Mineral Economics
https://doi.org/10.1007/s13563-024-00455-w

ORIGINAL PAPER

Technological advances and trends in the mining industry: a systematic review

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Received: 14 March 2024 / Accepted: 24 June 2024

Abstract
Nowadays, in a competitive world, industries are faced with the urgent need to establish strategies for innovation, this is how the mining industry, a sector that contributes to the global economy, has been implementing digital technologies obtaining great results. Therefore, this paper aims to identify the most used technologies in the mining industry, determine in which mining processes these technologies are applied, assess their positive environmental impact, and analyze the benefits derived from their application to provide an integral view on the use and advantages of technology in the mining industry. The PRISMA methodology was applied, considering 63 manuscripts from databases such as Scopus, Web of Science, Taylor & Francis and ScienceDirect. As a result, it was found that the main digital technologies applied in the mining industry are Internet of things (IoT) and artificial intelligence (AI). The main benefits of the application of digital technologies in the mining industry are increased productivity, cost reduction, occupational safety, better working conditions, improved operational efficiency and reliability of information. It is concluded that digital technologies achieve economic benefits, but above all they contribute to the care of the environment and provide better working conditions. In other words, mining companies that adopt digital technologies will be well positioned to succeed in the future.

Keywords Artificial intelligence · Mining · Technology · Automation · Mining exploration · Sensors

Introduction

The mining industry, is today, one of the main sectors that contributes greatly to the global economy. However, monitoring factors associated with sustainability and safety in mining operations globally is crucial to mitigate negative socio-environmental effects. This includes the efficient use of water, reduction of the carbon footprint, adoption of renewable energies, reduction of mining waste and minimization of occupational hazards Cacciuttolo et al. (2023). In addition, with the evolution of geotechnology during the Fourth Industrial Revolution, it focused on its application by mining companies globally, offering significant benefits in terms of operational optimization, informed decision making and risk management Minbaleev et al. (2022).

In Colombia, one mining company has played a significant role in the region of Segovia and Remedios, Antioquia, providing approximately 20% of employment and contributing to gross wealth generation. In the 2002 period, the company generated 22,711 million pesos, and in 2003, 21,873 million pesos. In Chile, there was a notable decrease in poverty levels in several localities between 2000 and 2006 due to the presence of mining companies. For example, in Antofagasta, the poverty rate decreased from 12.9% to 6.1%; in Sierra Gorda it fell from 3.4% to 2.7%; in Maria Elena from 14.6% to 5.3%; and in Tatlal from 32.9% to 5.5%. These places experienced an increase in the quantity and quality of jobs due to mining operations. In Peru, the mining industry has had a significant impact on the economic and social development of the southern region from 2007 to 2020, with a contribution of 94.6% Simon et al. (2023)

It is indisputable that technologies have had a growth in recent years involving continuos development in computer

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applications, network technology, data storage technology. However, choosing which digital technologies to apply is no simple task Barnewold and Lottermoser (2020). Regardless of the sector, the application of digital technologies provides multiple benefits because it facilitates the collection and transmission of data between devices, leaving behind traditional methods that lead to higher investment, costs, and maintenance. AI can be combined with cloud computing, big data, computational intelligence, intelligent sensors, IoT and others Wei et al. (2023). In other words, soon it will be possible to significantly outperform human performance in a variety of applications that are currently carried out Ong and Gupta (2019). Specifically, AI is playing a key role in helping companies address these challenges and find more effective solutions Barnewold and Lottermoser (2020). In the mining industry, the implementation of AI is being considered for two main reasons: first, to optimize productivity and, second, to reduce the potential impact on the environment through the adoption of ethical mining practices Mishra (2021). So, in recent years, there has been a significant increase in the application of AI, especially machine learning Sirisha et al. (2022) and deep learning (Ali and Frimpong 2020), in production environments. This progress has led to the development of intelligent tools capable of instantaneous information gathering and sharing Sirisha et al. (2022) to solve different problems related to mineral exploration, extraction, and processing Ali and Frimpong (2020). The selection and operation of both underground and surface equipment, drilling and blasting of rocks, etc., are also important factors Ali and Frimpong (2020). In other words, greater accuracy in the extraction of minerals can be obtained with respect to conventional methods, improving time, safety, productivity, and profitability Yadagir et al. (2023). This means that machines are being built that perform their functions more efficiently, perform tasks more quickly and safely, and are also more environmentally friendly Ali and Frimpong (2020). Therefore, the integration of data from various sources is important, considering important aspects such as ethics and safety McGaughey (2020).

The adoption of advanced technology has had a positive impact in several areas of the mining industry. For example, Onifade et al. (2023) analyzed the technological evolution in mining, highlighting the possible adoption of digital technologies such as: automation, virtual reality, Big Data, IoT, cyber security. Improvements are foreseen in processes such as drilling, ventilation, and subway support, as well as in communication. However, identified challenges, such as privacy, legislation, and limitations in wireless networks in complex mines.

Xu et al. (2023) reported on the relationship between digital transformation (DT) and corporate social responsibility (CSR) in the mining sector, analyzing 1305 publicly traded mining companies. Technologies such as AI, blockchain, cloud computing and big data were highlighted for application in the mining industry. It was concluded that miners can use emerging technologies to improve efficiency, address social and environmental concerns, and reduce negative impact on the environment and employee health.

In addition, Pouresmaieli et al. (2023) focused on understanding the impact of IoT technology on mining and sustainable development. They concluded that IoT, by interacting with industrial machinery and interconnected networks, enables real-time monitoring and operation of production systems, improving efficiency and reducing human intervention. This impacts on increased production, occupational safety, and reduced pollution. The results indicated that IoT-based mining can boost productivity, wealth, revenue, and gross domestic product (GDP), as well as reduce operating expenses and depreciation costs, with a positive impact on the environment by reducing pollution.

Zhironkin and Taran (2023) explored the influence of digitalization on open-pit mining and its impact on global energy supply. Predicted that by 2050, 80–90% of the mining industry will adopt digital technologies such as AI, IoT, machine vision and unmanned equipment to address energy, environmental and social issues. In addition, it was recognized that the transition to renewable energy sources will take time and it is crucial to drive innovation in Mining 4.0 to reduce environmental impact. In this regard, the need to modernize fossil energy production in a more efficient pointed out that sustainable alternatives to renewable energy will remain important. In other words, mining companies can maintain their profitability through smart mining systems based on Industry 4.0 and Mining 4.0.

Similarly, Zhironkina and Zhironkin (2023) addressed the transition of the mining industry to Mining 4.0 in the context of Industry 4.0. They emphasized the importance of humanization, with "smart" unmanned machines and consideration of post-mining recycling activities. Digitization in mining opens opportunities to improve productivity and occupational safety. As for Mining 4.0 it differs from previous industrial revolutions by focusing on the connection between people, machines, and technologies, not just automation. It was concluded that Mining 4.0 has the potential to increase production, reduce costs and improve occupational safety.

This paper aims to identify the most used technologies in the mining industry, determine in which mining processes these technologies are applied, assess their positive environmental impact, and analyze the benefits derived from their application to provide an integral view on the use and advantages of technology in the mining industry.

Materials and methods

This study uses the PRISMA methodological approach, which provides advantages for authors, editors and reviewers involved in the evaluation of systematic reviews. This methodology guides researchers in the task of concisely synthesizing the information contained in articles or research sources related to the research. It aims to improve the transparency, completeness, and accuracy of publications to facilitate decision-making based on solid evidence Sohrabi et al. (2021).

Prisma offers a structure that acts as a set of guidelines for a more systematic and understandable development. The following are the corresponding steps according to the PRISMA method:

– Include documents relevant to the research.
– Exclude duplicate documents.
– Eligibility analysis is developed.

Research questions

The questions for the present research in the systematic review are:

RQ1: What are the most used technologies in the mining industry?
RQ2: In which process of the mining industry can the technologies be applied?
RQ3: What is the positive environmental impact of these technologies?
RQ4: What are the benefits of applying the technologies in the mining industry?

Search strategy

The string used for the research-responsive manuscript search is presented in Fig. 1.

After searching the databases using the search strings described in Table 1 the manuscripts that meet the research objective were reviewed as shown in Fig. 2 the largest number Web of Science.

A total of 1755 scientific articles were identified during the search in various databases. These articles were subjected to exclusion criteria that included verification of duplicities between the results of the databases and relevance to the research topic. After this process, 63 articles relevant to the research were selected, as detailed in Fig. 3 which illustrates the application of the PRISMA methodology in the selection process.

Manuscripts were selected by applying the inclusion and exclusion criteria, as shown in Table 2.

"mining industry" OR "mining exploration" AND "mining activity" AND "minerals" AND technology

Fig. 1 Search chain for documents related to the research topic

Table 1 Search string

Database	*Search string*	*Filters*
Scopus	"mining industry" OR "mining exploration" AND "mining activity" AND "minerals" AND technology	TITLE-ABS-KEY ("mining industry" OR "mining exploration" AND "mining activity" AND "minerals" AND technology) AND PUBYEAR > 2012 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp"))
Web of Science		"mining industry" OR "mining exploration" AND "mining activity" AND "minerals" AND technology (All Fields) and 2024 or 2023 or 2022 or 2021 or 2020 or 2015 or 2014 or 2013 or 2016 or 2017 or 2018 or 2019 (Publication Years) and Open Access and Article or Proceeding Paper (Document Types) and English (Languages)
Taylor & Francis		[All: "mining industry"] OR [[All: "mining exploration"] AND [All: "mining activity"] AND [All: "minerals"] AND [All: technology]] AND [Article Type: Article] AND [Publication Date: (01/01/2013 TO 12/31/2023)]
ScienceDirect		"mining industry" OR "mining exploration" AND "mining activity" AND "minerals" AND technology

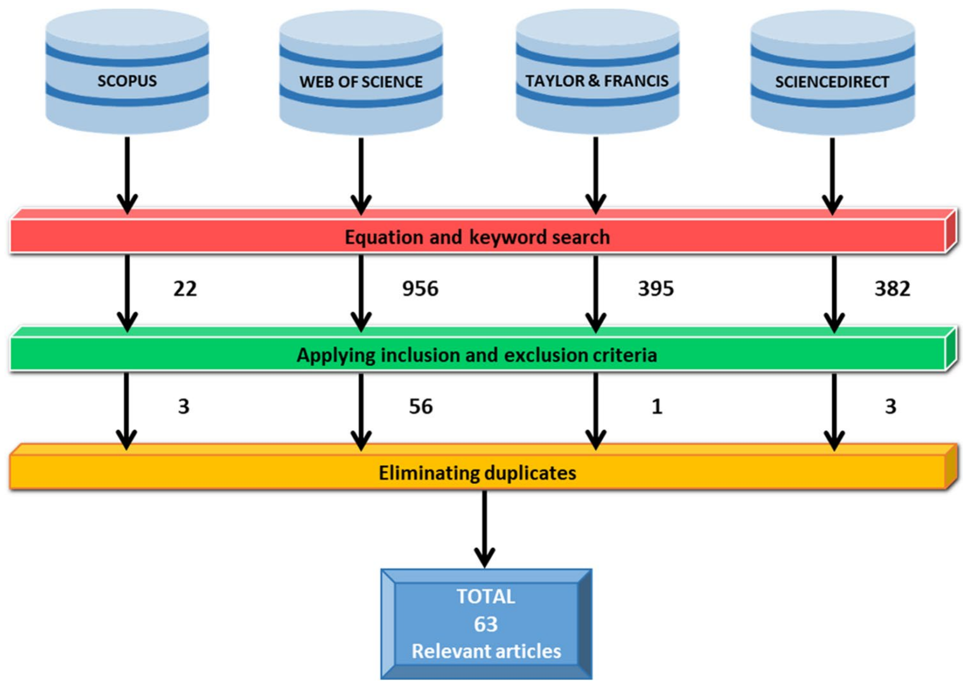


Fig. 2 Information resources

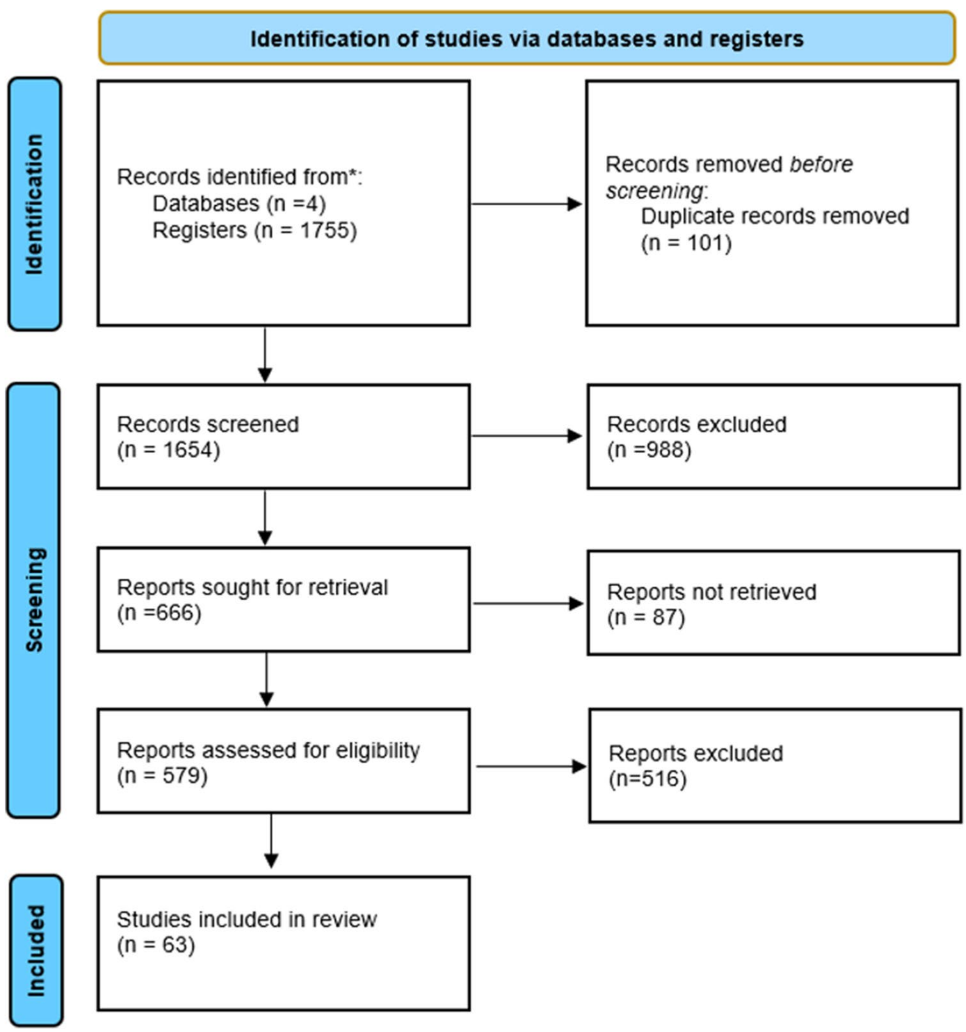


Fig. 3 Scientific article selection process according to PRISMA methodology

Table 2 Inclusion and exclusion criteria

Inclusion criteria	*Justification*
• Manuscripts related to technological advances and trends in the mining industry	• Aligned with the research objective
• Manuscripts mentioning mining industry processes in which technologies can be applied	• Obtain specific and practical knowledge that is valuable for the improvement and sustainable development of the industry
• Manuscripts mentioning the contribution to environmental care of the technologies applied in the mining industry	• To provide essential information to assess the environmental sustainability of mining practices, facilitating responsible decision making and the promotion of greener approaches in the sector
• Manuscripts mentioning the benefits of the application of technologies in the mining industry	• Analyze how technologies improve efficiency, reduce costs, optimize processes, and contribute to safety, facilitating informed decisions for the development and competitiveness of the mining sector
• Manuscripts no more than 11 years old	• It guarantees the relevance and timeliness of the information, allowing access to recent research that reflects advances and current trends in the application of technologies in the mining industry
• Full text manuscripts	• Increased number of publications and reliability
• Manuscripts in English	• Increased number of publications and reliability
• Papers published in relevant databases	• Credibility ensuring the authenticity of the investigation
Exclusion criteria	***Justification***
• Research other than articles	• Books, theses, manuals, or similar research
• Studies unrelated to technological developments and trends in the mining industry	• They do not contribute to the research
• Items over 11 years old	• Recent information is needed to contribute to the study

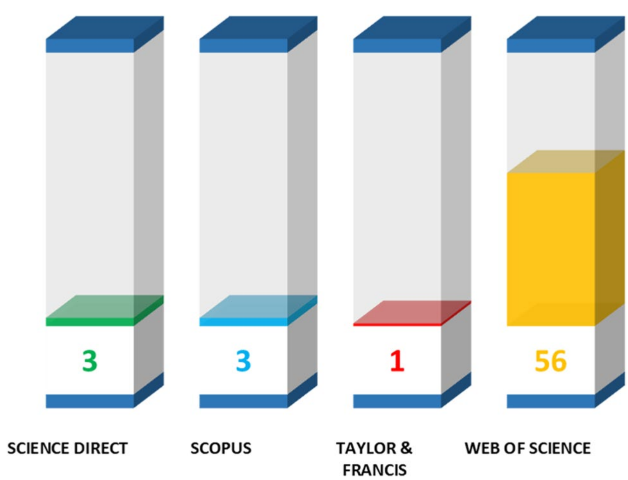


Fig. 4 Articles grouped by database

Results

In the present study, 1755 articles obtained from the various databases were analyzed. After applying the PRISMA methodology, as shown in Fig. 4, 3 articles were found in Science Direct, 3 articles in Scopus, 1 article in Taylor & Francis and 56 articles in Web of Science for a total of 63 scientific articles with relevant information were obtained.

Figure 4 shows the distribution of articles obtained from the different databases with the keywords used, with a clear majority of articles obtained from Web of Science for the period from 2013 to 2023.

Figure 5 specifies the database and the year of publication of the articles, showing that 17 manuscripts were published in 2022 which is the year when publications peaked in the given time frame.

The country with the highest number of published articles significant for this research is China with a total of 10 manuscripts, the United States with 7, Poland with 6, South Africa with 5 and Russia with 4, as shown in Fig. 6.

As what continents the research was focussed on it was found that Asia and Europe are the leading continents with a total of 23 articles respectively, followed by the Americas with 12 publications and finally Africa with 5 publications, as can be seen in Fig. 7.

A bibliometric analysis was performed, which consists of a quantitative analysis using statistical methods, bibliographic mapping, among others, with the objective of finding trends in a specific topic Rahman et al. (2020).

VOSviewer was the tool used to perform the bibliometric analysis, which makes graphical representation of bibliometric networks possible. These networks can consider journals, researchers or individual publications being created from citations, co-authorships, bibliometric coupling, or co-citation VOSviewer—Visualizing Scientific Landscapes (2024).

Figure 8 shows the network diagram which represents the main digital technologies that are having a great impact on the mining industry. The technologies are grouped

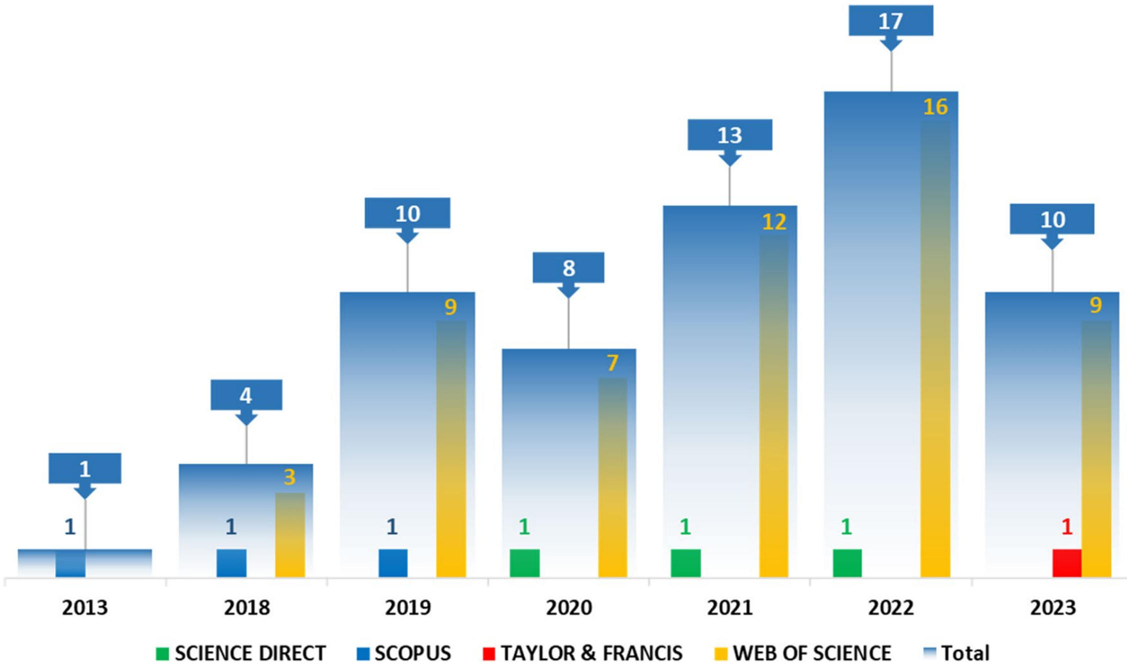
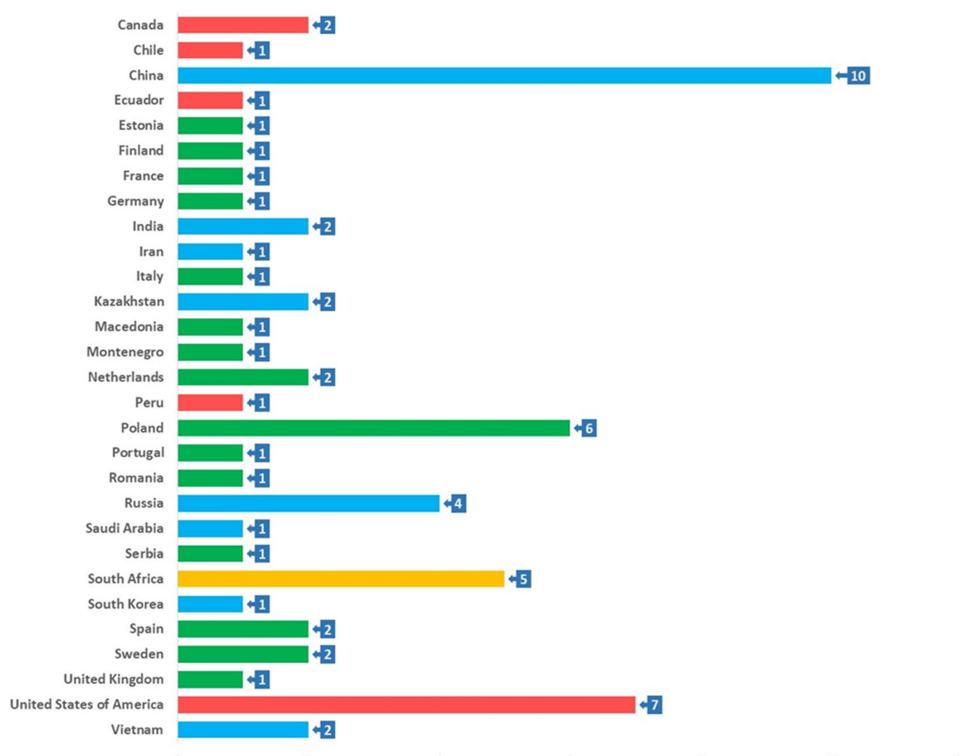


Fig. 5 Articles grouped by year and database

Fig. 6 Articles grouped by country of affiliation of first author



around four main themes: first sustainability because they seek to reduce the environmental impact they cause when extracting minerals, the second theme is artificial intelligence with which it is possible to ensure job safety and efficiency, highlighting robotics, artificial vision, and autonomous mining. The third theme is digitalization because with IoT, big data and augmented reality data are collected in real time for analysis and finally the theme of

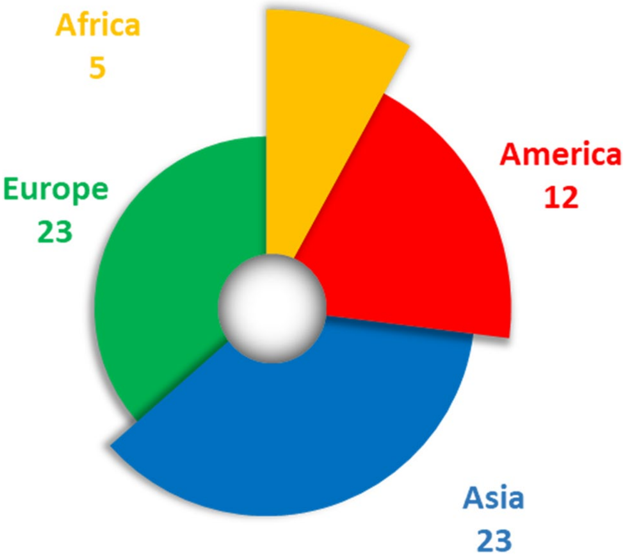


Fig. 7 Articles grouped by continent

innovation stands out because with digital technologies new approaches to mining such as space mining and urban mining are presented.

In other words, digital technologies are driving the transformation of the mining industry, making it more sustainable, efficient, and safe. Considering the reduction of environmental impact and achieving sustainability by finding ways to operate sustainably.

Discussion

RQ1: What are the most used technologies in the mining industry?

As can be seen in Table 3 and Fig. 9, in the last ten years, IoT is the most used digital technology in the mining industry. Involves the creation of a networks where various devices communicate making possible remote monitoring and access to information in real time of the activities performed by workers in the mine. Sensors integrated into work clothes monitor the health and physical conditions of workers and thus can assess urgent medical situations. Also, with IoT you can monitor environmental conditions such as temperature, humidity, and air quality to identify hazardous situations. Therefore, with IoT it is possible to improve efficiency, reduce human intervention, increase production, reduce pollution, and ensure occupational safety Pouresmaieli et al. (2023). According to Adjiski et al. (2019) nowadays worker safety has become a priority with the objective of using all the information collected to prevent accidents. As for other digital technologies, it was found that artificial intelligence (autonomous learning, neural networks, machine learning, automatic speech recognition (ASR), Big Data and robotics) represent important new applied digital technologies for the automation of processes, simulate human behavior, autonomous vehicles, robotization of operational and risky activities, in all making mining more sustainable Onifade et al. (2023).

Fig. 8 Visualization of the bibliometric analysis network

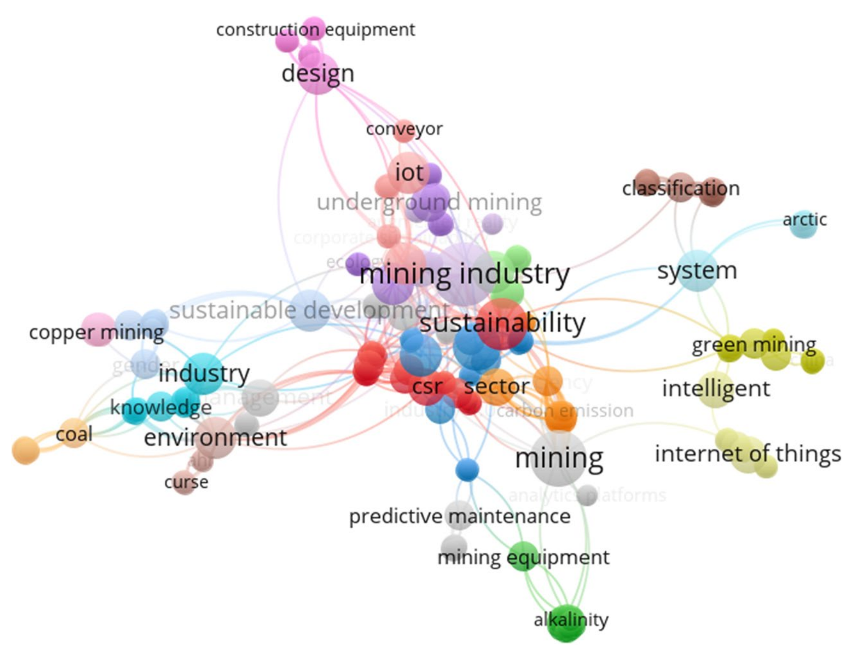


Table 3 Most applied digital technologies in the mining industry

	Technologies	*%*	*Manuscripts*
Industrial Revolution 3.0	Internet of Things (IoT)	35	(Adjiski et al. 2019; Aguirre-Jofré et al. 2021; Alenezi et al. 2022; Barnewold and Lottermoser 2020; Bi et al. 2022; Bisschoff and Grobbelaar 2022; Bui et al. 2019; Evsutin and Meshcheryakov 2020; Gackowiec and Podobinska-Staniec 2019; Jacksha and Raj 2021; Li et al. 2021; Lööw et al. 2019; Majstorovic et al. 2021; McNinch et al. 2019; Min et al. 2023; Oltmanns and Petruska 2023; Pandey and Mishra 2022; Radonjic et al. 2022; Samylovskaya et al. 2022; Stefaniak et al. 2023; Van Hau et al. 2022; Zulu et al. 2021)
	Big Data	13	(Barnewold and Lottermoser 2020; Bi et al. 2022; Bisschoff and Grobbelaar 2022; Evsutin and Meshcheryakov 2020; Pytel et al. 2020; Samylovskaya et al. 2022; Van Hau et al. 2022; Zulu et al. 2021)
	Cloud computing	10	(Aguirre-Jofré et al. 2021; Bi et al. 2022; Majstorovic et al. 2021; Newman et al. 2018; Pandey and Mishra 2022; Van Hau et al. 2022)
Indust rial Revolution 4.0	Autonomous learning	11	(Barnewold and Lottermoser 2020; Bi et al. 2022; Gackowiec and Podobinska-Staniec 2019; Li et al. 2021; Mtotywa and Dube 2023; Stefaniak et al. 2022; Zulu et al. 2021)
	Neural networks	3	(Li et al. 2023; Santoro et al. 2022)
	Machine learning	3	(Barnewold and Lottermoser 2020; Min et al. 2023)
	Blockchain	5	(Bi et al. 2022; Evsutin and Meshcheryakov 2020; Liang et al. 2020)
	Robotics	8	(Barnewold and Lottermoser 2020; Li et al. 2022; Lopes et al. 2018; Samylovskaya et al. 2022; Zulu et al. 2021)
	Augmented reality	3	(Kim et al. 2018; Samylovskaya et al. 2022)
	Virtual reality	3	(Kim et al. 2018; Samylovskaya et al. 2022)
	Automatic Speech Recognition (ASR)	2	(Stefaniak et al. 2022)

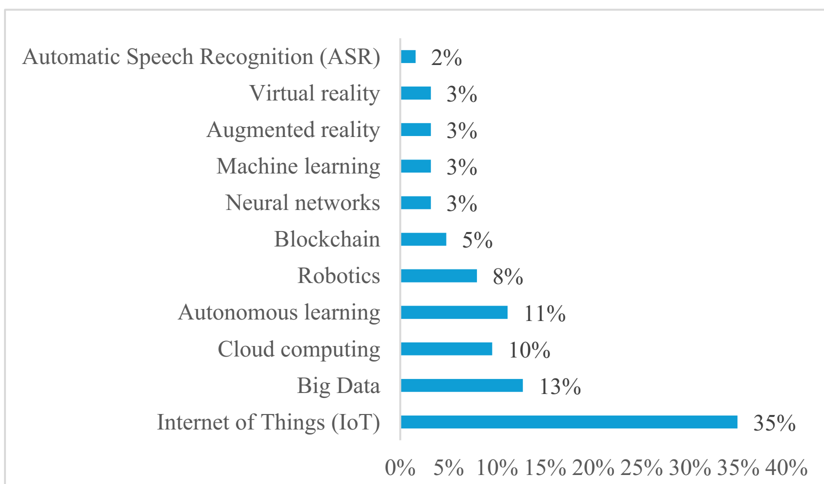


Fig. 9 Most applied digital technologies in the mining industry

RQ2: In which process of the mining industry can the technologies be applied?

Table 4 and Fig. 10 shows the various processes in the mining industry in which digital technologies are being applied to improve efficiency and sustainability. For example, in the exploration process, remote sensors, satellite sensors and drones are used to analyze geological and topographic data considering the ruggedness of the area, in addition to the fact that there may not be a wireless communications infrastructure that makes possible the application of IoT, which enables accessibility to information in a more accurate and efficient way Pouresmaieli et al. (2023). In addition, with machine learning it is possible to analyze historical data to locate the occurrence of minerals, thus optimizing the exploration process. As for the extraction process, which includes excavation, great achievements have also been made with digital technologies such as improving the safety of personnel, ensuring much more responsible practices, use of machines that

Table 4 Mining industry processes where digital technologies are being applied

Processes	*%*	*Manuscripts*
Exploration	17	(Alenezi et al. 2022; Bertoni et al. 2022; Evsutin and Meshcheryakov 2020; Kim et al. 2018; Li et al. 2023; Lopes et al. 2018; Newman et al. 2018; Ozhigin et al. 2022; Qarahasanlou et al. 2022; Shrivastava and Vidhi 2020; Stefaniak et al. 2022)
Extraction (Excavation)	44	(Evsutin and Meshcheryakov 2020; Flores et al. 2020; Gackowiec and Podobinska-Staniec 2019; Karu et al. 2013; Li et al. 2023; Liang et al. 2020; Lopes et al. 2018; Majstorovic et al. 2021; McNinch et al. 2019; Min et al. 2023; Newman et al. 2018; Ngoma et al. 2023; Ozhigin et al. 2022; Pandey and Mishra 2022; Pesa 2021, 2022; Pytel et al. 2020; Radonjic et al. 2022; Raevich et al. 2023; Rahimi et al. 2022; Rebbah et al. 2021; Samylovskaya et al. 2022; Shrivastava and Vidhi 2020; Sobczyk et al. 2021; Van Hau et al. 2022; Zarubin et al. 2021; Zeng et al. 2023)
Processing	11	(Gackowiec and Podobinska-Staniec 2019; Li et al. 2021, 2022; Li et al. 2023; Lööw et al. 2019; Min et al. 2023; Shrivastava and Vidhi 2020)
Transportation	8	(Aguirre-Jofré et al. 2021; Evsutin and Meshcheryakov 2020; Li et al. 2021; Shrivastava and Vidhi 2020; Stefaniak et al. 2023)
Closing	3	(Qarahasanlou et al. 2022; Shrivastava and Vidhi 2020)

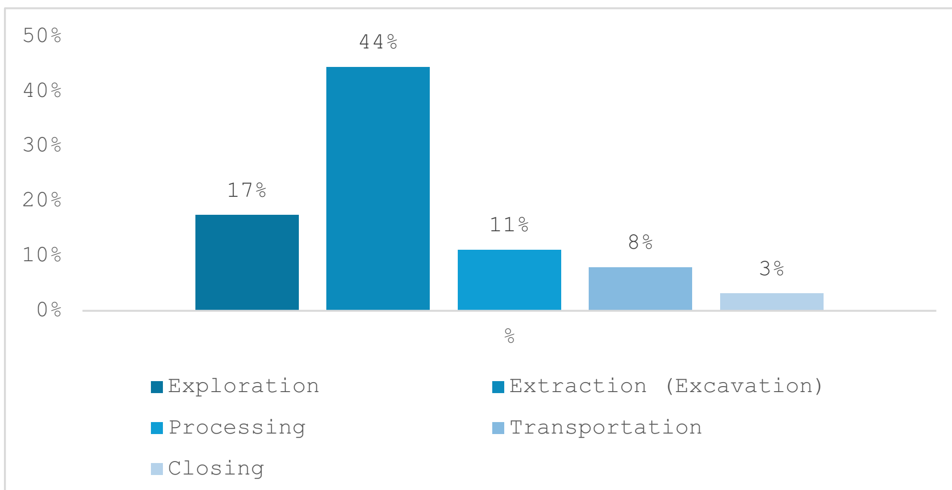


Fig. 10 Mining industry processes where digital technologies are being applied

have an autonomous learning which can perform operational activities risky for humans Lopes et al. (2018). Processing is the third process in which processes have been automated to increase efficiency, and an important factor is the quality of the minerals extracted to meet established standards. The transportation process continues with the routes followed to transport the minerals, as well as the importance of remote monitoring of the vehicles to ensure safety. Finally, the closing process, which must be planned to minimize the environmental impact, the Blockchain technology is applied to know the traceability of this process through the registration of activities, verification and compliance, waste management, audits, and mine closure certifications Zhironkin and Taran (2023).

In conclusion, all mining industry processes can evolve significantly, to make more informed decisions, reduce risks, and optimize the identification of valuable mineral deposits with the application of digital technologies.

RQ3: What is the positive environmental impact of these technologies?

It is no secret that human activities have negatively impacted the environment with decreased biodiversity, pollution of land, air, and water, work related injuries and causalties as well negative impact on local communities as a consequence Zhironkin and Taran (2023). Table 5 and Fig. 11 lists digital technologies that have a positive environmental impact on the mining industry by facilitating accurate planning and process automation, contributing to the protection and restoration of terrestrial ecosystems. In addition, real-time monitoring, water purification and air quality control ensure pollution reduction, while process optimization reduces waste and favors the use of renewable energy. The implementation of these technologies not only protects the surrounding ecology, but also reduces the overall ecological footprint of the mining activity,

Table 5 Positive environmental impact because of the application of digital technologies

Positive environmental impact	%	*Manuscripts*
Social responsibility	10	(Litvinenko et al. 2020; Posleman and Sallan 2019; Shrivastava and Vidhi 2020; Turcotte and Lachance 2023; Wozniak and Pactwa 2018; Yousefian et al. 2023)
Sustainable Development (Protect, restore, and promote the sustainable use of terrestrial ecosystems)	17	(Litvinenko et al. 2020; Marimuthu et al. 2021; Nguyen et al. 2021; Pandey and Mishra 2022; Poudyal et al. 2019; Qarahasanlou et al. 2022; Shrivastava and Vidhi 2020; Sobczyk et al. 2021; Van Hau et al. 2022; van Wyk and de Villiers 2019; Zulu et al. 2021)
Reduction of environmental impact	14	(Bertoni et al. 2022; Bi et al. 2022; Li et al. 2022; Ngoma et al. 2023; Oncioiu et al. 2019; Van Hau et al. 2022; van Wyk and de Villiers 2019; Wozniak and Pactwa 2018; Zarubin et al. 2021)
Water purification	5	(Karu et al. 2013; Li et al. 2022; Stander and Broadhurst 2021)
Air quality monitoring	2	(Bui et al. 2019)
Waste reduction	10	(Karu et al. 2013; Li et al. 2022; Lopes et al. 2018; Marimuthu et al. 2021; Shrivastava and Vidhi 2020; Stander and Broadhurst 2021)
Increased use of renewable energy	5	(Marimuthu et al. 2021; Shrivastava and Vidhi 2020; Stander and Broadhurst 2021)
Ecological protection	2	(Zeng et al. 2023)
Improves ecological quality	2	(Tang et al. 2022)
Reduction of the ecological footprint	3	(Rebbah et al. 2021; Turcotte and Lachance 2023)

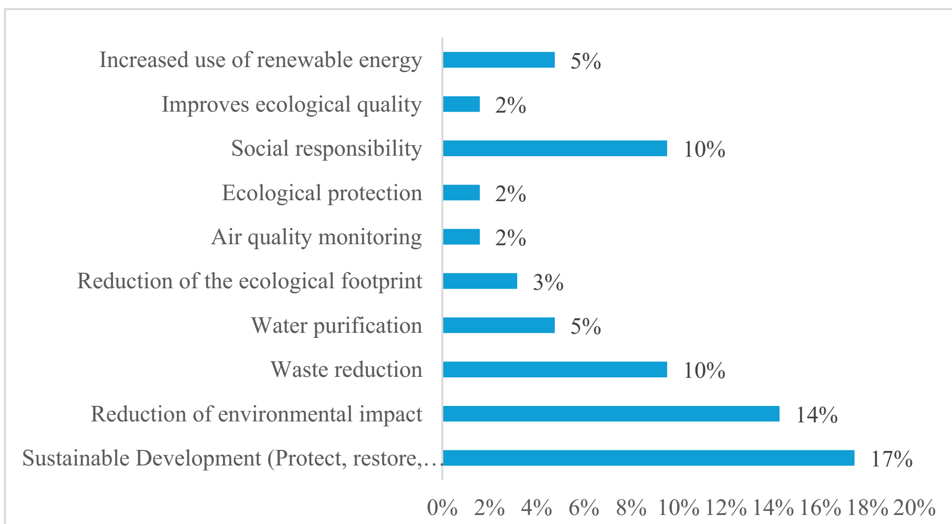


Fig. 11 Positive environmental impact because of the application of digital technologies

improving ecological quality and promoting sustainable practices in the industry Zhironkina and Zhironkin (2023). Therefore, the mining industry is applying digital technologies because there are many benefits that are achieved from an economic perspective and the added value that these technologies reduce the negative impact on the environment and ensures the health of workers Zhironkina and Zhironkin (2023).

Effective implementation of these technologies can lead to more environmentally responsible mining, allowing the industry to move towards more sustainable practices and mitigate the historical negative impacts associated with the extraction of mineral resources.

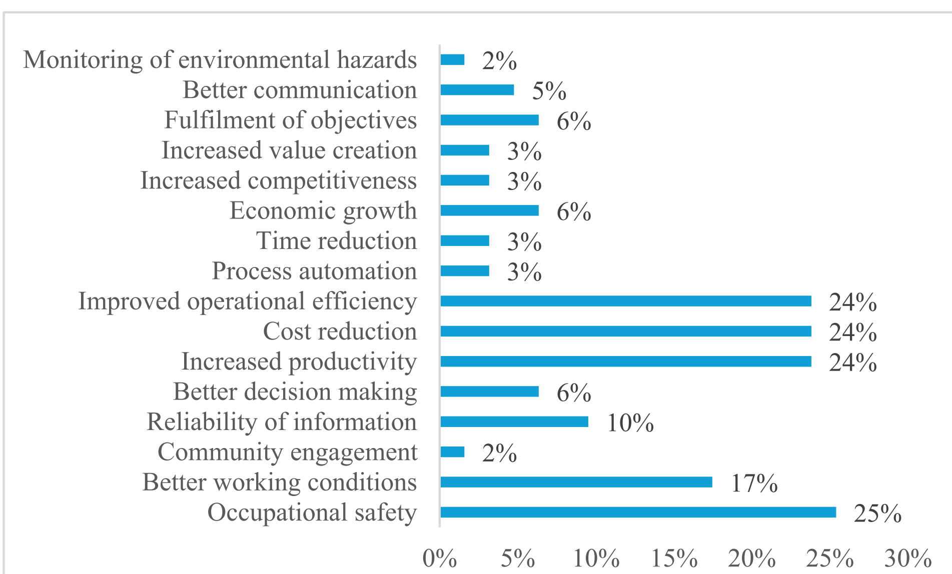
RQ4: What are the benefits of the application of technologies in the mining industry?

Today it has been demonstrated that digital technologies bring with them many benefits in the various sectors in which they are applied and that one of their main objectives is to improve the quality of life of people. The application of technologies in the mining industry brings several significant benefits in several key aspects as mentioned in Table 6 and Fig. 12. These benefits include significantly increased productivity and competitiveness, effective reduction of operating costs, strengthened occupational safety through monitoring systems, enhanced value creation both

Table 6 Benefits of the application of technologies in the mining industry

Benefits	%	Manuscripts
Increased productivity	24	(Aguirre-Jofré et al. 2021; Barnewold and Lottermoser 2020; Flores et al. 2020; Gackowiec and Podobinska-Staniec 2019; Kim et al. 2018; Li et al. 2021, 2022; Lopes et al. 2018; Mtotywa and Dube 2023; Oncioiu et al. 2019; Ozhigin et al. 2022; Radonjic et al. 2022; Van Hau et al. 2022; van Wyk and de Villiers 2019; Zulu et al. 2021)
Increased competitiveness	3	(Bi et al. 2022; Mtotywa and Dube 2023)
Cost reduction	24	(Aguirre-Jofré et al. 2021; Barnewold and Lottermoser 2020; Bertoni et al. 2022; Bui et al. 2019; Gackowiec and Podobinska-Staniec 2019; Li et al. 2022; Lööw et al. 2019; Lopes et al. 2018; Marimuthu et al. 2021; Oltmanns and Petruska 2023; Oncioiu et al. 2019; Pesa 2022; Radonjic et al. 2022; Samis and Steen 2020; Samylovskaya et al. 2022)
Occupational safety	25	(Adjiski et al. 2019; Gackowiec and Podobinska-Staniec 2019; Jacksha and Raj 2021; Li et al. 2021; Liang et al. 2020; Lopes et al. 2018; McNinch et al. 2019; Nguyen et al. 2021; Nguyen and Pham 2019; Oltmanns and Petruska 2023; Ozhigin et al. 2022; Pacheco et al. 2022; Shrivastava and Vidhi 2020; Stefaniak et al. 2023; Van Hau et al. 2022; van Wyk and de Villiers 2019)
Increased value creation	3	(Lopes et al. 2018; Stander and Broadhurst 2021)
Monitoring of environmental hazards	2	(Adjiski et al. 2019)
Process automation	3	(Aguirre-Jofré et al. 2021; Samylovskaya et al. 2022)
Fulfillment of objectives	6	(Aguirre-Jofré et al. 2021; Kim et al. 2018; Marimuthu et al. 2021; Oncioiu et al. 2019)
Time reduction	3	(Aguirre-Jofré et al. 2021; Stefaniak et al. 2022)
Better communication	5	(Alenezi et al. 2022; Min et al. 2023; Stefaniak et al. 2022)
Better decision making	6	(Bisschoff and Grobbelaar 2022; Evsutin and Meshcheryakov 2020; Newman et al. 2018; Zulu et al. 2021)
Better working conditions	17	(Jacksha and Raj 2021; McNinch et al. 2019; Nguyen et al. 2021; Oltmanns and Petruska 2023; Ozhigin et al. 2022; Pacheco et al. 2022; Shrivastava and Vidhi 2020; Stefaniak et al. 2022; Turcotte and Lachance 2023; Yousefian et al. 2023; Zulu et al. 2021)
Improved operating efficiency	24	(Gackowiec and Podobinska-Staniec 2019; Li et al. 2023; Liang et al. 2020; Lopes et al. 2018; McNinch et al. 2019; Min et al. 2023; Newman et al. 2018; Oltmanns and Petruska 2023; Ozhigin et al. 2022; Pandey and Mishra 2022; Radonjic et al. 2022; Samylovskaya et al. 2022; Stefaniak et al. 2023; Zarubin et al. 2021; Zulu et al. 2021)
Reliability of information		(Evsutin and Meshcheryakov 2020; Min et al. 2023; Samis and Steen 2020; Samylovskaya et al. 2022; Santoro et al. 2022; Stefaniak et al. 2023)
Economic growth		(Pandey and Mishra 2022; Pesa 2022; Yousefian et al. 2023; Zulu et al. 2021)
Community engagement		(Posleman and Sallan 2019)

Fig. 12 Benefits of the application of technologies in the mining industry



economically and environmentally, efficient monitoring and mitigation of environmental hazards, process automation for more efficient production, effective achievement of operational and sustainable goals, reduced production times, improved communication, more informed decision making, safer working conditions, increased operational efficiency, reliability of information supported by advanced data analytics, fostering economic growth, and enhanced engagement with local communities through sustainable and responsible practices. Taken together, these benefits contribute to more efficient, safer, and sustainable mining Pouresmaieli et al. (2023) thanks to optimization, autonomous learning, constant monitoring, among others. Undoubtedly the decision to implement digital technologies involves a thorough and deep analysis of all that it implies, considering the legislation and the limitations that may arise during the process Onifade et al. (2023).

The mining industry is important for the world economy because it provides the necessary resources to produce goods and services; however, it is essential to provide job security to workers because they are the ones who carry out the processes inside and outside the mine.

The Table 7 shows a matrix detailing in which mining processes the most used digital technologies are applied and the benefits obtained.

Conclusions

Manuscripts from 2013 and 2023 have been selected, finding at the beginning 1755, of which 63 manuscripts meet the inclusion and exclusion criteria, as for the methodology PRISMA was applied. Regarding the questions posed, the following results were obtained: First, the digital technologies applied in the mining industry are: Iot which stands out because it allows the use of sensors and digital twins, artificial intelligence (autonomous learning, neural networks, machine learning, automatic speech recognition (ASR), big data and robotics), augmented reality, virtual reality, cloud computing and blockchain. Secondly, it was found that the process of exploration and extraction (excavation) is where a greater application of digital technologies is evident because a key factor is to obtain information about the area and minerals to be extracted, another key factor is how to excavate and extract the minerals efficiently, as well as the processing, transportation, and closure of the mine. Thirdly, it is important to analyze the contribution of digital technologies to environmental care because there is still time to reverse all the damage that has been caused by contributing to sustainable development, reducing environmental impact, purifying water and monitoring air quality, reducing waste, promoting greater use of renewable energy, protecting the ecology and reducing the ecological footprint as a result of the processes carried out in the mining industry: increased productivity, cost reduction, labor safety, better working conditions, improved operational efficiency and reliability of information. In other words, mining companies that adopt digital technologies will be well positioned to succeed in the future.

Finally, the results of this research will help future researchers to investigate in which branches of digital technologies are specifically applied in the mining industry considering the size and geographical location of the mine, as well as the type of ore they extract. In addition, considering the evolution of technology in a changing environment, it will be possible to consider the application and integration of the technologies that are being created focused on achieving a more responsible and technologically advanced mining industry.

In terms of limitations, a relevant aspect is the investment required to implement digital technologies, followed by time, knowledge, resistance to change, geographical barriers and accessibility to information. However, it is all part of a transition process that today is necessary for any company seeking to stay in the market. Finally, mining companies must create awareness of the working conditions they offer their workers, as well as focus on environmental preservation.

The systemic limitations found in the literature review are as follows: there is a possibility that some relevant studies have been omitted in the review due to the limited availability of specific databases for the mining industry. On the other hand, the diverse nature of technological advancements in the mining industry can result in significant heterogeneity among the included studies, making it difficult to present quantitative data. As for the specific limitations, there is a lack of comparative studies in the selected articles, as no studies were found that directly compare different technologies, benefits, or approaches in the mining industry, limiting the review's ability to provide clear recommendations on which technologies are most effective in different contexts. Finally, the studies included in the review come from specific geographical regions or operational contexts, which limits the generalization of the results to a global level or to different types of mining operations.

The systematic review process highlights the pivotal role of the Internet of Things (IoT) in the mining industry, specifically in the extraction process. The implementation of IoT allows real-time monitoring of excavation operations, leading to significant improvements in operational efficiency. Additionally, IoT contributes to sustainable development by minimizing negative environmental impact, protecting, restoring, and promoting the sustainable use of terrestrial ecosystems. These benefits are crucial for various stakeholders, including mining companies, workers, and local communities, underscoring the importance of IoT in optimizing the mining industry.

Table 7 Matrix of digital technologies, mining processes and benefits of their application

Technologies	Mining industry processes where digital technologies are being applied					Benefits of the application of technologies in the mining industry															
	Exploration	Extraction (Excavation)	Processing	Transportation	Closing	Increased productivity	Increased competitiveness	Cost reduction	Occupational safety	Increased value creation	Monitoring of environmental hazards	Process automation	Fulfilment of objectives	Time reduction	Better communication	Better decision making	Better working conditions	Improved operational efficiency	Reliability of information	Economic growth	Community engagement
Internet of Things (IoT)	x	x		x		x	x	x	x		x	x	x	x	x	x	x	x	x		
Big Data	x	x	x			x	x	x								x	x	x	x	x	
Cloud computing	x	x	x	x		x		x	x			x	x	x							
Autonomous learning	x	x				x	x	x						x	x		x				
Robotics	x	x		x		x		x	x	x		x				x	x	x	x	x	
Blockchain	x	x			x		x		x							x		x	x		x
Neural networks		x	x																x		
Machine learning			x			x		x							x			x	x		
Augmented reality		x						x				x						x	x		
Virtual reality		x						x				x						x	x		
Automatic Speech Recognition (ASR)	x													x	x		x				

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Rosalynn Ornella Flores-Castañeda], [Sandro Olaya-Cotera], [Máximo López-Porras], [Esther Tarmeño-Juscamaita] and [Orlando Iparraguirre-Villanueva]. The first draft of the manuscript was written by [Rosalynn Ornella Flores-Castañeda] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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