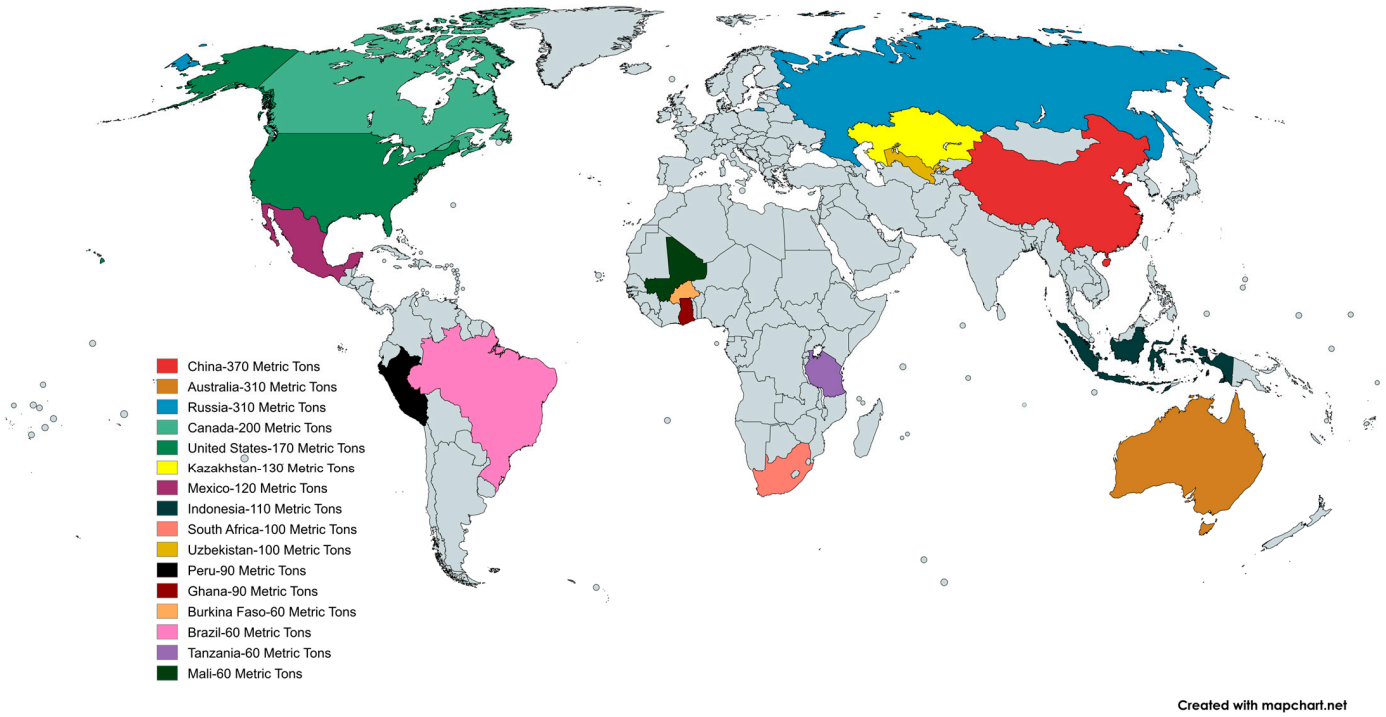


Figure 1. World-leading gold mining countries in 2023 [4].

2. Emerging Technologies for Mining Solutions

Despite the mining industry's socioeconomic impact, the sector faces numerous challenges, such as accidents, safety concerns, and environmental degradation. A study by Nicholaus Chusi et al. [7] identified poor capital, poor infrastructure system, lack of skilled labour, decline of mineral deposits due to over-exploitation, lack of water and energy supply, poor condition of workers, political barriers, and local market issues, among others. The numerous problems facing the mining sector were grouped into environmental, operational, and social challenges with a lack of automation and technological intervention [8]. Hence, some of the opportunities to address these challenges are to develop and incorporate clean technologies and utilise intelligent industry 4.0 solutions to improve mining efficiency and occupational safety [9]. The essence of technological interventions lends credence to the general understanding that ETs can revolutionise various sectors of the economy when adopted and embraced holistically. For an industry such as mining, it is, therefore, imperative that ETs play a significant role in reinventing the operations,

processes, and activities of the industry to minimise the challenges that have plagued the sector drastically.

Digitalisation in the mining industry entails using ETs or innovative digital systems to transform mining practices, improve productivity, and reduce costs [10]. Technological systems and innovations greatly benefit mining firms in improving mineral recovery, increasing production, lessening environmental impacts, and reducing costs associated with mining processes and activities [11,12]. Some notable ETs in the mining sector are 3D printing, machine learning, the internet of things, drones, remote operating centres, autonomous guided vehicles, quantum computing, power generation and storage, cybersecurity and encryption, text, image, and voice processing, digital trade and e-commerce, augmented reality, advanced process control, digital twins, cloud-based solutions, real-time data, real-time mine planning, artificial intelligence, enterprise resource planning, predictive maintenance, virtual reality mine training, real-time location sensing, cloud and edge computing, supply chain planning, robotics, automation and process integration, and blockchain, to mention a few [10,12–14]. Against the different mining value chains (exploration, establishment, mining, processing, waste management, smelting and refining, sales, and closure), these technologies have the potential to significantly affect and transform the mining sector [15]. As further alluded to by a study by Lazarenko et al. [12], ETs will improve resource management, enhance performance management, and advance marketing management for the core stages of the mining value chain that consist of exploration, planning and mine development, engineering and construction, operations and logistics, and sales and marketing. Hence, this study explores the exploitation of ETs in the global mining sphere, utilising a bibliometric analysis to visualise and ascertain their development and trends.

3. Research Methodology

This study is intended to determine the key subjects of interest in publications about ETs in the global mining industry. Consequently, a bibliometric methodology was employed to identify research trends and map out areas of knowledge. Relevant publications for the investigation were found using the Scopus search engine. This is because Scopus has wider coverage and indexes most papers in other databases, including Web of Science, ScienceDirect, and Google Scholar [16,17]. Similarly, Scopus is adjudged as the largest citation and abstract database of peer-reviewed scholarly publications and is highly subscribed to by most higher education institutions [18]. Some studies have acknowledged the significance of Scopus as a more recent and rapidly expanding database and a favoured option for literature search [17,19]. The search keywords were “Emerging Technologies” OR “Emerging Technology” OR “Digital Technologies” OR “Digital Technology” AND “Mining Industry” OR “Mining Sector”. All mining-related fields were considered, including engineering, environmental science, computer science, energy, earth and planetary science, etc. The period that was considered was 1986–2025. The search was conducted on 17 November 2024. Journals, conference articles, and book chapters were all included. The search, which was limited to English, produced 136 publications. VOSviewer, a program appropriate for bibliometric literature evaluations, was used to graphically analyse the data [20]. Figure 2 depicts the research process and outputs, namely “Publication per year”, “publications per country”, “publications by document source”, “most cited publications”, and “co-occurring analysis”.

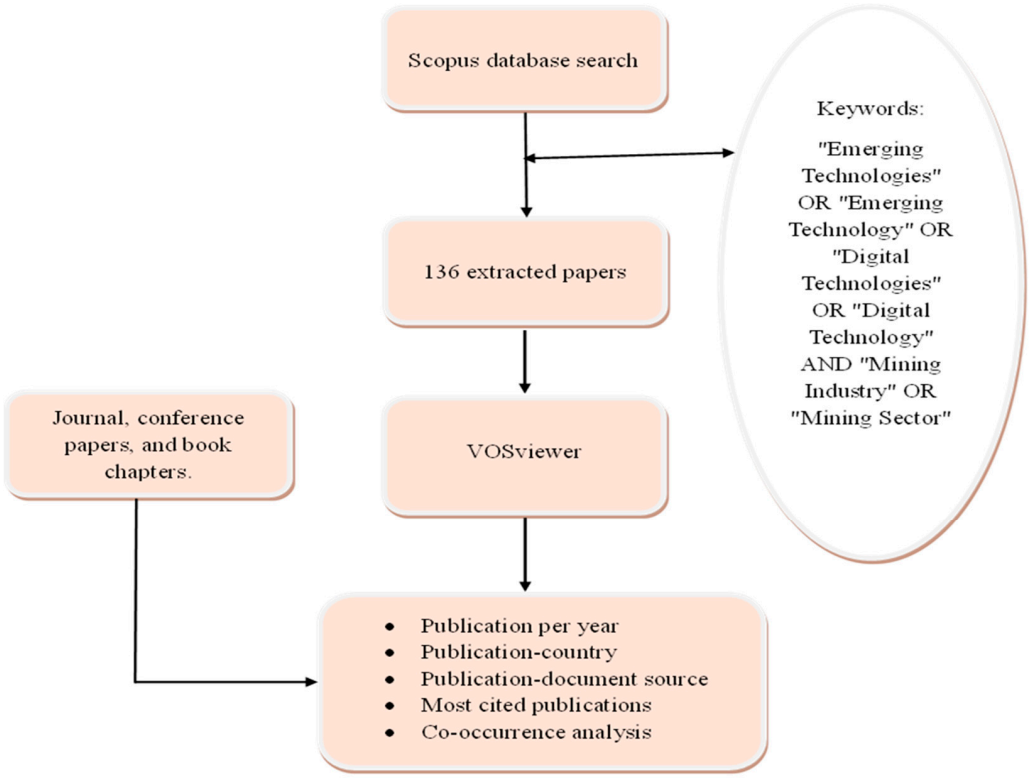


Figure 2. Research methodology flowchart.

4. Results and Discussions

This section presents the results and discusses the analysis of the 136 articles that constitute the dataset employed for the bibliometric analysis in this study.

4.1. Publications per Year

Figure 3 indicates yearly publications in the Scopus database relating to emerging technologies in the mining sector from 1986 to 2025. Results showed that one publication was made yearly from 1986 to 2003 except for the years 1989, 1990, 1993, 1995, 1996, and 1997 with no publication. Similarly, one publication was made in 2006 and 2007. Also, other years with no publications included 2004, 2013, 2014, and 2016. Conversely, two publications were made in 2008, 2011, and 2015, while three were made in 2009, 2010, and 2012. From 2017, a major improvement and upward growth was seen with four publications, followed by six publications in 2018, and twelve and thirteen publications in 2019 and 2020, respectively. However, there was an increase to nineteen publications in 2021 and another decrease to sixteen and thirteen publications in 2022 and 2023, respectively. Notably, the highest number of publications (twenty-four) was recorded in 2024. Generally, the results indicate a rollercoaster ride and very scanty publications, especially from 1986 to 2016. However, findings revealed a significant improvement in published works from 2017 to 2024. Overall, results indicate a need for more scholarly output in the mining sector relating to the adoption, influence, and utilisation of emerging technologies.

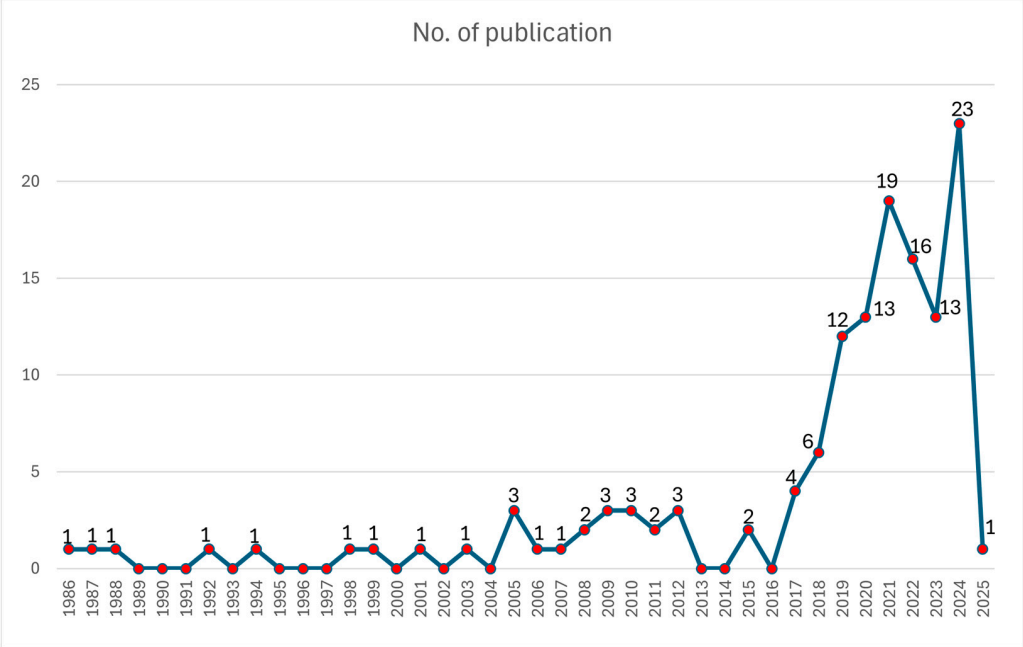


Figure 3. Number of publications per year.

4.2. Publications per Country

The 136 extracted documents were published in 48 countries. However, ten countries dominated the field at a threshold of five documents. The revealed countries are shown in Figure 4. Russia recorded the highest number of publications, with 22 documents and 184 citations. This was followed by Australia (21 documents; 239 citations), the United States (16 documents; 131 citations), China (12 documents; 137 citations), and Canada (11 documents; 42 citations). These were the top 5 countries among the listed 10 countries in Figure 3. India and South Africa were bracketed with 10 publications and ranked sixth position. Germany (nine documents; 161 citations) was ranked 8th, while Kazakhstan (six documents; 17 citations) and Chile (five documents; 27 citations) were ranked 9th and 10th, respectively. The results indicate a very wide range of significant publications on the subject in Asian, North American, and European countries. Notably, these countries are among the top mining countries in the world, known for their significant contributions to global mineral production [21,22]. Similarly, South Africa has contributed significantly to the subject compared to other African countries and is one of the leading African mining countries. Regrettably, Chile was the only South American country represented in the top category. Consequently, there is a great opportunity for African and South American countries, especially Congo (DRC), Zambia, and Brazil, which are among the top mining countries in their continent, to make significant research contributions to using emerging technologies in the mining sector [21–23]. Lumadi and Nyasha [24] highlighted frequently mentioned difficulties in adopting emerging mining technologies. These challenges include the sector's cyclical nature, high cost, uncertainty, poor involvement with external stakeholders, and significant risk associated with the implementation of unproven technologies and performance systems centred on volumetric production [24,25]. Consequently, proper learning culture and knowledge sharing were recommended as critical to adopting mining technology [24,25].

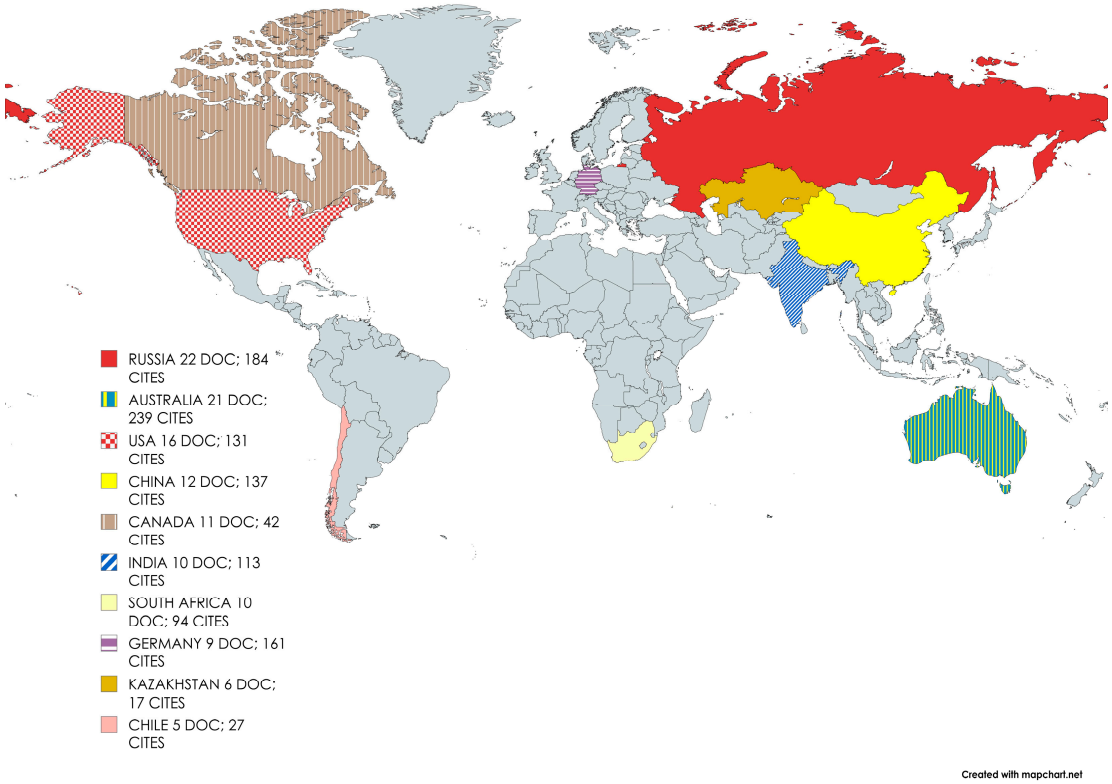


Figure 4. Number of publications per country.

4.3. Publications per Document Source

The 136 downloaded documents had 105 sources. However, with the VOSviewer default threshold of three documents, nine sources were unearthed and displayed in Table 1. According to Table 1, the ranked source included *E3S Web of Conferences* (six documents; 39 citations). This was seconded by *Resources Policy* (five documents; 85 citations). The rest of the sources had three documents. However, results showed that articles published in *Eurasian Mining*, MDPI's *Sustainability* (Switzerland), and the *Journal of the Southern African Institute of Mining and Metallurgy* had more citations compared to the rest with three documents. Overall, the results indicate scantiness in published works. Hence, there is a need for more publications of documents that Scopus indexes in reputable publication sources that are not listed in Table 1.

Table 1. Number of documents per source.

Source	Number of Documents	Citations
E3S Web of Conferences	6	39
Resources Policy	5	85
Eurasian Mining	3	36
Sustainability (Switzerland)	3	14
Journal of the Southern African Institute of Mining and Metallurgy	3	14
IOP Conference Series: Earth and Environmental Science	3	8
News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences	3	8
Journal Of Mines, Metals and Fuels	3	5
Canadian Mining Journal	3	0

4.4. Most Cited Publications

The 136 retrieved articles were examined to identify the most often cited papers and their primary topics for understanding emerging technologies research in the mining sector. Twelve relevant publications emerged when a criterion of 25 citations was applied. The significance and ambition to further the topic are reflected in the study with significant citation counts as seen in Table 2. Table 2 shows that reviews and experiments were the most employed approaches. Most of the focus was on blockchain technology, productivity, and supply chain improvement in the mining sector, especially in oil, gas, and energy. The results suggest that the concept is at the developing stage. It is critical to comprehend how emerging technologies can be adopted in the mining industry. Finding the ideal combination for the mining industry can only be accomplished through case studies and experimentation. Consequently, more studies on experiments and case studies are recommended.

Table 2. Most cited publications.

Author(s)	Title	Citations	Method
Johnson and Hallberg [26]	"Acid mine drainage remediation options: a review".	1715	Review
Barnewold and Lottermoser [10]	"Identification of digital technologies and digitalisation trends in the mining industry".	121	Review
Samylovskaya et al. [27]	"Digital Technologies in Arctic Oil and Gas Resources Extraction: Global Trends and Russian Experience".	62	Review
Mann et al. [28]	"Blockchain technology for supply chain traceability, transparency and data provenance".	42	Review
Divyasudha et al. [29]	"Analysis of Smart Helmets and Designing an IoT based Smart Helmet: A cost-effective solution for Riders".	32	Review
Quayson et al. [30]	"Building blockchain-driven dynamic capabilities for developing circular supply chain: Rethinking the role of sensing, seizing, and reconfiguring".	30	Case Study
Onifade et al. [31]	"Challenges and applications of digital technology in the mineral industry".	29	Review
Smith et al. [32]	"Spatial distribution and management of total actual acidity in an acid sulfate soil environment, McLeods Creek, northeastern NSW, Australia".	29	Experimental
Lacey et al. [33]	"Public perceptions of established and emerging mining technologies in Australia".	28	Survey
Bissell [34]	"Encountering automation: Redefining bodies through stories of technological change".	28	Interview
More et al. [35]	"Automated measurement systems in mine water management and mine workings–A review of potential methods".	26	Review
Carr et al. [36]	"Development of a method to determine operator location using electromagnetic proximity detection".	25	Experimental

4.5. Publications Based on Co-Occurring Keywords

A keywords co-occurrence map was made to properly characterise the focus subjects from the prior investigation. Among the keywords were author and indexed keywords. Consequently, the 136 papers that were downloaded contained 1241 keywords. Using the VOSviewer's default threshold of five co-occurrences, 24 keywords were left. Three clusters were produced as a result. The mapped keywords are displayed in Figure 5 and tabulated in Table 3.

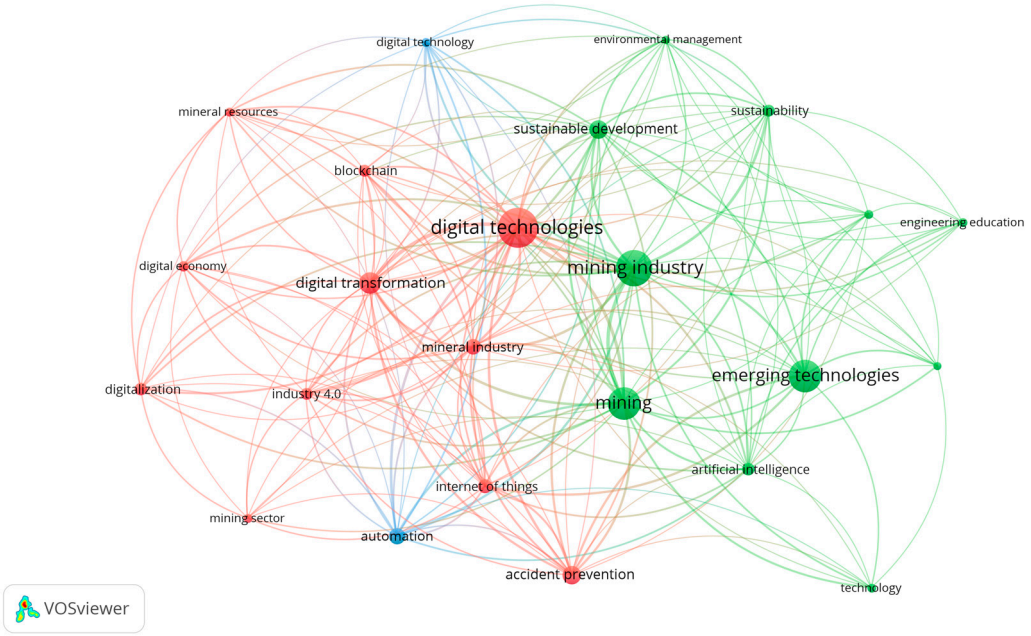


Figure 5. Network visualisation map for co-occurring keywords.

Table 3. Clusters of co-occurring keywords.

Clusters	Keywords	Occurrence	Link Strength
Cluster 1: Digital Transformation and Safety Management	Digital technologies	36	94
	Digital transformation	17	62
	Accident prevention	14	50
	Mineral industry	11	54
	Internet of things	10	41
	Digitalisation	9	26
	Blockchain	8	23
	Industry 4.0	8	34
	Digital economy	7	26
	Mineral resources	6	26
	Mining sector	6	15
	Total	132	451
Cluster 2: Sustainability Growth	Mining industry	32	93
	Emerging technologies	28	41
	Mining	28	87
	Sustainable development	14	54
	Artificial intelligence	9	35
	Sustainability	8	32
	Engineering education	6	14
	Environmental technology	6	18
	Technology	6	15
	Environmental management	5	21
	Mining operations	5	15
	Total	147	425
Cluster 3: Automation	Automation	12	43
	Digital technology	6	26
	Total	18	69

4.5.1. Cluster 1: Digital Transformation and Safety Management

This cluster comprised eleven keywords mapped with red with a total link strength of 451. Based on priorities/number of occurrences, the keywords included digital technologies, digital transformation, accident prevention, mineral industry, internet of things, digitalisation, blockchain, industry 4.0, digital economy, mineral resources, and mining sector. Consequently, the keywords in this cluster relate to Digital Revolution in the Mineral Industry: Leveraging IoT and Blockchain and Industry 4.0 for Transformation and Safety Management. For instance, routine tasks can be automated using IoT, improving workflows and lowering human error [37,38]. Costs are reduced, and productivity is raised as a result [38]. When utilised in an industrial setting, the insights gathered can be used right at once to improve asset management, worker safety, machine health, and process optimisation [37,39]. Similarly, with little human assistance, IoT can help real-time platforms remotely monitor and manage a complicated manufacturing system [37,39].

Conversely, blockchain technology is transforming the mining industry by enhancing transparency, security, and efficiency [40,41]. It makes adhering to rules and standards simpler by offering a safe and unchangeable record of transactions [40,42]. It can help with smart contracts (self-executing contracts) by automating procedures like payments and compliance, reducing the need for intermediaries [40,43].

4.5.2. Cluster 2—Sustainability Growth

This cluster, represented in green, is characterised by 15 items with a total link strength of 425. The keywords/items included mining industry, emerging technologies, mining, sustainable development, artificial intelligence, sustainability, engineering education, environmental technology, technology, environmental management, and mining operations. These keywords, therefore, relate to emerging technologies for sustainable growth in the mining industry. A typical example is the use of artificial intelligence (AI). AI is used for exploration, predictive maintenance, and environmental monitoring [44,45]. It lowers maintenance costs and downtime by improving the accuracy of mineral deposit identification and anticipating equipment faults before they happen [44,45]. Technological progress is fueled by the desire for sustainability, which results in cleaner and more effective mining techniques [46]. According to the International Institute for Sustainable Development (IISD) [47], sustainable mining methods limit emissions, waste, and land disturbance. Sustainable mining will improve the well-being of employees and local communities through enhanced safety protocols and cleaner operations [48]. Particularly through community engagement, it can offer communities long-term economic benefits, including infrastructure development and job generation [48].

4.5.3. Cluster 3—Automation

This cluster is represented in blue and has two keywords (automation and digital technology) with a total link strength of 69. The use of automation in the mining industry has been acknowledged to enhance efficiency, safety, and productivity [14,49]. The applications of automation in mining include autonomous haulage systems (AHSs), remote operation centres, automated drilling systems, and process optimisation [49,50]. AHSs' mining trucks and vehicles are equipped with autonomous technology, which enables them to function without direct human supervision [50]. AHSs lower operating costs, increase safety, and boost efficiency [49,50]. Similarly, remote operation centres enable mines to be operated remotely using sophisticated control systems and monitoring technologies [50]. Operational efficiency is increased through quick responses to possible problems made possible by real-time data collecting and analysis [50]. Conversely, automated drilling systems increase the speed and accuracy of drilling operations, reducing the need for manual labour and im-

proving safety [50]. Generally, the primary advantages of using digital technologies in the mining industry include "increased productivity, cost reduction, occupational safety, better working conditions, improved operational efficiency and reliability of information" [14].

4.6. Research Focus by Year of Publication

Figure 6 displays the "network map overlay visualisation" for the co-occurring keywords. It was observed that, in at least five occurring keywords, the predominant focus of the studies on emerging technologies in the mining industry included digital transformation and safety management, sustainability growth, and automation. Focus on keywords like automation, environmental management, and engineering education became evident in 2018. From 2019, studies majored in IoT, accident prevention, and sustainable development. From 2020 to 2021, keywords like digital transformation, digital technologies, digital economy, industry 4.0, and AI were viral. Also, from 2022 until now, studies on digitisation and digital technologies have further grown with blockchain technology and sustainability becoming more evident. However, keywords like 3D printing and additive manufacturing, augmented reality (AR), virtual reality (VR), bio-mining, phytomining, renewable energy integration, water recycling and treatment technologies, and clean tech solutions were missing. This indicates a major gap in studies on emerging technologies in the mining industry.

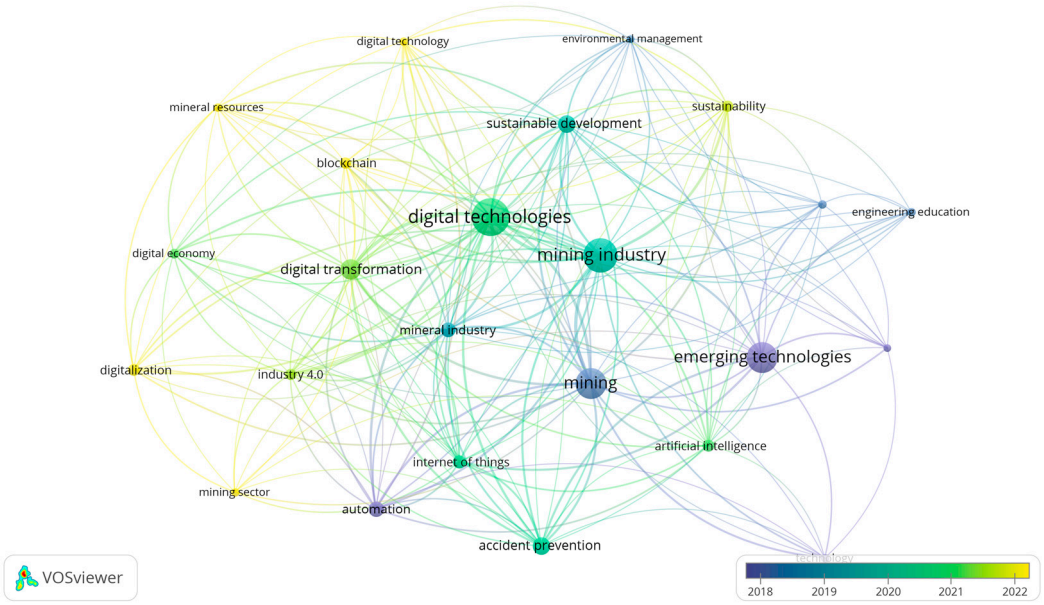


Figure 6. Overlay visualisation map for co-occurring keywords.

Nevertheless, the gaps provide opportunities for future researchers to contribute majorly to the highlighted areas. For instance, 3D printing can produce on-site mining equipment and spare parts, enabling less storage and transportation [45]. It also makes it possible to create equipment specifically suited to certain mining operations [45]. AR and VR technologies are used for training, simulation, and remote mining equipment operation, providing immersive experiences that improve worker safety and operational efficiency [45,51]. Renewable energy integration will reduce reliance on fossil fuels and lower greenhouse gas emissions [52]. Similarly, mines can reuse water through sophisticated water recycling and treatment systems, which minimise wastewater discharge and the demand for freshwater [52]. Reverse osmosis and membrane filtration are two technologies that guarantee more ecologically conscious mining operations [52]. Furthermore, clean tech solutions like carbon capture, storage, and utilisation, as well as waste

management technologies, can reduce the environmental impact of mining operations [45]. These technologies, therefore, should be carefully considered in newer research.

5. Conclusions and Recommendations

This study used a bibliometric technique to ascertain the focus on emerging technology research in the mining industry. The extracted papers span more than 20 years and are listed in the Scopus database. The results indicate a rollercoaster ride and very scanty publications, especially from 1986 to 2016. However, countries like Russia, Australia, the US, China, Canada, India, Germany, Kazakhstan, and Chile have made significant contributions. The highest number of publications on the subject in Scopus-indexed research was in 2024. Nevertheless, countries, especially in developing nations, are encouraged to make a substantial contribution towards the subject matter. The advantages of emerging technologies cannot be overemphasised.

Emerging/digital technologies have been found to improve operational efficiency, save costs, improve occupational safety, improve working conditions, raise production, and increase information dependability. Considering the clusters revealed, research on emerging technologies in the mining industry focused on digital transformation and safety management, sustainability growth, and automation. Furthermore, the study discovered that recent research in this field indicates enhancing transparency, security, and efficiency using blockchain technology.

However, there was a dearth of research on emerging technologies such as AR and VR, 3D printing and additive manufacturing, clean tech solutions, and water recycling and treatment technologies. These areas need to be more researched. Consequently, more studies on these technologies are required. For instance, the potential of AR and VR to enhance operational efficiency, training, and safety needs to be researched. Similarly, the efficacy of 3D printing and additive manufacturing in reducing inventory needs, minimisation of downtime, and cost reductions should be thoroughly studied. Similarly, energy raw material consumption is expected to climb by 2035, and the switch to renewable energy sources like solar and wind, and electric vehicles (EVs) necessitates a significant rise in vital minerals like lithium, cobalt, nickel, and rare earth elements. To guarantee the availability and affordability of raw materials, it is imperative to make investments in mining, refining, and supporting infrastructure.

This research has contributed to the body of knowledge by highlighting areas where studies on emerging technology in the mining industry have focused on. Its conclusions have also indicated possible directions for future research. However, this study only looked at papers from the Scopus database. For a more thorough grasp of the research topic, it is recommended that further studies be conducted to explore other databases or merge Scopus with other databases.

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