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Digitization of the mining industry: Pathways to sustainability through enabling technologies

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ABSTRACT

Mining is one of the biggest industries in terms of product generation and revenue earned, and is deemed as the lifeline for countries around the world. However, in current times, it is ridden with several problems right from environmental threats to the slow turnover and throughput rate of production it offers. As a result, the demand of digitization and advancement of the mining process emerges so as to improve efficiency. With so many technological breakthroughs, there exists a need to realize what technologies are best suited for the development of a more sustainable mining industry. This study aims to recognize the enabling technologies for digitization of the mining processes using a three-step novel methodology. The findings indicate that sustainability is the most important criterion while big data analytics, machine learning, autonomous vehicles and artificial intelligence are most important technologies that enables digitization of the mining processes for sustainable mining.

1. Introduction

Historically, mining has played a significant role in enabling any country to embark on the path of prosperity due to the advantages it offers such as – enabling discovery of new resources, facilitating easy accessibility to minerals embedded deep in the earth's surface, which enables infrastructure development and being a huge source of job opportunities for people around the world (Duvall, 2019). The financial benefits that mining brings is immense for those who are involved in this industry right from companies, stakeholders to even the workers who are very much involved in the actual process as it opens up new opportunities for earning income and paves new ways for economic development. In spite of the benefits that mining offers, the disadvantages that it is associated with often outweighs the benefits. One of the biggest issues that mining faces in today's time are 2 things in general – how it harms the environment and how outdated the current mining practices have become (Borley, 2022).

It has become crucial for companies around the world to strive for making mining more advanced and sustainable. Over the past couple of decades several efforts have been made in this direction such as – scrap mining, recycling, green mining, land-site reclamation, usage of eco-friendly equipment, 3D modeling, using GPS technology, cease and closure of illegal mining etc. With the urge for sustainable mining techniques continues to grow, the need of developing new methodologies and processes continue to rise. One of the aspects that has gained traction in recent times is the growing induction of modern technologies and disciplines within the existent mining processes (Lucero, 2023). This shift is nowadays termed as the process of digitization of mining processes and has been widely implemented over the last decade to make mining more sustainable and advanced. Technologies such as Artificial Intelligence (AI), Machine Learning (ML), Robotics, Blockchain, Big Data Analytics, Cloud Computing, Cybersecurity etc. have seen a steady rise in terms of their application within the mining industry (Duvall, 2019). Right from mineral detection to land reclamation, such technologies have not only made the current mining processes much more smarter and easier to implement but has also resulted in the invention of new methodologies and processes as well, paving the way for many other similar technologies to be used and introduced for the same purpose (Cashman, 2022).

Today many companies around the world have implemented technologies to simplify their mining practice. For Example – Vale, a Brazil based metal mining corporation and the largest producer iron ore and

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nickel, engages in the use of IoT based measures for their mining processes such as instrumentation, vibrational monitoring, conveyor belt and rollers operations etc. It uses autonomous trucks and drones for transportation and monitoring operations, and has approved the use of special analysers for online iron ore measurement (Kumar, 2023a; Kumar, 2023b). Fortescue (formerly Fortescue Metals) an Australia based mining and green energy company and 4th largest iron ore producer in the world, uses autonomous haulage systems and has deployed over 200 autonomous trucks at its hubs, whilst integrating their existing equipment with their autonomous fleet, and intends to use the data collected from such vehicles for optimising their workflows for maintenance, road design etc. (Gleeson, 2019). Rio Tinto, a British-Australian mining company and the second largest metals and mining corporation in the world, has also been pretty active when it comes to integration of technology in the mining practices, as it employs the use of autonomous trucks, drills and trains for minimizing human error. It operates Auto-Haul - the world's first autonomous long distance railway system for iron ore transportation (Sahota, 2023). It also uses IoT to engage in predictive maintenance by establishing an analytics excellence centre in Pune, India wherein data gets captured via sensors and gets assessed for predicting and preventing engine breakdowns and faults (Kumar, 2023a; Kumar, 2023b). The BHP group (formerly known as Broken Hill Proprietary company), a Australia based metals mining company and the largest metals and mining corporation in the world by market cap, has established a maintenance Centre of Excellence that uses ML to provide insights on the data collected, which allows them to engage in predictive maintenance of their equipment and better supply chain management. It also intends to use ML for other tasks such as geological data interpretation and uses analytics to make their supply chain more robust. Apart from this, it also deploys autonomous trucks and drills across its mining sites, employs the use of technology to enable workers to collect data remotely, uses IoT driven sensors for its machinery and protection of workers and utilises cloud services in combination with mixed reality headsets for assisting electricians on-site with their work (Kumar, 2023a; Kumar, 2023b).

With so many technologies now surrounding the mining industry, the potential for an extensive modernisation and digitization of the mining process is imminent. However, this also brings in a bout of difficulties, as it leaves companies strained with the choices they have with them when it comes to innovative development of mining processes. Firstly even though companies are surrounded by such a vast amount of options and opportunities of modernising their mining methods, they are often limited by the amount of experience they tend to have with such technologies. Usually companies involved in the mining industry tend to lack knowledge and expertise related to modern technologies like AI, Cybersecurity etc. due to the lack of exposure they have. Secondly there exists a lack of definition of factors for ensuring development of innovative and modern mining processes, which tends to confuse companies and leaves them unsure of what they need to choose. Lastly, there is a severe lack of definition for certain technologies as their real life use case scenarios doesn't exist for understanding their efficacy in application, industry relevant opinions and inputs, user based experience etc (Lucero, 2023).

In order to improve how mining as an industry fares in terms of efficiency, performance and sustainability, it is crucial to realize ideal processes that aid towards the same. While digitization of mining processes has emerged as a highly effective solution, studies reveal that there is a significant gap in terms of hypothesizing and application of digitization related methods, owing to factors like lack of industrial level experience with modern tech, resistance towards adoption of new processes and fearing the changes that this might bring. Hence, recognizing the current gaps and caveats that exist in digitization and innovative development of mining process. This work emphasizes and ascertains the technologies and factors ideal for innovative development of sustainable and advanced mining processes, which has been achieved through answering the following research questions (RQs) –

RQ1: What technologies, processes and principles emerge to be ideal for digitization and innovative development of sustainable mining processes?

For this question, we decided to engage in an extensive literature review using the Preferred Reporting Items for Systematic Meta Analyses (PRISMA) method (Page et al., 2020) to compile relevant material needed and consult industry specific experts for their opinion for recognizing factors and technologies ideal for digitization and innovative development of sustainable mining processes by incorporating the Pythagorean Fuzzy Delphi method (PF-Delphi) (Sindhwani et al., 2023).

RQ2: Which of the factors recognized emerge to be of significance when it comes to digitization and development of mining from a sustainable perspective?

For answering this question, wwe decided to engage in the use of a novel 2-step methodology that would allow us to establish a ranked list of technologies and factors ideal for developing digitised sustainable mining processes. In the first stage, we ranked the factors by weightage through implementing Pythagorean Fuzzy Analytical Hierarchal Process (PF-AHP) (Lahane and Kant, 2021). We then ranked the technologies using the Pythagorean Fuzzy Combined Compromise Solution (PF-CoCoSo) method (Peng et al., 2019).

In this study we intend to identify what technologies and deterministic factors are crucial for sustainable digitization of mining processes and rank them by their importance via consulting experts across different domains for their opinions. Post introducing the nature and intent in the 1st section, the 2nd Section discusses the technologies and factors deemed suitable for sustainable digitization of the mining processes and their subsequent validation. The 3rd section discusses the methodology implemented in detail and the ranking of parameters defined. The 4th section discusses the results obtained via the ranking and what they indicate. The 5th section highlights the implications of this study. The study is concluded with the 6th Section which sheds light upon the conclusions inferred.

2. Literature review

This section discusses the technologies and factors deemed suitable for mining digitization. and their subsequent validation and sheds light on the research gaps.

2.1. Appropriate article selection

To answers the questions formulated for this study, it is important to determine what factors influence digitization of mining processes, by understanding what affects the development in the mining industry, what has been accomplished so far and what is the future scope. This would be analyzed through reviewing relevant pieces of literature material. However, with the sheer abundance of research surrounding us, it is crucial to select the right literature for further review, which is why it is essential to adopt a method or process that can aid in selection. In this study we used the PRISMA methodology for collecting relevant literature. PRISMA is a process used for selecting relevant studies and acts a reporting guide for the same (Page et al., 2020). It comprises of 4 steps - paper identification, screening, inclusion/exclusion factors and paper selection based on outcome relevancy. The reason why we have used the PRISMA guidelines in this study to select the literature is because of the strength of this technique in being systematic and convenient. The following sub-sections highlight the complete process that was undertaken. Fig. 1 illustrates in detail the PRISMA process undertaken for this study.

2.1.1. Identifying relevant literature

The first step in this methodology is the identification of appropriate

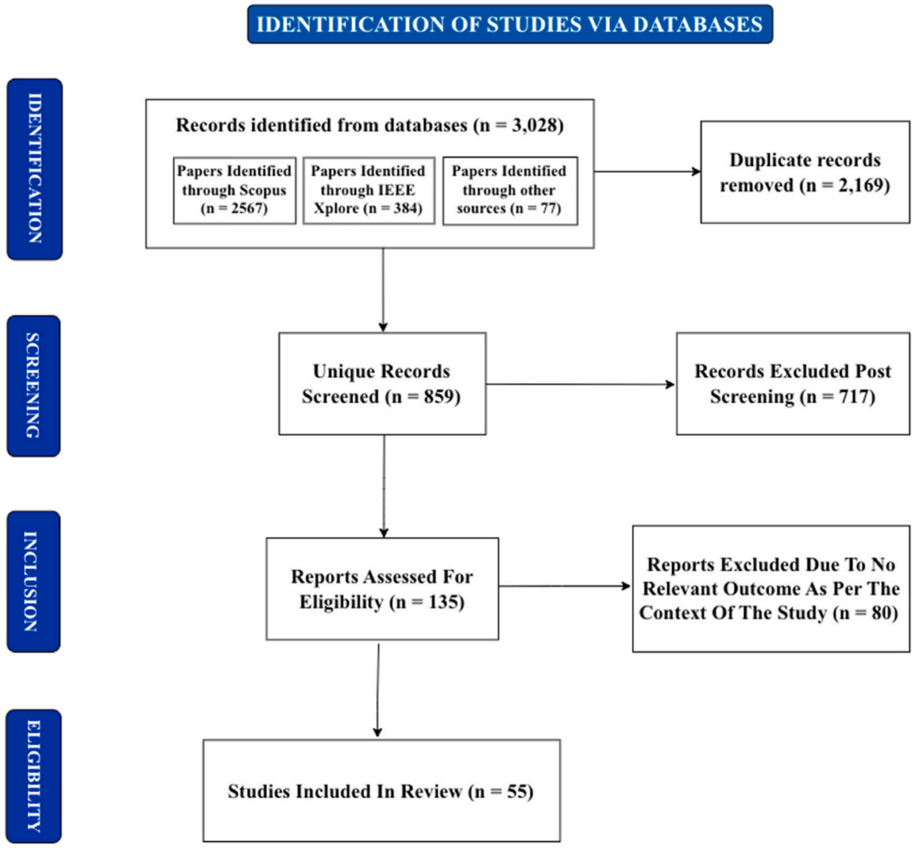

Fig. 1. Flowchart of the PRISMA process undertaken.

literature through screening of several databases and libraries. In this phase, we mainly screened through 2 databases – Scopus and IEEE Xplore along with other sources as they were easily accessible and hosted the material that was relevant to the study in comparison to other databases like Web of Science etc. (Chadegani et al., 2013). For identifying the initial literature, we resorted to use of keywords relevant to our field of study such as 'Sustainable Mining' OR 'Ecosystem Management' OR 'Technologies' OR 'Criteria' OR 'Digitization' in combination with several terms related to technologies such as 'Blockchain', 'AI', 'ML', 'IoT', Big Data Analytics', 'Robots', 'Autonomous Vehicles', 'Cloud Computing', 'Cybersecurity', 'Profitability', 'Govt. Policy', etc. We opted to use such keywords that bore a substantial significance and relevance to the topic of our research. Such an approach enabled us to find around 3028 papers from both databases and other sources.

2.1.2. Screening of papers for uniqueness

After identifying the initial set of papers, we embarked on the second phase which was to select papers that were unique to our research and offered material that could be easily related to our goals. In this phase, one of our biggest factors was to select literature which is unique and relevant. To search such type of literature, we ran a search query string which could ensure that such papers can be identified. We ran the following string in the Scopus database - TITLE ('mining') OR TITLE ('mining AND industry') OR TITLE ('sustainable AND mining') OR TITLE ('enabler') OR TITLE ('criteria') OR TITLE ('sustainability') OR TITLE ('profitability') OR TITLE('government AND policies') OR TITLE ('government AND support') AND TITLE ('digitization') OR TITLE ('blockchain') OR TITLE ('ai') OR TITLE ('iot') OR TITLE ('ml') OR TITLE ('cybersecurity') OR TITLE ('cloud AND computing') OR TITLE ('robots') OR TITLE ('autonomous AND vehicles') OR TITLE ('data AND analytics') AND (LIMIT-TO (OA,"all")). This phase of screening enabled us to further remove 2169 papers, leaving us with 859 papers that were deemed to be unique in nature.

2.1.3. Selection of literature based on inclusion and exclusion factors

Post screening literature based on its uniqueness quotient, we engaged in the third phase, which was to select literature using customized inclusion and exclusion criteria. For this phase, we came up with our own inclusion factors to segregate and identify useful literature for indulging in further analysis. We selected papers from various subjects such as 'Engineering', 'Sustainability', 'Environment Sciences', 'Sustainable Development', 'Risk Management', 'Information Management', 'Energy Utilization' and the document type was 'Article'. The papers were from sources such as 'Journal', 'Conference Paper' and 'Book Chapter' and were of the language type 'English'. Additionally, we also included papers that belonged to the timeframe we chose for the literature review i.e., from 2015 until December 2023. The reason as to why we went with such elaborate time period was due to several reasons. Firstly, digitization in mining industry has seen its emergence in this time period, as there has been a rise observed with the demand of improving mining practices using technology. Secondly, the need for innovative development of mining processes from the viewpoint of sustainability has emerged to become the need of the hour within this time period itself. Thirdly, the period of 2015–2023 has witnessed the most amount of integration between mining processes and technologies as companies have been observed to challenge their capabilities and embark onto new endeavours. Fourthly, this time period has seen the emergence of several new technologies considered to be beneficial across a myriad of sectors such as AI, ML, Data Analytics, Cloud Solutions, etc., Lastly, by limiting our research within this specific time period, we are able to ensure that we can get the maximum grasp on the developments made in this field and what is being planned for the future. To effectively engage in this screening process, we ran the following string in the Scopus Database - TITLE ('mining') OR TITLE ('mining AND industry') OR TITLE ('sustainable AND mining') OR TITLE ('enabler') OR TITLE ('criteria') OR TITLE ('sustainability') OR TITLE ('profitability') OR TITLE ('government AND policies') OR TITLE ('government AND support') AND TITLE ('digitization') OR TITLE ('blockchain') OR TITLE ('ai') OR TITLE ('iot') OR TITLE ('ml') OR TITLE ('cybersecurity') OR TITLE ('cloud AND computing') OR TITLE ('robots') OR TITLE ('autonomous AND vehicles') OR TITLE ('data AND analytics'). AND PUBYEAR >2015 AND PUBYEAR <2023 AND (LIMIT-TO (SRCTYPE, "p") OR LIMIT-TO (SRCTYPE, "k") OR LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (OA, "all")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENVI")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ch")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (EXACTKEYWORD, "Sustainable Development") OR LIMIT-TO (EXACTKEYWORD, "Decision Making") OR LIMIT-TO (EXACTKEYWORD, "Miners") OR LIMIT-TO (EXACTKEYWORD, "Social Sustainability") OR LIMIT-TO (EXACTKEYWORD, "Climate Change") OR LIMIT-TO (EXACTKEYWORD, "Energy Utilization") OR LIMIT-TO (EXACTKEYWORD, "Environmental Sustainability") OR LIMIT-TO (EXACTKEYWORD, "Information Management") OR LIMIT-TO (EXACTKEYWORD, "Case Study") OR LIMIT-TO (EXACTKEYWORD, "Case-studies") OR LIMIT-TO (EXACTKEYWORD, "Governance Approach") OR LIMIT-TO (EXACTKEYWORD, "Industry 4.0") OR LIMIT-TO (EXACTKEYWORD, "Risk Assessment") OR LIMIT-TO (EXACTKEYWORD, "Performance") OR LIMIT-TO (EXACTKEYWORD, "Optimization") OR LIMIT-TO (EXACTKEYWORD, "Automation") OR LIMIT-TO (EXACTKEYWORD, "Supply Chain Management") OR LIMIT-TO (EXACTKEYWORD, "Robotics") OR LIMIT-TO (EXACTKEYWORD, "Life Cycle") OR LIMIT-TO (EXACTKEYWORD, "Learning Systems") OR LIMIT-TO (EXACTKEYWORD, "Urban Transportation") OR LIMIT-TO (EXACTKEYWORD, "Forecasting") OR LIMIT-TO (EXACTKEYWORD, "Data Visualization") OR LIMIT-TO (EXACTKEYWORD, "Wireless Sensor Networks") OR LIMIT-TO (EXACTKEYWORD, "Production Process") OR LIMIT-TO (EXACTKEYWORD, "Neural Networks") OR LIMIT-TO (EXACTKEYWORD, "Industrial Development") OR LIMIT-TO (EXACTKEYWORD, "Energy Conservation") OR LIMIT-TO (EXACTKEYWORD, "Ecosystems") OR LIMIT-TO (EXACTKEYWORD, "Sensors") OR LIMIT-TO (EXACTKEYWORD, "Security") OR LIMIT-TO (EXACTKEYWORD, "Safety") OR LIMIT-TO (EXACTKEYWORD, "Risk Management") OR LIMIT-TO (EXACTKEYWORD, "Risk Analysis") OR LIMIT-TO (EXACTKEYWORD, "Recycling") OR LIMIT-TO (EXACTKEYWORD, "Environmental Protection") OR LIMIT-TO (EXACTKEYWORD, "Ethics")). This phase of screening allowed us to remove 724 papers that did not meet the eligibility criteria, leaving us with 135 papers that projected information needed for this study.

2.1.4. *Selection of papers based on outcome relevance*

After filtering the literature through the custom inclusion-exclusion criteria, we initiated the final step of including those papers whose outcome was relevant to our study. In this phase we scanned through papers that hosted results that could be deemed useful to our study, which allowed to remove 80 papers because they did not project any outcome relevant to our study. This left us with 55 papers as references for elucidating the technologies and factors for digitization and innovative development of the mining. Fig. 2 showcases the year wise distribution of the literature considered for review.

2.2. *Identifying factors which enable digitization and innovative development for sustainable mining*

In order to engage in digitization for sustainable mining, it is crucial that the incorporated technologies are able to generate maximum results in actual practice. To accomplish the same, it is important to define factors that can enable effective integration of the technologies in the mining industry. For this we recognized three factors that emerge ideal for sustainable digitization in mining.

2.2.1. *Sustainability*

Sustainability is a major factor when it comes to digitization, as mining generates different types of pollution and waste, which threatens the local ecosystem (Zhou, 2023). Hence when integrating technologies into the mining industry, not only do they simplify the mining process but they also minimize the impact on the environment. It can be achieved in several ways such as reduction of waste, recycling of materials, prevention of pollution, and exposure of hazardous substances etc. (Asr et al., 2019).

2.2.2. *Profitability*

Profitability is a key factor for digitizing the mining industry as with digitization the main goal is not only to make the process more efficient and sustainable but also ensure that such solutions are able to generate substantial amounts of revenue (Bikubanya and Radley, 2022). Hence, it is crucial to develop solutions that can generate profit to pave the way for future investments and development opportunities. It can be

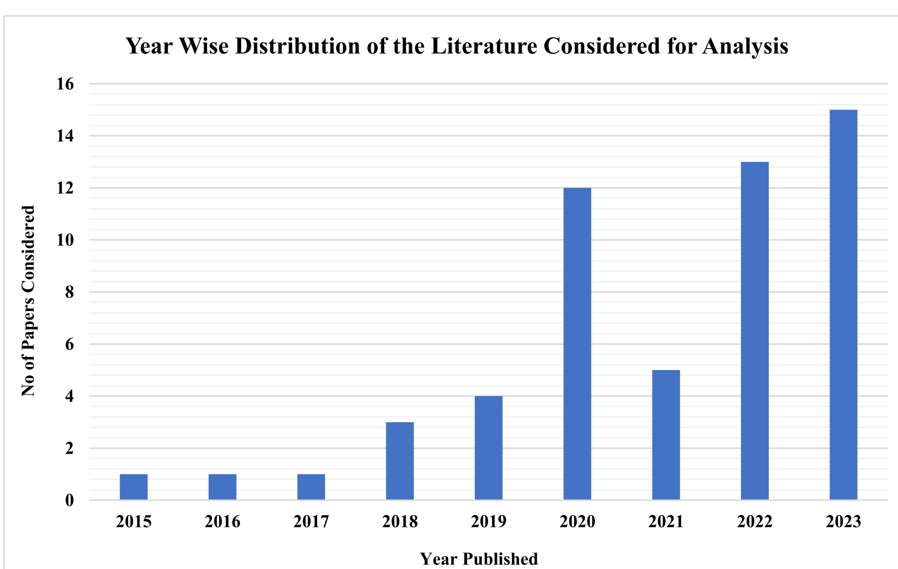

Fig. 2. Year wise distribution of final literature collected for review.

achieved through measures like raw material re-use, strong engagement practices, developing holistic approach and broadening scope of development (Hirdinis, 2019).

2.2.3. Government Support

Government Support is a key criterion for digitization, as mining generates sizeable profits, acts as a reliable stream of revenue and provides job opportunities to the locals (Burton et al., 2023). Hence supporting digitization of mining is beneficial for the governments, who see an opportunity in this regard which makes their support as a key factor for digitization. It can support the endeavors by providing subsidies, market shares, and grants, setting environmental regulations etc. (Emetumah and Okoye, 2018).

2.3. Recognizing enabling technologies that pave the way for digitization and development for sustainable mining

When we attempt to improve mining through digitization, it is important to know what technologies are ideal for the same to simplify the process of digitization. In this section we discuss such technologies followed by a detailed description of them via a table (Table 1).

2.4. Research gaps

Despite the fact that mining as an industry has seen an exponential growth when it comes to adoption of technologies, at the same time it also faces a variety of issues in terms of its application. While digitization of mining processes is a much-needed endeavor, its applications so far has witnessed many difficulties in terms of its implementation. Following are some of the issues that the current phase of technology adoption faces when comes to engaging in sustainable mining.

1. Operational Constraints – Mining is quite expensive as it incurs an extensive amount of money in terms of facilitation and management. Hence, some of the biggest factors that need to be kept in mind are the environment that the technology needs to operate in, the degree of work it is anticipated to facilitate, the amount of capital it needs for operation, continuous maintenance etc. (Innovapptive, 2023). Integration of technology for sustainable mining is embroiled with challenges, such as inability to operate in certain environment, the unprecedented issues it can face, lack of support and resources or smooth operation, the dearth of opportunities for problem resolution, high amount of budget needed for its implementation and safekeep (Stewart, 2023). As a result, mining companies often find it difficult to integrate technologies within their mining processes due to the insurmountable number of issues they face owing to the lack of experience they could have with the solutions they intend to implement (Sirait, 2023).
2. Lack of exposure and association with modern technology – Companies that are involved in the mining industry are quite traditionalistic in their approach, as they prefer the continuous use of traditional mining practices owing to the high degree of familiarity they have with such measures (Duvall, 2019). As a result, companies have found it difficult to digitize their mining processes owing to their lack of exposure to the modern technologies (Insig, 2022). This often deters them from investing their infrastructure due to the lack of opportunities to test out such technologies in real time, their inability to predict factors such as the result, the risk associated etc., severe lack of skilled workforce needed to implement such measures and the intensive number of regulations that are needed to be adhered to for sustainable production, environmental protection and habitat conservation. (Abhary, 2023).

3. Methodology adopted

Awering the fter ansfirst RQ formulated by recognizing the

Table 1
Key technologies for digitization and innovate development for sustainable mining.

Technologies	Use-Case	References
Integration of Blockchain Technology for Traceability and Authenticity of Sustainable Mining Processes (E1)	i. It enables companies to engage in responsible sourcing of materials from the mine sites as it allows for better tracking for pollution causing factors and allows real-time collection and analysis of carbon offset from the minerals for decision making. ii. It allows for easy traceability of the minerals right from their excavation to their final production stage, establishing accountability and transparent records of the materials collected, the working condition, the workers profile etc. iii. It allows for easy authentication of data by enabling companies to verify the data sent in from the service machines originating at the mining sites using methods like digital watermarks, encrypted keys etc. for easy data association and identification.	Mugurusi and Ahishakiye, 2022 Calvão and Archer, 2021 Chadly et al. (2023) Evsutin and Meshcheryakov (2020) Ahmed and MacCarthy, 2023
Adoption of Artificial Intelligence (AI) based techniques for Digitization and Optimization of Sustainable Mining Processes (E2)	i. It enables companies to easily determine the concentration of ore within a mineral so as to detect the quality of the mineral and to procure the highest grade and amount of material possible post mineral cleaning. ii. It allows companies to engage in easy maintenance and monitoring of machines and other equipment at the mining site as it enables them to easily determine any problems or issues early on with the equipment, ensuring maximum operational efficiency. iii. It enables companies to engage in simulation and mapping of potential routes for tasks like mineral transportation, hauling from the mining sites which allows companies to get a fair idea of the prospective routes which are ideal for mineral collection and operation optimization. iv. It enables organizations to engage in on-site anomaly detection, mineral identification and classification which allows them to easily detect	Bendaouia et al. (2023) Dayo-Olupona et al. (2023). Torres (2022) Ghorbani et al. (2022) Long et al. (2022) Nwaila et al. (2022) Ghorbani et al., (2022),

(continued on next page)

Table 1 (*continued*)

Technologies	Use-Case	References
	the kind of ores and deposits they are obtaining from the sites.	
Usage of Machine Learning (ML) processes for Predictive Sustainable Mining (E3)	i. It enables companies to optimize mining operations such as drilling and blasting by overcoming the limitations such processes face like landscape centric uncertainties, safety hazards along with environmental and financial limitations. Apart from this it also enables companies to collect information such as rock fragmentation and mineral structural recognition. ii. It enables companies to engage in the effective visualization of the prospective mining sites by enabling them to engage in processes which can help them in predicting the different aspects of the mining sites like predictive mapping of minerals and ore prospective mapping. This enables them to analyze the data collected from the mining site and other surrounding areas to develop a better understanding of the prospects offered at the mining site and the quality of minerals detected. iii. ML processes can help on-site workers to easily predict the landscape condition by deploying algorithms for predicting the extent of land reclamation in the mining site, planning achievable long-term mining schedules and risk level prediction of the mining sites.	Munagala et al., (2023), Fernández et al., 2023 Josso et al. (2023) Zheng et al. (2023) Levinson and Dimitrakoupoulos (2023), Zheng et al. (2023)
Integration of Robotic Process Automation for Innovation of Mining Processes (E4)	i. It allows companies to engage in development of intelligent mining equipment for purposes such as extraction of minerals from areas like small-scale mineral deposits and others wherein it is not financially viable to mine minerals. ii. They can also be utilized for path mapping in mining networks as it enables prediction of useable routes for excavation, enabling them to collect minerals from areas which is difficult for humans to reach. iii. Robots can be also deployed for engaging in rescue operations as they	Lopes et al. (2020) Boloz and Bialy 2020 Solar et al. (2016) Reddy A et al. (2015) Fryanov et al. (2017)

Table 1 (*continued*)

Technologies	Use-Case	References
	can be used for tasks such as accident location detection, first aid treatment of the survivors, generating alerts for medical team and detecting severity of accident.	
Adoption of Cloud Computing techniques for Maintenance and Safety for Sustainable Mining (E5)	i. Allows companies to engage in geospatial data processing of the mining sites, enabling them to map out the possible areas of mineral deposits, forecast mineral resources and engage in assessment of mineral resources. ii. Cloud Computing can be used for engaging in predictive maintenance and monitoring of mining equipment, enabling companies to improve operational efficiency, maintain robustness, measure the overall effectiveness of the equipment, monitor and alert issues arising with the tools, facilitate real-time repair and offer customization of equipment to suit mining and processing needs. iii. It enables companies to engage in safety monitoring of the mining sites using cloud enabled platforms for analysis of seismic waveforms and deploying early warning for potential mishaps. It allows companies to engage in safety training via simulation of accident scenarios so as to train workers and enable them to adapt to the situations.	Yang et al., 2016 Kruczek et al. (2019) Zhang et al. (2020) Li et al. (2020) Bi et al. (2022)
Integration of Cybersecurity Measures for Secure Sustainable Mining Processes (E6)	i. It allows safeguarding of mining equipment like hauling vehicles and ensure that they are able to operate safely by tackling factors that may act as a hindrance such as prevention of data loss and IP loss etc. ii. It enables companies to engage in protection of the mineral data gathered from the mining site by ensuring that the data gathered is secured from malware attacks, phishing and data stealing. iii. It also empowers companies to engage in effective risk management as it enables them to identify factors such as possible risks, their probability of occurrence and the	Gaber et al. (2021) Skenderas and Politi (2023) Litvinenko (2019) Tyuleneva (2020) Nawa and Nwaila, 2023

(*continued on next page*)

Table 1 (*continued*)

Technologies	Use-Case	References
	severity of impact they could have.	
Adoption of Internet of Things (IoT) for Robust Development of Sustainable Mining Processes (E7)	i. It enables companies to engage in identification of different mining aspects such as mineral and ore recognition, landscape recognition using Radio Frequency Identification (RFID) technology. It also allows for seamless capturing of data with the help of Wireless Sensor Networks (WSN) technology as it result it better rate of data collection in comparison to cabled systems. ii. It empowers companies to engage in predictive maintenance of equipment, real time monitoring of sites, safety assessments, disaster prediction, site surveillance using sensors, wireless technologies, automation, GPS and other technologies so as to maintain operation efficiency, safety of workers, prevent accidents and disasters iii. From a sustainability perspective, IoT allows companies to engage in analysis and monitoring of different aspects such as mining environment monitoring, pollution monitoring, transport management, water monitoring, mineral supply monitoring etc. to ensure that no irreversible damage is done to the mining site and its surrounding areas and to reduce the environmental impact of mining.	More et al. (2020) Salam (2020) Jha et al. (2021). Song et al., (2023), Park et al., (2021), Jo and Khan (2018)
Integration of Autonomous Vehicles for Automation of Sustainable Mining Process (E8)	i. It enables companies to engage in the location assessment of the mining sites when used with technologies like Light Detection and Ranging (LiDAR) sensors for landscape estimation and mapping of driveway and ore tunnels so as to ensure easy navigation of the vehicles and easy area prediction ii. Autonomous vehicles can be also used by organizations to automate different kinds of tasks at a mining site such as – Production drilling, atmosphere monitoring, area-specific problem detection, condition simulation and prediction. This enables	Kim and Choi (2021) Ge et al. (2022) Androulakis et al. (2020) Chehri and Fortier (2020) Voronov et al. (2020)

Table 1 (*continued*)

Technologies	Use-Case	References
	them to achieve automation of complex tasks, maintain operational efficiency and reduce human intervention. iii. It can also enable companies to engage in the use of self-dependent and intelligent vehicles like mineral excavators and mineral shuttle cars for quicker extraction and collection of minerals from the mining site and to facilitate its related tasks like vehicle upkeep, fleet management, material loading and transportation management.	
Integration of Big Data Analytics for Resilient Sustainable Mining (E9)	i. It enables companies to engage in development of resilient supply chains and allows them to engage in effective planning, resource management, resource conservation etc. ii. It enables organization to engage in the process of pollution risk assessment by allowing them to analyze data related to minerals extracted. iii. It allows companies to engage in easy identification of anomalies within complex minerals by enabling them to assess geoscience data using big data analytics in combination with mining geochemistry, engage in predictive maintenance of mining equipment, as it allows them to analyze the data collected from the equipment deployed so as to gain a better understanding about its condition, overall performance and work efficiency.	Bag et al. (2022) Cheng et al. (2022) Abedini et al. (2023) Li et al., (2022), Sarker et al. (2022)

parameters and elucidating their importance, we proceed to the phase of developing the answer for the second RQ theorized. For this, we rank the technologies and factors identified for their relative importance for digitization of sustainable mining processes using a three-step methodology comprising of PF-Delphi for validation of technologies, PF-AHP for ranking factors and PF-CoCoSo for ranking the technologies. Fig. 3 displays the complete process followed for this study –

3.1. Data collection

To validate and rank the technologies and factors finalized we developed a survey questionnaire which enlisted details related to the enabling technologies and criteria, offered suitable grading scales for assessing the technologies which enabled respondents to express their views easily (Sindhwani et al., 2023). In this methodology, we contacted experts across different domains and asked them to express their honest opinions and inputs about such technologies within the survey. In this study out of 9 total experts consulted, we were able to connect with 6

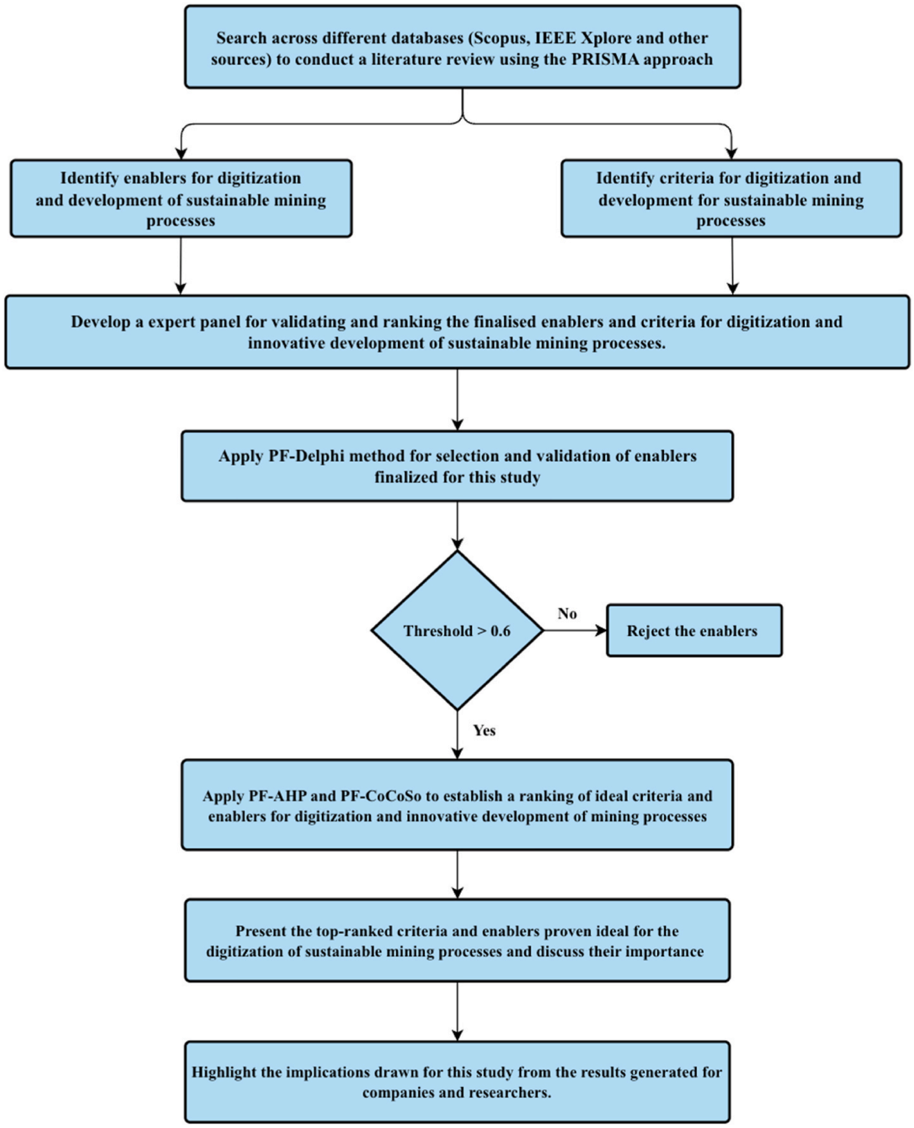

Fig. 3. Flowchart depicting the workflow followed for this study.

experts located in India, the country relevant to our study from different sector domains and collected their opinions, as they possessed the relevant knowledge and expertise that we desire in this study for validation and ranking. The details of the experts consulted are shown in the following table (Table 2).

3.2. Validation of technologies using the Pythagorean Fuzzy Delphi technique

For validating the technologies based on their suitability in real-life scenarios, we utilized the Pythagorean Fuzzy Delphi method (PF-Delphi). PF-Delphi is a research methodology which involves validation of

Table 2
Experts consulted for this study.

S No.	Domain	Qualification	Years of Experience	Hierarchy Level	Job Responsibilities
1	Blockchain Technology	Graduation	8	Executive Manager	Mainly responsible for realizing potential of Blockchain across a multitude of sectors and spearheading the implementation of the same.
2	Design	Post-Graduation	12	Project Manager	Accountable for harnessing the potential of sustainable design principles across mining sectors.
3	Mining	Graduation	14	Project Manager	Mainly responsible for solution development, stakeholder mapping, assessment along with engagement within the mining domain.
4	Management	Post-Graduation	8	Senior Manager	Accountable for estimation, identification and realizing the potential of sustainable management practices in the projects being undertaken.
5	Pre-Sales	Graduation	2.8	Specialist	Mainly responsible for customer engagement, services and delivery of solutions within the enterprise domain
6	Supply Chain	Post-Graduation	12	Project Manager	Accountable for capacity planning for cloud-based supply chain along with solution development and stakeholder mapping, assessment along with engagement within the supply chain domain.

parameters considered for a study on the basis of analysis of scale-based ratings offered by the experts. This involves usage of scales specifically designed for categorization of factors solely based on their weightage associated with each grade on the scale. Unlike the Delphi method, this methodology uses Pythagorean Fuzzy Numbers (PFNs) for analysis, which improves the credibility of inputs offered and maintains the consistency of information, both of which enable PF-Delphi to easily outweigh Delphi (Alharbi and Khalifa, 2021). In comparison to Rough Set theory, PF-Delphi tends to fare better as the parameters used for validation of the technologies are known to some degree, which makes its application more viable (Yao, 1998). When it comes to Kendall score coefficient, PF-Delphi boasts a score of 0.758, which is the ideal score needed to achieve a consensus on agreement between 2 or more experts (Tee et al., 2022). After collecting expert opinions, we initiated the process of an extensive analysis of the opinions offered for the technologies using the PFNs and other factors related to this method. Thus, we were able to reach an effective conclusion as we selected the technologies which emerged to be ideal for digitization in sustainable mining, the following table (Table 3) showcases the selected technologies using the PF-Delphi method.

Post analysis, we discovered that all the technologies were chosen for consideration owing to the positive inputs provided by the experts, when measured against a threshold value of 0.6 considered for selection post achieving a consensus of measurement between all the experts.

3.3. Ranking factors based on their relative importance using the pythagorean fuzzy AHP technique

The PF-AHP technique is used to evaluate factors related to a piece of data. It uses fuzzy logic and Pythagorean Fuzzy Numbers (PFNs), for assessment based on relative importance, making it ideal for cases related to Multi-Criteria Decision-Making (MCDM) process. PF-AHP, unlike AHP, relies on the use of fuzzy sets which enables it to eliminate redundant and unnecessary data during evaluation, thus developing concrete conclusions, making this method a preferred choice (Lahane and Kant, 2021). When compared to processes of Analytic Network Process (ANP) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), it tends to have significant advantages as PF-AHP emerges as a far better option due to its ability to measure and rank factors based on the individual weightage that signifies how much its aids to the cause whilst independent of external solutions, as TOPSIS ranks criterion based on the relativity to the ideal solution (Lima Junior et al., 2014), PF-AHP also considers the factors independently, whereas ANP ranks criterion based on their dependency on the technologies (García and Guitart, 2022). To rank the criteria, we analyzed the inputs offered by experts by converting them into PFNs and computed our results. After deducing the insights offered, we were able to rank the criterion based on their relative importance. Table 4 showcases the relative weightage of the criterion to other factors and Table 5 showcases the ranking of factors that was observed post analysis (Sindhwani et al., 2023).

Table 3
Pythagorean fuzzy weights and de-fuzzified values.

Enabler	Pf-Weights		Hesitancy	De-fuzzified Value	Selected (S)/Rejected (R)
	μ	**ν**	**π**		
E1	0.95	0.2	0.0575	0.929597	S
E2	0.95	0.2	0.0575	0.929597	S
E3	0.95	0.2	0.0575	0.929597	S
E4	0.95	0.2	0.0575	0.929597	S
E5	0.95	0.2	0.0575	0.929597	S
E6	0.85	0.35	0.155	0.787988	S
E7	0.95	0.2	0.0575	0.929597	S
E8	0.95	0.2	0.0575	0.929597	S
E9	0.95	0.2	0.0575	0.929597	S
			Threshold Value		0.6

As we can see in Table 5, the factors were ranked as follows – the factorsC1 (Sustainability) emerges as the top most ranked criterion. as it boasts the maximum weightage (0.744179). This is then followed by the factors C2 (Profitability) with weightage (0.138562), with criterion C3 finishing last with weightage (0.117259).

3.4. Ranking technologies by assessing their relative importance using pythagorean fuzzy CoCoSo technique

PF-CoCoSo is a technique that assess the factors based on their relative importance to each other and to other factors. Like PF-AHP, it is ideal for solving cases involving the use of MCDM based processes. Unlike CoCoSo method, PF-CoCoSo tends to use a combination of mathematical models, PFNs and fuzzy sets for deriving effective insights and concrete conclusions making it an optimum choice for researchers (Peng et al., 2019). PF-CoCoSo is also preferable when compared to VIKOR and Additive Radio Assessment (ARAS), as it evaluates the technologies on their weightage measuring in importance and efficacy in achieving a solution. VIKOR ranks technologies based on how well they mimic the ideal solution and ARAS ranks technologies based on the alternatives it offers (Bołoz and Biały, 2020; Zhang et al., 2023; Zavadskas and Turskis, 2010).

To rank the technologies identified using PF-CoCoSo, we analyzed the inputs offered by converting them into PFNs and computed our results based on the insights it offered. After deducing the insights offered by the experts' opinions, we were able to rank the technologies based on their relative importance which are showcased in Table 6 (Sindhwani et al., 2023).

In Table 6, technologies E9 (Big Data Analytics) and E3 (Machine Learning) emerge as the top most ranked technologies in terms of relative importance as they boast the highest K_i weightage (7.529836 each). Enabler E8 (Autonomous Vehicles) comes next in 3rd place as it scores the second highest K_i weightage (6.082041). Finally we have enabler E2 (Artificial Intelligence). at 4th place as it scores the 3rd highest K_i weightage (3.730804).

4. Results and discussion

Post the evaluation of all the factors and technologies using the methodologies, we were able to identify one criterion and four technologies that emerged ideal for digitization of sustainable mining practices, based on the weightage of the relative importance they demonstrated. In our study, we discovered that sustainability emerged as the top most criterion amongst all the other factors when it comes to digitization of mining processes. Also, technologies like Big Data Analytics, Machine Learning, Autonomous Vehicles and Artificial Intelligence emerged as the top technologies for enabling digitization of mining processes.

Of all the criteria considered, sustainability is of most importance for digitization of mining. As conservation of habitats becomes important, ensuring that no damage is inflicted on them during mining is crucial, which makes development of sustainable mining processes as the ideal solution. Hence, reducing the waste generated, recycling materials, reducing pollution, developing ecological literacy and corporate social responsibility, engaging in land restorations etc. are crucial for effective digitization and development of mining processes (Asr et al., 2019).

Amongst all the four technologies identified, big data analytics emerges as one of top 2 technologies for enabling digitization of mining processes. Integration of big data analysis is crucial for development of resilient sustainable mining practices (Bag et al., 2022). This is because it helps in development of resilient supply chains and propagates effective planning, resource management and conservation (Abedini et al., 2023). It also enables companies to engage in pollution risk assessment by analyzing data related to minerals extracted, identify areas of high-risk pollution, detect anomalies within complex minerals and engage in predictive maintenance of mining equipment (Li et al.,

Table 4
Pair wise comparison matrix.

Factors	C1				C2				C3			
	μ(L)	μ(U)	ν(L)	ν(U)	μ(L)	μ(U)	ν(L)	ν(U)	μ(L)	μ(U)	ν(L)	ν(U)
C1	0.1965	0.1965	0.1965	0.1965	0.55	0.65	0.35	0.45	0.8	0.9	0.1	0.2
C2	0.35	0.45	0.55	0.65	0.1965	0.1965	0.1965	0.1965	0.45	0.55	0.45	0.55
C3	0.1	0.2	0.8	0.9	0.45	0.55	0.45	0.55	0.1965	0.1965	0.1965	0.1965

Table 5
Normalized criteria weight of matrix.

Criteria	W
C1	0.744179
C2	0.138562
C3	0.117259

Table 6
Ranking of technologies based of 'k_i' values*.

ENABLER	k_{ia}	k_{ib}	k_{ic}	k_i	RANK
E1	0.058406	4.252899	0.339571	1.988849	8
E2	0.113122	7.90781	0.657688	3.730804	4
E3	0.172	17.11773	1	7.529836	1
E4	0.110549	7.594349	0.642724	3.596662	5
E5	0.042459	2	0.246857	1.038835	9
E6	0.100408	6.190916	0.583769	3.00497	7
E7	0.106126	7.05855	0.617011	3.367068	6
E8	0.124929	14.13533	0.72633	6.082041	3
E9	0.172	17.11773	1	7.529836	1

Note: *K_{ia}- Arithmetic mean of WSM and WPM, K_{ib}- Relative score of WSM and WPM, K_{ic}- Balanced compromise of WSM and WPM, K_i- Final assessment value.

2022).

The top ranked technology for digitization in mining is machine learning. Use of machine learning techniques has been observed to significantly contribute towards digitization for sustainable mining (Josso et al., 2023). It helps companies to optimize mining operations like drilling and blasting and overcome their limitations, collect different types of data related to minerals, visualize prospective areas for mining and engage in predictive mapping of minerals (Zheng et al., 2023). It also helps on-site workers to predict landscape conditions, engage in land reclamation, enable companies to plan achievable mining schedules and engage in risk level prediction (Levinson and Dimitrakoupoulos, 2023).

The third most important technology for mining digitization are autonomous vehicles. Adoption of autonomous vehicles has provided several benefits in terms of development of sustainable mining practices (Kim and Choi, 2021). It enables companies to engage in location assessment of the mining sites for landscape estimation, automate different kinds of tasks such as production drilling, atmosphere monitoring etc (Ge et al., 2022). It also reduces human dependency for dangerous tasks via integration of self-dependent and intelligent vehicles like excavators and shuttle cars, and easily manage tasks related to its maintenance like vehicle upkeep fleet management and material loading management (Chehri and Fortier, 2020).

The fourth most important enabler when it comes to digitization of mining, is artificial intelligence in mining processes. Use of AI in mining provides several benefits like allowing companies to determine the concentration of ore in a mineral for quality detection, easily maintain and monitor machines (Torres, 2022), determine problems early on with the equipment, simulate and map potential routes for transportation (Rahmani et al., 2023), engage in on-site anomaly detection, mineral identification and classification (Ghorbani et al., 2022a,b).

As we have seen with the results yielded, technologies like ML, Big Data Analytics, Autonomous Vehicles and AI play a significant role in enabling digitization of mining process, as they contribute heavily towards making mining more sustainable and seamless. In this study, we initially emphasized over the fact as to how mining in its current stage is ridden with a multitude of issues, right from operational constraints, financial limitations, lack of exposure to modern technology and skilled workforce etc. By discussing the possible technologies, their potential applications and ranking, we present the prospective mining organizations with insights into how certain technologies have evolved to be ideal for addressing different issues. This is achieved by offering possible solutions for resolving several issues such as - streamlining the equipment maintenance process using AI (Dayo-Olupona et al., 2023), detecting prospective spots with high mineral ore concentration using ML (Zheng et al., 2023), using pollution risk assessment using big data analytics (Cheng et al., 2022), automating complex tasks using autonomous vehicles among several others (Voronov et al., 2020). Not only that, it also provides an insight into how these technologies also help in future-proofing the mining industry as they emerge effective for development of other solutions as well.

5. Study implications

This section discusses the implications the technologies considered ideal for digitization of mining would have on the mining industry from a theoretical, practical and other.

5.1. Theoretical implications

From a theoretical perspective, the results are found to be in favor of the technologies observed ideal for sustainable digitization of mining process (Dilge, 2022). When compared to Natural Resource Based View model (Andersén, 2021), all of the technologies have instances of applications that encourage sustainable mining digitization. For example – Big Data Analytics helps miners to engage in pollution risk assessment via analyzing data for the presence of dangerous pollutants in the freshly extracted metals. This enables mining companies to predict and pinpoint possible regions of high-risk pollution within a mining site, which allows them to curb the risk of pollution and environmental damage (Cheng et al., 2022). ML allows mining companies to engage in visualization of probable prospects for land reclamation through predicting landscape condition for exploring the possible opportunities for land reclamation, which is ideal as it presents the opportunity to rejuvenate the land, thereby minimizing environment damage (Fernández et al., 2023). Autonomous Vehicles provide miners a chance to utilize self-dependent and intelligent vehicles for excavation of minerals and other tasks, which makes mining more sustainable as it enables us to minimize the damage and effort spent towards extracting minerals, making it safer (Voronov et al., 2020). AI allows miners to easily determine ore concentration in a mineral, making it easier to excavate better quality minerals, and makes the process more sustainable by reducing human effort, reducing energy consumed and minimizing mineral wastage (Bendaouia et al., 2023).

In comparison to Task-Technology Fit model (Marikyan and Papagiannidis, 2023), the technologies are seen as the ideal choices for solving mining problems. For Example – miners find it difficult to obtain high quality minerals, as they run into issues due to presence of impurities. In such cases, Big Data Analytics emerges to be useful as it can be used to easily detect and analyze anomalies in a mineral, so as to remove them and ensure yield of high-quality material (Abedini et al., 2023). ML also emerges as useful when issues are presented while extracting minerals due to prohibitions like – landscape complexities, environmental constraints etc. In such cases, ML allows miners to optimize drilling and blasting operations by analyzing the constraints present on site, making it ideal for resolving such problems (Munagala et al., 2023). Autonomous Vehicles emerge to be effective when issues such as navigating through colonies for excavation emerge, due to climate-induced landscape changes, making it difficult to predict what path should be considered to reach the same. Autonomous Vehicles allow miners to do the location assessment of the mining site using LiDAR sensors to map the vehicle driveways, ensure easy navigation of mining vehicles and prediction of ideal mining routes (Kim and Choi, 2021). AI is also deemed suitable for mining as it is effective in solving issues related to the upkeep of mining equipment, as they enable miners to engage in regular maintenance of equipment and early problem detection in machines, thereby ensuring maximum operational efficiency (Nwaila et al., 2022).

5.2. Practical implications

From a practical perspective, it was realized that adopting policies that empowered integration of technologies and sustainable practices in the mining industry enabled companies to revolutionize the way they engage in mining. (Alonso, 2022). When we consider the technologies that came out as ideal for digitization of mining post analysis, we realize that they emerge as practical choices for ensuring fool-proof application of digitization of mining processes as indicated through several studies and when measured against the Technology Acceptance Model (Burgess and Worthington, 2021). For example – Big Data Analysis has a positive acceptance in the mining sector due to its efficiency for developing resilient supply chains, for effective planning, resource management and conservation, making mining more robust (Bag et al., 2022). ML has a positive perception in the mining industry due to its efficiency in mapping the prospective mining areas via prediction of possible points of mineral deposits, making mineral extraction easier (Zheng et al., 2023). Autonomous Vehicles has had a positive acceptance for mining as it allows for developing automations for different mining tasks such as atmosphere monitoring, problem detection, condition simulation and prediction, thereby maintaining human intervention and dependency (Ge et al., 2022). AI has also developed a positive perception in the mining sector due to the benefits it presents when it comes to mineral identification and classification, as it enables them to easily detect and differentiate between minerals obtained from different sites and possible areas of deposits (Long et al., 2022).

When we analyze the parameters considered, we realize that the technologies deemed ideal for digitization of mining processes stay true to the concepts associated with the Theory of Diffusion of Innovations (Dearing and Cox, 2018). When we consider the discussion of how the concept of using these technologies for digitization of mining evolved, it is usually seen that sustainability plays a huge role towards the same (Asr et al., 2019). Through the literature reviews undertaken, it was observed that sustainability emerged as a focal point for all the top technologies considered ideal for mining digitization. In big data analytics, sustainability is a major point when it comes to its rise in popularity amongst the miners as it enables them to plan long-term schedules, optimize their work and predict risks beforehand so as to maintain human safety, reduce wastage of resources and reduce the time and effort spent (Sarker et al., 2022). In case of ML, sustainability plays a major role in the growth for its acceptance in mining as it allows for easy collection of key data of minerals like rock fragmentation, mineral structural recognition etc. which would help in minimizing mineral wastage by enabling them to predict the quality of material they would find during excavation (Josso et al., 2023). Autonomous Vehicles has also seen a steady rise in terms of acceptance within the mining industry thanks to sustainability, as it allows miners to routinely maintain mining equipment and automate complex tasks, which reduces the amount of resource needed and energy consumption (Androulakis et al., 2020). AI has also seen unprecedented rate of popularity amongst the miners due to sustainability, as it enables them to easily predict ideal routes for mineral excavation, making it easier to quickly excavate minerals, and makes the process more sustainable by reducing human effort and minimizing land wastage (Ghorbani et al., 2022a,b).

5.3. Managerial and policy implications

From a managerial perspective, when the results are contrasted against theories such as Institutional Theory (David et al., 2019) and Classical Management Theory (O'Leary, 2023), encouraging adoption of technologies at a management level enables companies to easily integrate such technologies at an internal level. It enables them to develop prior understanding of the technologies suitable to their needs, understand their applications, test the use cases, sensitize and train workers to adapt and develop new processes. Adopting sustainable practices at a management level enables companies to help its workers develop ecological literacy, instill a sense of societal and environment consideration and develop corporate social responsibility. (Oizom, 2023).

From a policy perspective, when the results are observed against theories such as Stakeholder Theory (McAbee, 2022) and Theory of Reasoned Action (Nickerson, 2023) engaging in digitization of mining enables one to increase the time period of sustenance for the processes adopted by enabling companies to reduce wastage, recycle unwanted materials, reduce pollution, increase material yield, and protect workers' lives. Adopting technologies such as AI, Big Data Analytics, ML and Autonomous Vehicles enables companies to increase operational efficiency, reduce costs, improve resource management, enhance performance and operations; and optimize mining practices (Soofastaei, 2023).

6. Conclusion, limitations and future scope

Mining as a practice has evolved in terms of both significance and relevance over the last many decades, as it emerges to be a job source for millions around the world and opens up a plethora of opportunities for many to collect and use crucial resources. However, it is maligned with the negative effects it leaves upon the environment, as it continues to threaten the local habitat endangers the flora, fauna and the people thriving in them. It also suffers from the impending threat of becoming obsolete as the mining processes themselves continue to become old, unwanted and outdated quickly, which endangers the workflow, the infrastructure and the people involved in the mining industry. As a result, making mining more sustainable and technologically advanced emerges to be the need to tackle such crises. Taking advantage of the prospective it presents, the study contribute towards the cause by identifying the best technologies and factors for digitization and innovative development of the mining sector.

In this study, we recognized nine technologies and three factors ideal for digitization of sustainable mining processes, by assessing the degree of usefulness and acceptance each technology and factors displayed and were subsequently evaluated in accordance to the technology acceptance model. This study emphasized on the importance of integrating them within the mining industry by highlighting their advantages, needs and illustrating potential use case scenarios and applications. This study also developed a rank-based list of technologies and factors suited best for digitization in mining, and highlighted the most important criterion and technologies that should be considered by integrating a three-step methodology and considering expert opinions from different domains.

However, despite the proposed solution, it is undeniable that there might exists the probability of insufficiency within the results presented, as it is directly dependent on the number of experts consulted, the subjectivity of opinions and the domains explored. Hence we intend to cover more ground related to this field by integrating more methodologies such as sensitivity analysis for measuring the degree of fitness of the factors and m-TISM model for deriving more intricate factors. Despite the limitations that this study might possess, we cannot deny the importance that its findings would have on the mining industry. We envision it to act as a stepping stone towards the journey of digitization of mining process, as it presents the researchers, academicians and companies with options on what technologies would best suit them for improving their mining workflows based on their needs and goals to be achieved.

CRediT authorship contribution statement

Chinmayee Chatterjee: Writing – original draft, Visualization, Validation, Formal analysis, Conceptualization. **Rahul Sindhwani:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Formal analysis, Data curation, Conceptualization. **Sachin Kumar Mangla:** Writing – original draft, Supervision, Formal analysis, Data curation. **Nitasha Hasteer:** Writing – original draft, Resources, Formal analysis, Conceptualization.

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Declaration of competing interest

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Data availability

Data will be made available on request.

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