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The paradoxical effects of emerging mining technologies on psychosocial work factors: An integrated framework and research agenda☆

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ABSTRACT

As industries strive for healthier, safer, and more productive workplaces, a comprehensive understanding of psychosocial work factors is essential for sustainable improvement. In the context of digital transformation, automation and emerging technologies have led to mixed health and safety outcomes. However, how emerging technologies are reshaping work and organisational structures and driving varied effects, remains unclear. This uncertainty provides little guidance for practitioners and researchers on systematically integrating new technologies to optimise health and safety. This paper argues that a deeper understanding of how the evolving technological landscape affects psychosocial work factors is essential for bridging this research gap. Focusing on the mining sector, this systematic literature review examines how emerging mining technologies influence psychosocial work factors, which can, in turn, have health and safety implications. This study suggests that technology implementation can simultaneously produce both beneficial and adverse psychosocial effects, spanning the physical, psychological and social spheres. It also highlights that the way workplace changes are integrated and managed is critical in determining these outcomes. These insights have important implications for strategical workplace design, highlighting the need for human-centric principles, continuous evaluation, and feedback mechanisms.

1. Introduction

Psychosocial work factors, or workplace psychosocial factors, as defined by the International Labour Organisation (ILO), refer to the "interactions between and among the work environment, job content, organisational conditions, and workers' capacities, needs, culture, and personal extra-job considerations that may, through perceptions and experience, influence health, work performance, and job satisfaction" (ILO, 1984, p. 3). Existing literature also links psychosocial work factors to various aspects of the work environment, including "work demands, the availability of organisational support, rewards, and interpersonal relationships in the workplace" (Jain et al., 2021, p. 1). Research on psychosocial work factors demonstrate their impact on both individual and organisational health and safety outcomes, such as individual well-being (Tims et al., 2013; Mudrak et al., 2018), job satisfaction (Han et al., 2020; Simbula, 2010), safety behaviours and performance (Zhu et al., 2020; Sampson et al., 2014), and organisational safety outcomes (Nahrgang et al., 20111; Huang et al., 2021). With growing research interest in psychosocial work factors, it is essential to clearly distinguish them from two relevant yet different concepts to prevent potential misconceptions: psychosocial hazards and psychosocial risks. Psychosocial hazards are sources arising from specific aspects of work organisation, design, and management that have the inherent potential to cause harm to individuals and organisations (WHO, 2010). In line with the concept of occupational risk (EU-OSHA, 2022; ISO, 2018), psychosocial risk refers to the likelihood and severity of harm resulting from exposure to psychosocial hazards (British Standards Institution, 2011; Neto, 2024). This comparison highlights that psychosocial work factors are distinct from psychosocial hazards and risks in one key way: psychosocial work factors are neutral. Depending on the context, they can manifest as adverse conditions associated with elevated risk or as beneficial elements that positively influence workers' experience and performance (Derdowski and Mathisen, 2023). For example, interpersonal relationship at work is a psychosocial work factor, the relevant psychosocial hazard would be the aspects that can cause harm—such as workplace bullying, or toxic team dynamics. From there, the

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psychosocial risk would be both the likelihood and potential severity of harm arising from bullying, or toxic team dynamics (the hazards), which can result in adverse outcomes such as stress, reduced job satisfaction, or poor performance.

Along these lines, the Job Demands-Resources (JD-R) model (Bakker and Demerouti, 2007) offers a comprehensive framework for examining psychosocial work factors, illustrating both the adverse (demands) and beneficial (resources) pathways and impacts on employees' health, safety performance, and safety outcomes (Derdowski and Mathisen, 2023). Contemporary research provides extensive evidence supporting both pathways, which lead to positive and negative impacts on workplace health and safety. These impacts span the physical sphere, covering tangible workplace conditions and ergonomic factors directly impacting physical health and safety (e.g., Zhu et al., 2020; Sampson et al., 2014), the psychological sphere, which includes factors influencing psychological well-being (e.g., Simbula, 2010; Tims et al., 2013; Han et al., 2020), and the social sphere, encompassing factors such as communication practices, organisational policies, and practices around safety (e.g., Leka et al., 2023; Nahrgang et al., 2011; Díaz-Cabrera et al., 2007). These categorisations serve as guidelines for the development of thematic framework of the emerging psychosocial work factors identified in this study. As industries strive for healthier, safer, and more productive workplaces, a comprehensive understanding of psychosocial work factors is essential for sustainable improvement.

With the rise of automation and emerging technologies, discussions have increasingly focused on their health and safety impacts, particularly in traditionally high-risk sectors such as mining. However, the implementation of new technologies in the mining industry has shown mixed impacts on health and safety outcomes. On the one hand, advanced digital technologies are enhancing health and safety in the mining industry by minimising worker exposure to hazardous environments, automating dangerous tasks (Mensah et al., 2022), improving efficiency and safety through complex task automation with minimal human intervention (Rogers et al., 2019), enabling predictive maintenance and accident prevention using real-time data (Marimuthu et al., 2023; Mitra et al., 2022), and strengthening safety competence through immersive training simulations (Grabowski and Jankowski, 2015; Gürer et al., 2023). On the other hand, these digital advancements also introduce new health and safety concerns in the mining workplace, including workplace incidents caused by technology malfunctions or operational errors (Mensah et al., 2022; Sidani et al., 2023), growing risks of security and privacy breaches (Dempsey et al., 2018; Onifade et al., 2023), cognitive overload (Kohler, 2015), and reduced job satisfaction (Lööw, 2022; Rogers et al., 2019).

It is notable that evidence regarding the health and safety impact of new technologies in mining remains fragmented. Moreover, the underlying mechanisms driving these varied outcomes are still unclear. This uncertainty provides little guidance for practitioners and scholars on systematically managing new technologies to optimise health and safety. This paper argues that a deeper understanding of how the evolving technological landscape in mining affects psychosocial work factors is essential for bridging this research gap. As the mining industry increasingly adopts automation and digital systems, it provides a suitable setting to investigate the impact of technology on psychosocial work factors. Failing to do so may result in unintended consequences, such as increased stress, decreased engagement in safety, or resistance to technological adoption, ultimately undermining the intended benefits of automation.

Research on the evolving nature of work in the mining industry suggests that technological advancements are reshaping workplaces by transforming work organisation, environments, and tasks, significantly influencing worker experiences (Cheng et al., 2022; Babalola et al., 2023; Sorensen et al., 2021). However, systematic literature reviews that comprehensively examine the holistic impact on psychosocial work factors are lacking. Derdowski and Mathisen (2023) explored the relationship between psychosocial work characteristics and safety in high-risk industries, confirming their association but without considering how technology implementation affects these dynamics. Babalola et al. (2023) examined occupational safety and health (OSH) hazards addressed through immersive training technologies, focusing on specific hazards like falls, fires, and chemical exposures. However, their study was limited to training applications, lacking a broader perspective on other technological domains and their impact on worker experience. Cheng et al. (2022) reviewed literature on emerging work models and workplace safety, noting the field's early stage and methodological limitations. While they emphasised the need for deeper insights into work design changes and worker well-being, they did not explore technology-driven transformations and their psychosocial effects. Despite this gap, their perspective on work changes and organisational dynamics provided valuable insights that informed our study design—particularly in examining how emerging mining technologies influence psychosocial work factors and, in turn, shape workplace health and safety outcome. Specifically, this paper seeks to answer the following questions.

RQ1. What are the key emerging technologies in the mining industry?

RQ2. How do these technologies affect psychosocial work factors in mining?

RQ3. What are the implications for future research and practice in technology management within the mining industry?

The structure of this paper is developed as follows. Section 1 introduces the background and motivation for this research. Section 2 outlines the literature review method, including the selection strategy and analysis approach. Section 3 presents the review results, highlighting the major themes of technologies and their impact on psychosocial work factors. In Section 4, we identify key research gaps emerging from the systematic review and highlight the implications of these gaps, which inform a future research agenda. Section 5 outlines the study's contributions, offering both theoretical insights and practical guidance for practitioners, decision-makers, and policymakers navigating digital innovation in the mining industry. Specifically, we discuss how the integrated framework developed in this study can serve as a practical tool for evaluating technological change and optimising its impact.

2. Method

A systematic literature review was conducted to synthesise existing research on the impact of emerging technologies in the mining industry, aiming to provide a comprehensive and robust understanding of the current literature. A systematic literature review approach is well-suited for this purpose, as it offers a transparent and replicable method for compiling and synthesising available evidence, and generating a framework that highlights research gaps and future research directions (Sivarajah et al., 2017; Miozza et al., 2024). This systematic review was conducted by following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Liberati et al., 2009). It includes three phases (1) selection of research papers, (2) descriptive analysis, and (3) thematic analysis. Phase 1 paper selection sets the boundary conditions of the study with inclusion and exclusion criteria clearly identified for the eligible studies for this review. Phase 2 descriptive analysis offers bibliometric results of the reviewed articles with their journal sources, data sources, research methods, and theory used. Phase 3 of the thematic analysis captures the salient themes of emerging technology and change in the mining sector and their respective categories. It follows an inductive process to identify themes related to psychosocial work factors arising from the implementation of these technologies in the mining industry.

2.1. Search strategy

The article selection process adopted is presented in Fig. 1. Web of

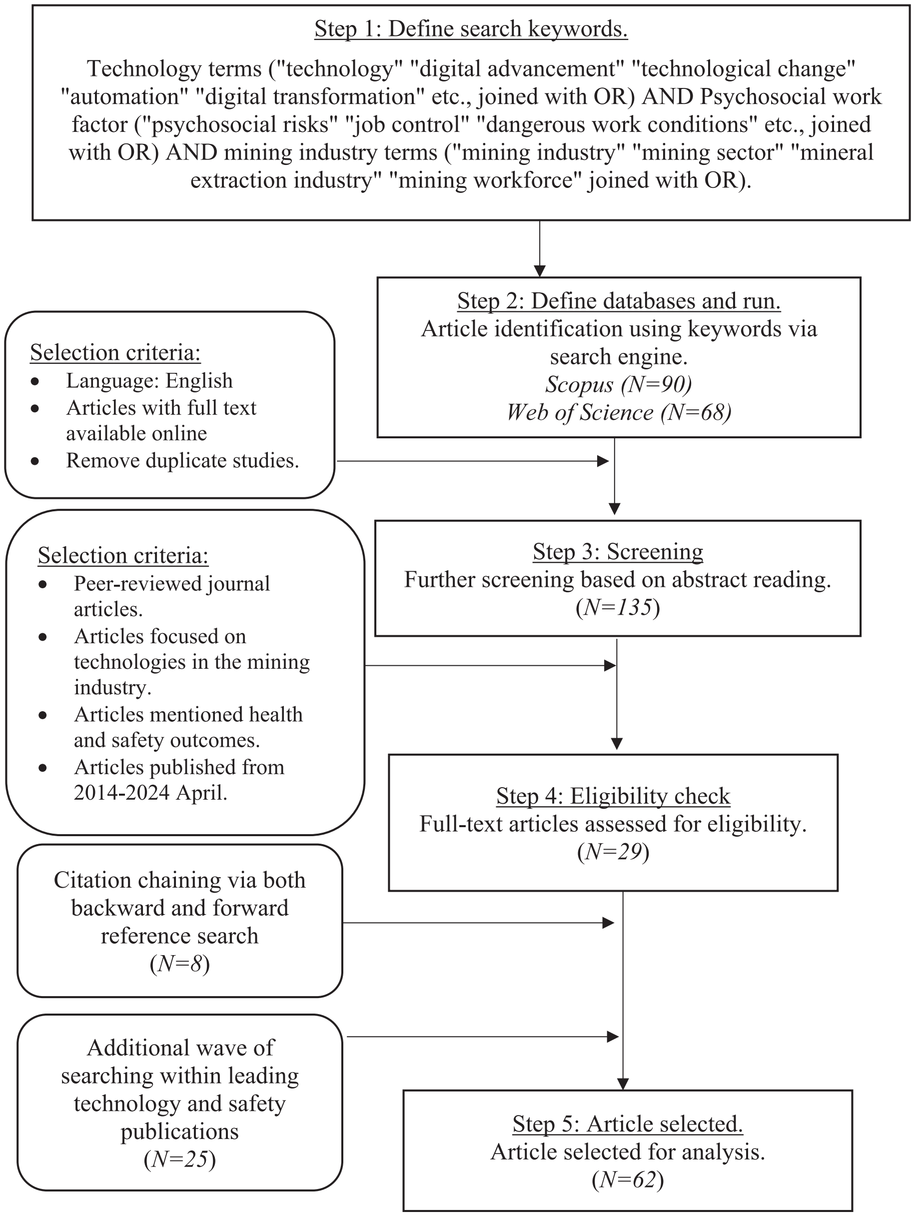

Fig. 1. Article selection process.

Science (WOS) and Scopus were used for initial searching because they include major online databases and provide a comprehensive basis for article selection in broad fields including arts and humanities; business; engineering, computing, and technology; and social and behavioral sciences (Li et al., 2022). Literature search was based on key terms from three focal areas: technologies, psychosocial work factors, and mining industry. The initial keyword list was derived from multiple systematic literature review papers on relevant topics (e.g., Yang et al., 2021; Ismail et al., 2021; Flores-Castañeda et al., 2025). This list was then refined through discussions among the author team and consultations with academic experts in occupational health and safety. To ensure comprehensive coverage of relevant studies, we systematically combined the finalised keywords using Boolean operators ("AND" and "OR"). The complete list of keywords can be found in Table 1.

The initial search yielded 158 records from the two databases. After manually selecting articles that are written in the English language, with full text available online, and removing duplicates, 135 articles remained for the screening phase. During this stage, four selection criteria were applied to ensure the quality and relevance of the studies: (1) only peer-reviewed journal articles were included to ensure reliability and validity. While non-academic sources may provide practical insights, they often lack the methodological transparency and systematic approach required for inclusion in a systematic literature review. This approach aligns with established practices in recent publications (e.g., Li et al., 2022; Gjergji et al., 2025); (2) studies focusing on the implementation of technologies within the mining industry were retained; (3) articles discussing psychosocial work factors arising from technology implementation were included; and (4) only articles published between 2014 and April 2024, the time of this search, were considered to capture contemporary technological advancements. Examples of articles that were removed included those focusing on the mining workforce skills shortage, construction, economics, industrial relations, skills development, health and safety regulations, and policy development, none of which related to the impact of mining technologies on psychosocial work factors.

As a result, twenty-eight papers were selected for further review. An additional eight articles were identified by citation chaining through both backward and forward reference searches within the screened

Table 1
Search keywords.

Focal area	Keywords
Technologies	"technology" OR "digital advancement" OR "technological change" OR "automation" OR "digital transformation" OR "Remote Operation" OR "Digital Communication" OR "Data Analytics" OR "Wearable Technology" OR "Virtual Reality" OR "Artificial Intelligence" OR "Decision Support Systems" OR "Robotics" OR "Internet of Things (IoT)" OR "Machine Learning" OR "Digital Twin" OR "Teleoperation" OR "Blockchain" OR "Renewable Energy" OR "3D Printing" OR "Augmented Reality (AR)" or "Digitalisation" OR "Drones" OR "Unmanned Aerial Vehicles" OR "Sensors" OR "Autonomous Vehicles" OR "Electric Vehicles" OR "Cybersecurity"
Psychosocial work factors	"work conditions" OR "job control" OR "job support" OR "career development" OR "Isolation and Loneliness" OR "Limited Access to Healthcare" OR "Workplace Culture and Bullying" OR "Role overload" OR "Role ambiguity" OR "Role conflict" OR "Cognitive demand" OR "Job insecurity" OR "Organisational injustice" OR "Lack of training" OR "Interpersonal conflict" OR "Work underload" OR "Safety concerns" OR "reward and recognition" OR "psychosocial risks" OR "health and safety" OR "mental health"
Mining industry	"mining industry" OR "mining sector" OR "mineral extraction industry" OR "mining workforce"

articles. As a result, thirty-six articles were selected for analysis. To avoid omissions of eligible papers, the authors conducted an additional wave of full-text search within leading technology and safety research publications, including Resources Policy, International Journal of Mining Science and Technology, Safety Science, Accident Analysis and Prevention, and so on. As a result, twenty-five additional articles were identified. Therefore, a total of sixty-two articles were kept for further descriptive and thematic analyses.

2.2. Analysis approach

To obtain a static and systematic flow, a descriptive analysis was first performed to analyze chronological patterns of publication, journal sources, key theories, and methodologies of the articles selected (Li et al., 2022). Microsoft Excel software was used to create the initial coding sheet to facilitate the analyses, where the demographic information of each article (including authors, article title, journal, keywords, and publication year) and attributes of each article (including the specific mining technology mentioned, function of the technology, its impact on psychosocial work factors, underpinning theory, methodology, as well as data source if mentioned) were noted. Experimental coding sessions were conducted to standardise methods and practices. The remaining papers were manually coded independently, followed by cross-examination to ensure accuracy and consensus among coders. Thematic analysis was conducted to identify the main categories of technologies, the workplace changes they introduce, and their effects on psychosocial work factors. This was achieved by organising the initial codes from each paper to identify similar concepts and develop overarching groups representing the substantive themes. These are discussed in the following sections of the paper.

3. Results

In this section, we present the results of the descriptive analysis of the reviewed articles, highlighting the main technology categories and key areas of impact. The findings provide insights into the nuances of technology implementation in the mining industry. We then present the themes related to psychosocial work factors emerging from these technologies, along with the mechanisms of workplace change that drive variations in these factors. These are illustrated in Fig. 2.

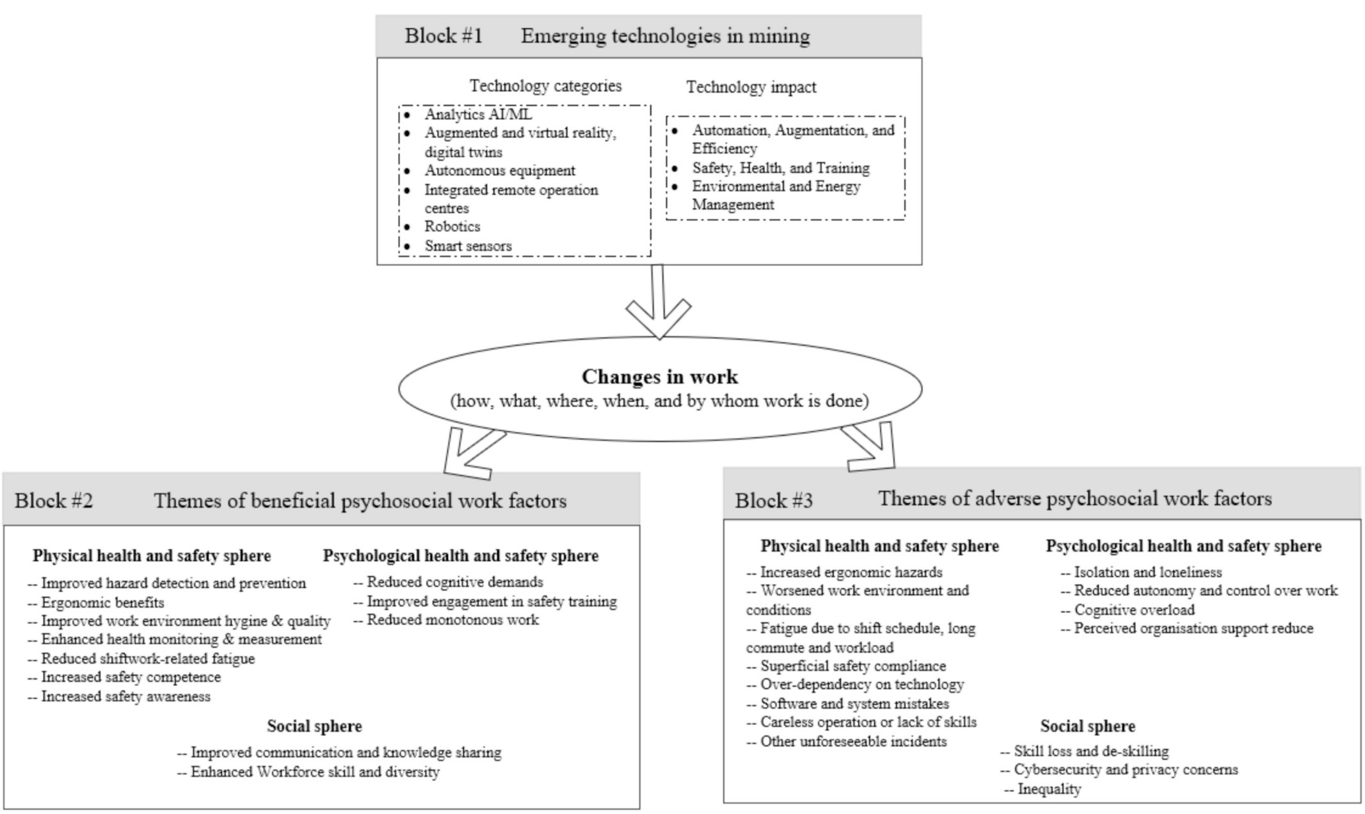

Fig. 2. Coding theme framework.

3.1. Descriptive analysis

3.1.1. Distribution of publication across journals

Table 2 presents the distribution of the articles across journals. The systematic review revealed that sixty-two articles related to the effects of technology in mining have been published in twenty-seven journals. Based on Clarivate's Journal Citation Reports, eighteen out of twenty-seven journals are in SCI or SSCI, within which, six journals are in Q1, four journals in Q2, five journals in Q3, and three journals in Q4. However, for brevity, Table 2 only shows the journals with two or more publications. As depicted by Table 2, International Journal of Mining Science and Technology, Safety Science and Resources Policy have the most numbers of publications, with fourteen, nine, eight articles published respectively. All these three journals are in SCI Q1. Following that, Mining Metallurgy & Exploration, an SCI Q3 journal, published four relevant articles. The remaining journals are the International Journal of Environment Research Public Health (Q2) and Mineral Economics (Q1) each containing three and two articles respectively, as shown in Table 2.

3.1.2. Countries or regions of data source

Table 3 shows the distribution of countries or regions where empirical data were collected in the reviewed papers (excluding $N = 15$ articles that didn't explicitly refer to countries or areas). Among the remaining articles, the number of samples from China ($N = 9$), United States ($N = 6$), Australia ($N = 5$) ranked first, followed by, European Union ($N = 2$), Brazil (N = 2), Poland(N = 2), India (N = 2), Sweden (N = 2), Turkey (N = 2) and South Africa (N = 2). This indicates that the reviewed studies drew data from a geographically diverse range of countries, reflecting a global perspective on the effects of technology in the mining industry.

3.1.3. Publication year

Fig. 3 provides insights into the number of articles published annually on the technological impact on health, safety and psychosocial issues in the mining industry. It is observed that the number of articles published in 2019 and 2023 was thirteen and eleven, respectively, which was the two highest number of articles published in a single year. It was also observed that from 2019 to April 2024 (the time of this search), about 65 % of the total relevant articles identified in this study were published. This indicates a strong and growing interest in the topic, despite the impact of the pandemic from 2020 to 2022. The highest number of articles were published in 2019 and 2023.

3.1.4. Methodology

The research methodologies employed in the reviewed articles are shown in Table 4. It is shown that thirteen out of sixty-two studies were conceptual in nature, thirteen articles adopted a literature review methodology, and the remaining thirty-seven were empirical. Of the thirty-seven empirical studies, fifteen employed applied case study methods, ten conducted surveys, six used experimental methods, four relied on secondary data analysis, and three adopted qualitative methods of interviews. Only two studies—Haas (2019) and Santos et al. (2023)—used a mixed-methods design, combining qualitative and quantitative approaches. Both incorporated surveys and interviews as their methodologies.

Table 2
Database search results: publications per journal.

Source title	No. of publications
International Journal of Mining Science and Technology	14
Safety Science	9
Resources Policy	8
Mining Metallurgy & Exploration	4
International Journal of Environmental Research and Public Health	3
Mineral Economics	2

Note: Only journals with at least two publications are included.

Table 3
Database search results: publications by country.

Country	No. of publications
China	9
United States	6
Australia	5
Brazil	2
European Union (EU)	2
Poland	2
India	2
Sweden	2
Turkey	2
South Africa	2
Finland	1
Ghana	1
Nigeria	1
Pakistan	1
Russia	1
Saudi Arabia	1
Africa	1
Western Balkan countries (Europe)	1

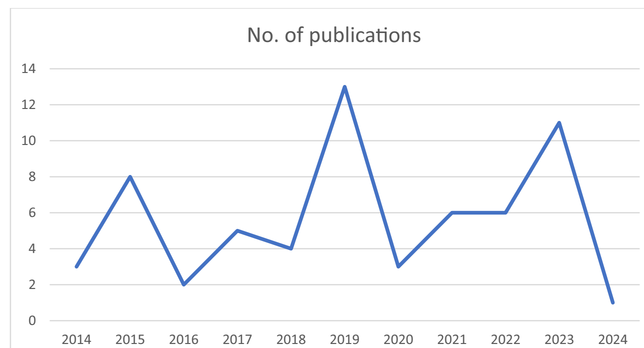

Fig. 3. Database search results: publications by year (from 2014 to 2024 April).

Table 4
Database search results: publications by methodology.

Methodology	No. of publications
Conceptual	13
Literature review	13
Experiment	6
Case study	15
Interviews	3
Secondary data analysis	4
Survey	10
Mixed-methods	2

The most adopted method for empirical studies is case study, where the data was collected through the implementation of specific technologies in mine operations (e.g., Jacobs et al., 2022; Kirsch et al., 2015; Zhou et al., 2018; Zujovic et al., 2021). Ten articles used surveys, and notably four of them were conducted to investigate the effectiveness of VR-based training programs (e.g., Grabowski and Jankowski, 2015; Gürer et al., 2023; Zhang, 2017). Six articles adopted an experiment method using lab simulation to test the technical qualifications and attributes (e.g., Dong et al., 2023; Henriques and Malekian, 2016; Oltmanns and Petruska, 2023).

3.1.5. Theoretical background

Table 5 shows the theoretical background of the reviewed articles. It is observed that only ten out of sixty-two clearly mentioned a theoretical

Table 5
Database search results: publications by theory.

Theoretical background	No. of publications
Socio-Technical Systems	1
Analytic Hierarchy Process	1
Institutional Theory	1
Media Equation Communication Spatial Presence	1
Mental model of the automation	1
Self-Determination Theory	1
Theory of Planned Behaviour (TPB)	1
Socio-economic benefit-sharing channels	1
SWOT analysis	1
Technology Acceptance Model	1

framework. Specifically, the theoretical frameworks used include socio-technical systems (Erkan et al., 2016), institutional theory (Ivic et al., 2021), analytic hierarchy process (Zhang et al., 2019), technology acceptance model (Gürer et al., 2023), media equation communication spatial presence (Grabowski and Jankowski, 2015), self-determination theory (Haas, 2019), theory of planned behaviour (Cao et al., 2019), socio-economic benefit-sharing channels (Muhirwa et al., 2023), swot analysis (Kapusta et al., 2020) and mental model of automation (Rogers et al., 2019). It is worth noting that majority (fifty-one out of sixty-two) articles did not clearly adopt a particular theoretical lens, highlighting the urgent need to expand and integrate existing theories or develop new ones to obtain a deeper understanding of this evolving topic.

3.2. Emerging technologies in the mining industry

Six categories of mining technology were identified in the reviewed articles. These are: analytics AL/ML; augmented and virtual reality (AR/VR), digital twins; autonomous equipment; integrated remote operation centres; robotics; and smart sensors. Table 6 summarises these technology categories, providing a brief description of their aims and purposes, along with examples within each category.

Analytics AI/ML category include technologies that use artificial intelligence (AI) and machine learning (ML) algorithms to analyze historical data, make predictions on maintenance needs or environmental impacts, and improve decision-making processes. This type of technology enables more efficient resource management and operational efficiency (Sidani et al., 2023; Ivic et al., 2021; Creus et al., 2021). Augmented and virtual reality, digital twins is the category where AR and VR technology provides immersive environments for training, simulation, and remote collaboration (e.g., Grabowski and Jankowski, 2015; Gürer et al., 2023). By creating digital representations of the physical world, digital twins are virtual replicas of physical systems that enable real-time monitoring, predictive maintenance, and scenario planning (e.g., Jacobs et al., 2022). Autonomous equipment includes driverless vehicle technology (e.g., Kiziroglou et al., 2017), loaders (e.g., Parasurama et al., 2022), and drills (e.g., Aminossadati et al., 2014) that operate with minimal human intervention. These technologies improve safety by reducing the need for human presence in hazardous areas, increasing efficiency through continuous operation, and optimising resource usage. Integrated remote operation centres use advanced communication and monitoring technologies to enable the monitoring and management of multiple mining operations remotely. This type of technology includes office workstations and communication tools (e.g., Dempsey et al., 2018), real-time positioning (e.g., Kiziroglou et al., 2017) and remote controls (e.g., Oltmanns and Petruska, 2023), enhancing coordination, reducing downtime, and improving overall efficiency. Robotics have various applications in the mining industry, such as scouting, drilling, ore extraction, and sorting (e.g., Lööw, 2022; Santos et al., 2023). The use of robots in dangerous and challenging environments can increase safety and productivity by reducing human exposure to hazardous conditions. Lastly, smart sensors can collect real-time data on various parameters such as temperature, vibration, and gas (e.g., Marimuthu et al., 2023) and monitor human health conditions such as heart rate and pressure (e.g., Dempsey et al., 2018). These sensors enable continuous monitoring of equipment and environmental conditions, facilitate predictive maintenance, and enhance safety.

3.2.1. Technological functions

Three key areas where these technologies have significant impact were identified: automation, augmentation, and efficiency function; safety, health, and training function; and environmental and energy management function.

First, the automation, augmentation, and efficiency function capture the use of technology to automate work tasks, enhance human capabilities, optimise work processes, and thus contribute to a more streamlined and productive mining workplace. There are a diverse range of technologies impacting this function. Examples include technologies that facilitate automation and remote operation, such as autonomous equipment (Duncan and Stolarczyk, 2015; Moore et al., 2021), automated machinery (Santos et al., 2023), and robotics (53, 54), which enhance productivity by achieving continuous operation and reducing human error and improve the speed and accuracy of mining operations. Augmentation technologies, such as wearable exoskeletons (Santos et al., 2023), assistive drones (Garcia-del-Real and Alcaráz, 2024), enhance the capabilities of workers, allowing them to perform tasks more effectively. Overall, these technologies work together to streamline operations, reduce costs, and increase productivity.

Second, the safety, health, and training function encompass technologies designed to improve safety, reduce the risk of accidents, improve health monitoring, and provide immersive training experiences that prepare workers for real-world challenges. Technologies like AR/VR, digital twins, smart sensors, are particularly influential in this area. These technologies can simulate hazardous scenarios for training, allowing workers to learn and practice safety procedures in a controlled environment, thereby improving their readiness and response to potential hazards (Grabowski and Jankowski, 2015). Other examples, such as smart sensors and real-time health monitoring technologies can provide continuous oversight of workers' health and environmental conditions, allowing for proactive approach to help prevent accidents and long-term health issues (Sidani et al., 2023; Baharfar et al., 2023).

Environmental and energy management focuses on the impact of technology on minimising the environmental impact of mining activities and improving energy efficiency. Battery electric vehicles (BEVs) are a prime example, as they reduce emissions and improve energy efficiency compared to traditional diesel-powered equipment, contributing to a cleaner and more sustainable mining operation (Halim et al., 2022). Autonomous drones and mining equipment equipped with AI can optimising energy usage, and reducing waste generation, leading to more efficient and successful operations in limited power environments (Garcia-del-Real and Alcaráz, 2024). Fig. 4 illustrates the technological functions of these categories as identified in the articles. It is important to note the overlaps between these key function areas, suggesting that many mining technologies can serve multiple functions simultaneously. This interconnectedness underscores the versatility and integrated nature of these technological solutions.

3.3. Effects on psychosocial work factors: Beneficial factors

Themes of psychosocial work factors emerging from the implementation of mining technologies were identified, including both adverse and beneficial factors. They were further grouped based on their implications into three spheres: physical health and safety, psychological health and safety, and social sphere. These are listed in Table 7 and Table 8.

3.3.1. Physical health and safety sphere

Physical health and safety is one key group encompassing emerging beneficial psychosocial work factors that will positively affect workers'

Table 6
Technology categories.

Technology category	Mining technology selected examples	Author(s), year & country (for each example)	Aim/focus	References
Analytics AI/ML	AI-based predictive analytics	Sidani et al., 2023, NA	AI-based predictive analytics uses artificial intelligence to analyze historical data and make predictions about future events, trends, or behaviours, helping organisations make data-driven decisions.	Cao et al. (2019); Creus et al. (2021); Dong et al. (2023); Garcia-del-Real and Alcaráz (2024); Ivic et al. (2021); Lööw (2022); Lööw et al. (2019); Marimuthu et al. (2023); Onifade et al. (2023); Sidani et al. (2023)
	Environment management systems structure-from-motion, multi-view stereo (SfM-MVS)	Ivic et al., 2021, European Union (EU) Creus et al., 2021, Australia	Environment management systems monitor, manage, and mitigate environmental impacts. Structure-from-Motion, Multi-View Stereo (SfM-MVS) technology utilises algorithms to generate highly accurate 3-D models from a series of 2-D images taken from multiple viewpoints and reconstructs detailed and realistic 3-D scenes.	
Augmented and virtual reality, digital twins	PC-based Virtual reality hazard awareness training simulator	Squelch, 2001, South Africa	A PC-based Virtual Reality hazard awareness training simulator is a computer application that uses virtual reality technology to create immersive, interactive environments for training individuals to recognize and respond to potential hazards safely.	Grabowski and Jankowski (2015); Gürer et al. (2023); Jacobs et al. (2022); Kapusta et al. (2020); Kohler (2015); Lööw et al. (2019); Onifade et al. (2023); Zhang (2017); Zhang et al. (2019); Zujovic et al. (2021)
	3-D scenes	Lucas et al., 2008, United States	The 3-D scene technology utilises advanced sensors and imaging techniques. It reconstructs physical spaces into interactive 3-D models, enhancing applications such as virtual reality by providing users with an unparalleled level of detail and realism.	
	Digital Twin for Ventilation Systems	Jacobs et al., 2022, NA	A Digital Twin for Ventilation Systems is a virtual replica of a physical ventilation system, utilizing real-time data and simulations to monitor, analyze, and optimise the system's performance and efficiency.	
Autonomous equipment	Load Hoal Dumps (LHD)	Paraszczak et al., 2015, NA	Load Haul Dumps (LHD) are specialised mining vehicles designed to load, transport, and dump materials like ore and waste within underground mines, improving the efficiency of material handling operations.	Johansson et al. (2018); Kapusta et al. (2020); Lööw (2022); Lööw and Nygren (2019); Marimuthu et al. (2023); Mensah et al. (2022); Moore et al. (2021); Onifade et al. (2023); Ribeiro-Duthie et al. (2017); Rogers et al. (2019); Santos et al. (2023); Sen et al. (2020)
	Driverless vehicle technology	Kiziroglou et al., 2017, NA	Driverless vehicle technology enables vehicles to navigate and operate without human intervention.	
	Water jet cable bolth drilling	Aminossadati et al., 2014, NA	Water jet cable bolt drilling is a technique that uses high-pressure water jets to drill holes for installing cable bolts.	
Integrated remote operation centres	RF Positioning (Real-time global positioning)	Kiziroglou et al., 2017, NA	RF Positioning (Real-time global positioning) is a technology that uses radio frequency signals to determine the precise location of objects or individuals in real time, providing accurate tracking and navigation capabilities.	Adjiski et al. (2019); Dempsey et al. (2018); Duncan and Stolarczyk (2015); Johansson et al. (2018); Kiziroglou et al. (2017); Kohler (2015); Lööw (2022); Lööw et al. (2019); Lööw and Nygren (2019); Mensah et al. (2022); Oltmanns and Petruska (2023);
	Technology and office workstations	Dempsey et al., 2018, NA	Technology and office workstations allow the miner to operate equipment from a safe location without exposure to hazards inherent in many mining operations.	
	Remote controls	Oltmanns and Petruska, 2023, Global	Remote controls are handheld devices that use wireless signals to operate electronic equipment or systems from a distance, providing convenience and ease of use for managing various functions and settings.	
Robotics	Scout robot	Lööw, 2022, Global	The scout robot is designed for mine exploration. Equipped with advanced sensors and mobility features, it navigates hazardous environments, detecting obstacles, toxic gases, and structural weaknesses, thus aiding in the efficient and safe rescue of trapped individuals.	Lööw (2022); Lööw et al. (2019); Marimuthu et al. (2023); Rogers et al. (2019); Santos et al. (2023); Sen et al. (2020)
	Semi-autonomous exploration and teleoperated robots	Rogers et al., 2019, Global	Semi-autonomous exploration and teleoperated robots are advanced machines that can perform tasks independently or be remotely controlled by humans.	
	Collaborative robots	Santos et al., 2023, Brazil	Robots designed to work alongside humans in industrial settings, assisting with tasks that might be ergonomically challenging.	
Smart sensors	Internet of Things (IoT)	Marimuthu R.; Sankaranarayanan B.; Karuppiah K, 2023, India	The Internet of Things (IoT) refers to a network of interconnected physical devices that use sensors and software to collect and exchange data, enabling smarter and more automated systems.	Adjiski et al. (2019); Aminossadati et al. (2014); Baharfar et al. (2023); Bauerle et al. (2022); Dempsey et al. (2018); Duarte et al. (2022); Haas (2019); Henriques and Malekian (2016); Ivic et al. (2021); Johansson et al. (2018); Kapusta et al. (2020); Kiziroglou et al.

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Table 6 (*continued*)

Technology category	Mining technology selected examples	Author(s), year & country (for each example)	Aim/focus	References
	Body-Worn Technology	Dempsey et al., 2018, Global	Body-worn technologies can collect human performance data, monitor ambient conditions, extend human capabilities, or mitigate the negative effect of activity on the body during work and leisure activities are developing at a rapid pace.	(2017); Lööw (2022); Lööw et al. (2019); Marimuthu et al. (2023); Mitra et al. (2022);
	Gas nanosensors	Baharfar et al., 2023, NA	Real-time monitoring of CH4 and O2 is therefore critical for the detection and prevention of underground explosions.	

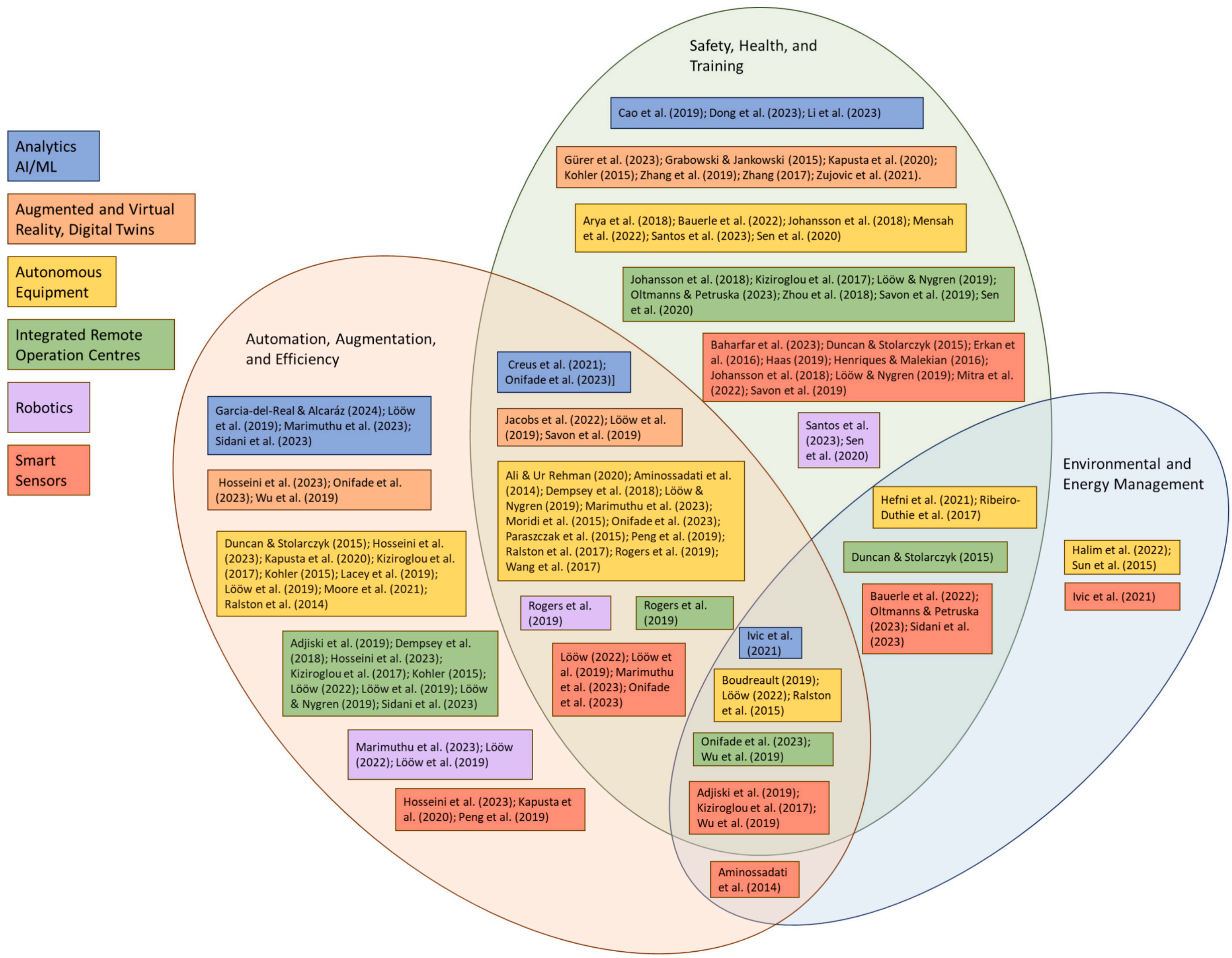

Fig. 4. Technology categories and impact areas.

physical well-being and safety. These psychosocial work factors include improved hazard detection and prevention, ergonomic benefits, improved work environment hygiene & quality, enhanced health monitoring & measurement, reduced shiftwork-related fatigue, and increased safety competence and awareness.

Improved hazard detection and prevention points out the benefits of emerging technologies in early identification and prevention of potential risks and reducing workers' exposure to potential dangers and extreme working conditions. For example, gas nanosensors are used to monitor CH4 and O2 in real-time, which is critical for the detection and prevention of underground explosions (Dempsey et al., 2018). Remote-controlled machinery allows mine workers to operate equipment from a safe location, minimising exposure to hazards inherent in many mining operations (Dempsey et al., 2018; Lööw and Nygren, 2019).

Ergonomics has long been a challenge in the mining industry due to heavy lifting, awkward postures, and repetitive tasks. Emerging technologies offer potential ergonomic interventions for mine workers. Devices like weight cancelers, exoskeletons, and load handlers reduce the physical strain associated with lifting and transporting materials, thus decreasing the risk of musculoskeletal disorders (Santos et al., 2023). Additionally, the design of active exoskeletons has proven effective in reducing contact pressure and musculoskeletal activity during lifting

Table 7
Beneficial psychosocial work factors.

Themes	Examples	References
Physical health and safety sphere		
Improved hazard detection and prevention	"Technologies such as smart helmets that send proximity warning signals to pedestrians, workers, and equipment operators significantly improve safety in mining operations. This technology helps reduce the danger to workers on foot from heavy machinery's 'blind spot' zones, thus potentially reducing accidents and enhancing worker safety" (Duarte et al., 2022).	Ali and Rehman (2020); Baharfar et al. (2023); Creus et al. (2021); Duarte et al. (2022); Garcia-del-Real and Alcaráz (2024); Gürer et al. (2023); Henriques and Malekian (2016); Jacobs et al. (2022); Johansson et al. (2018); Kapusta et al. (2020); Marimuthu et al. (2023); Mitra et al. (2022); Moore et al. (2021); Oltmanns and Petruska (2023); Onifade et al. (2023);
Ergonomic benefits	"The researchers determined that the exoskeleton reduced the musculoskeletal activity of the trunk as designed and did not add any perceived effort to the legs" (Dempsey et al., 2018).	Dempsey et al. (2018); Halim et al. (2022); Johansson et al. (2018); Lööw and Nygren (2019); Marimuthu et al. (2023); Paraszczak et al. (2015); Santos et al. (2023); Sen et al. (2020)
Improved work environment hygiene & quality	"BEVs reduce negative impact on the working conditions by increasing air quality and reducing noise level" (Halim et al., 2022).	Adjiski et al. (2019); Boudreault (2019); Dempsey et al. (2018); Dong et al. (2023); Duarte et al. (2022); Duncan and Stolarczyk (2015); Haas (2019); Halim et al. (2022); Henriques and Malekian (2016); Lööw (2022); Lööw and Nygren (2019); Moore et al. (2021); Moridi et al. (2015); Onifade et al. (2023);
Enhanced health monitoring & measurement	"New wearable technologies that can collect human performance data, monitor ambient conditions, extend human capabilities, or mitigate the negative effect of activity on the body during work and leisure activities are developing at a rapid pace" (Dempsey et al., 2018).	Adjiski et al. (2019); Dempsey et al. (2018); Sidani et al. (2023)
Reduced shiftwork-related fatigue	"Another potential benefit of automation is the change in number of hours of work per week. In the early 1900s, the typical work week could be as much as 70 h. Now, the average work week is closer to 40–45 h of work per week. Automation has played a significant role in this reduction. Also, the time required to complete a typical manufactured product is reduced due to automation" (Rogers et al., 2019)	Bauerle et al. (2022); Johansson et al. (2018); Rogers et al. (2019)
Increased safety competence	"in the event of a disaster, a central system driven by IoT can provide improved rescue and evacuation procedures" (Onifade et al., 2023).	Cao et al. (2019); Dong et al. (2023); Grabowski and Jankowski (2015); Haas (2019); Ivic et al. (2021); Johansson et al. (2018); Kapusta et al. (2020); Kirsch et al. (2015); Knights and Scanlan (2019); Kohler (2015); Lööw and Nygren (2019); Marimuthu et al. (2023); Zhang et al. (2019).
Increased safety awareness	"After the implementation of this technology system, all the workers in Geting Coal Mine exhibit increasing safety awareness and the managers at all levels show enhanced responsibility for safe production" (Zhou et al., 2018)	Cao et al. (2019); Dong et al. (2023); Grabowski and Jankowski (2015); Haas (2019); Ivic et al. (2021); Kapusta et al. (2020); Kirsch et al. (2015); Knights and Scanlan (2019); Kohler (2015); Lööw and Nygren (2019); Marimuthu et al. (2023);
Psychological health and safety sphere		
Reduced cognitive demands (e.g. from constant concentration, mental effort)	"Autonomous LHD operation is less intensive and less tiring than the constant concentration required when teleoperating the whole cycle" (Paraszczak et al., 2015)	Dempsey et al. (2018); Halim et al. (2022); Paraszczak et al. (2015)
Improved engagement in safety training	"It is found that the HMD-based intuitive VR training system has a dramatically higher score of immersion (4.8 out of 5) than the screen-based general system out of 5, and 1.5 to 2 times higher grade of intuitive, interactive and ease of use." (Zhang, 2017)	Grabowski and Jankowski (2015); Gürer et al. (2023); Johansson et al. (2018); Lööw and Nygren (2019); Rogers et al. (2019); Zhang (2017); Zhang et al. (2019); Zujovic et al. (2021).
Reduced monotonous work	In the optimistic visions of Mining 4.0, smart systems, automation, and remote control will take over dangerous as well as routine work so that operators can focus on learning, creating, and valuing work tasks in a safe environment. (Lööw et al., 2019)	Dempsey et al. (2018); Lööw et al. (2019); Santos et al. (2023)
Social sphere		
Improved communication and information sharing	"With respect to the importance of remote sensing to stablishing mechanisms for collaboration, information sharing, and the equitable distribution of resources and their benefits, it is important to note that the use of this technology could be crucial not only to overcome the potential obstacles derived from information sharing among stakeholders, but also to assess the equitable distribution of benefits and the conflict prevention among participating	Adjiski et al. (2019); Duarte et al. (2022); Garcia-del-Real and Alcaráz (2024); Haas (2019); Kirsch et al. (2015); Moridi et al. (2015)

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Table 7 (*continued*)

Themes	Examples	References
	nations" (Garcia-del-Real and Alcaráz, 2024).	
Enhanced workforce skill and diversity	"A mining 4.0 plan can lead to employment opportunities and generate jobs and incomes for future generations."	Ivic et al. (2021); Kapusta et al. (2020); Lööw (2022); Lööw et al. (2019); Moore et al. (2021); Paraszczak et al. (2015)

movements (Dempsey et al., 2018).

Improvements in workplace hygiene and quality have also emerged as a primary benefit for safety and health outcomes in mining. New technologies, such as automated underground mine monitoring and communication systems, are able to sense environment attributes in the workplace, such as temperature, humidity and gases concentration (Moridi et al., 2015). Battery electric vehicles (BEV) also have the potential to improve the air quality of the work environment as they use BEVs instead of diesel machines, reduce gas and heat emissions, and produce no exhaust, thus reducing the need for ventilation (Boudreault, 2019; Halim et al., 2022).

Mining technologies also contribute to real-time health monitoring and measurement through devices, such as include physiological and biochemical sensors, to track workers' vital signs (e.g. heart rate, blood pressure, body temperature, and respiration rate), detect early signs of health issues, and measure exposure to harmful conditions. This enables immediate response to potential threats and preventive actions before conditions worsen. By collecting and analysing data on human performance and ambient conditions, body-worn technologies provide valuable health and safety information to mine workers, promoting overall physical health and safety (Dempsey et al., 2018; Sidani et al., 2023).

The articles also emphasised the benefits of emerging technologies in reducing shiftwork-related fatigue. Automation, for instance, reduces the physical and cognitive demands placed on workers by replacing humans in repetitive and routine mining tasks (Johansson et al., 2018; Rogers et al., 2019). This shift not only decreases the risk of harmful workloads, but also significantly shortens the time required to complete tasks, resulting in a notable reduction of labour hours, and consequently, shiftwork-related fatigue (Rogers et al., 2019). There are opportunities to leverage automation through machine learning to enhance fatigue-specific health and safety management in mining by analysing early indicators of sleepiness and performance declines (Bauerle et al., 2022). Another example is the implementation of advanced lighting technologies. These technologies can serve as interventions to address shiftwork-related fatigue and circadian disruptions. By regulating circadian rhythms and reducing acute effects, these lighting systems can enhance alertness, improve concentration, and boost performance on cognitive tasks (Bauerle et al., 2022).

The reviewed studies highlighted that the application of emerging technologies could enhance safety competence and awareness among mine workers. Safety competence refers to mine workers' ability, knowledge, skills, and attitudes needed to perform tasks safely, such as correctly using mining equipment and adhering to safety procedures that mitigate potential risks (Hystad et al., 2014; Mahsoon and Dolansky, 2021). Safety awareness involves mine workers' understanding, recognition, and attentiveness to potential hazards, risks, and safe behaviours within their workplace (Mohammad et al., 2022; Li and Griffin, 2022). These two components were often integrated into safety training programs enabled by new technologies and training methods (e.g., Kapusta et al., 2020; Knights and Scanlan, 2019; Kohler, 2015; Lööw and Nygren, 2019).

For example, VR training programs have been developed to teach miners safety knowledge and skills with immersive and hands-on learning opportunities (Zhang et al., 2019). Such programs enhance workers' confidence and competence in safely performing their duties.

Table 8
Adverse psychosocial work factors.

Themes	Example	References
<u>**Physical health and safety sphere**</u>		
Increased ergonomic Hazards	"The effects of this mechanical assistance on the overall fitness, strength, and production capability of the user over time may result in a worker developing greater future risk for injury due to weakness." (Dempsey et al., 2018)	Bauerle et al. (2022); Dempsey et al. (2018); Lööw (2022); Paraszczak et al. (2015)
Worsened working environment and conditions	"Using light-emitting diode (LED) lighting technologies has raised concerns of exposure to potential blue-light hazards resulting in retinal damage that is typically irreversible" (Bauerle et al., 2022)	Bauerle et al. (2022); Knights and Scanlan (2019); Lööw (2022); Paraszczak et al. (2015)
Fatigue due to shift schedules, long commute and workload	"with remote control, operators can get the freedom to decide where she or he should work. But freedom might also mean higher demands of availability, perhaps 24 h a day, 7 days a week, 365 days a year" (Lööw et al., 2019).	Dempsey et al. (2018); Kohler (2015); Lööw et al. (2019); Rogers et al. (2019); Zhang (2017)
Superficial safety compliance	"Complexity in maintaining and updating safety management systems, and potential for regulatory compliance to overshadow proactive safety measures" (Lööw and Nygren, 2019).	Kohler (2015); Lööw and Nygren (2019); Zhang (2017)
Over-reliance on technology	"Over-reliance on technology for ensuring safety could be risky if there are failures or inaccuracies in the system" (Duncan and Stolarczyk, 2015).	Baharfar et al. (2023); Duncan and Stolarczyk (2015); Lööw and Nygren (2019); Mitra et al. (2022); Onifade et al. (2023); Ribeiro-Duthie et al. (2017)
Software and System mistakes	"Like any sensor technology, there is a risk of false alarms or missed detections, which can have serious implications in mining safety"(Baharfar et al., 2023).	Baharfar et al. (2023); Lööw (2022); Mitra et al. (2022)
Careless operation or lack of skills	"Mining machinery, such as haul trucks, loaders, and drilling equipment, can cause accidents if not operated and maintained properly" (Sidani et al., 2023)	Ali and Rehman (2020); Duncan and Stolarczyk (2015); Lööw and Nygren (2019); Mensah et al. (2022); Ribeiro-Duthie et al. (2017); Rogers et al. (2019); Sidani et al. (2023)
Other unforeseeable incidents	"Risk of fire. Nearly everyone has heard of batteries catching fire, but it is important not to generalize because not all batteries are created equal" (Boudreault, 2019).	Boudreault (2019); Halim et al. (2022); Lööw (2022)
<u>**Psychological health and safety sphere**</u>		
Isolation and loneliness	"Among other concerns regarding the general intersection of fatigue, automation, and human–machine interaction in mining, the added facets of isolation, remoteness, dynamicity, significantly sized equipment, and massive throughputs of big data" (Bauerle et al., 2022)	Bauerle et al. (2022); Lööw (2022); Lööw et al. (2019)

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Table 8 (*continued*)

Themes	Example	References
Reduced autonomy and control over work	"…automation has the potential to change an individual's relationship to work as well, with a reduction in job autonomy negatively affecting operator's health" (Rogers et al., 2019).	Bauerle et al. (2022); Dempsey et al. (2018); Haas (2019); Lööw (2022); Lööw et al. (2019); Rogers et al. (2019); Zhang et al. (2019)
Cognitive overload	"As with the design and implementation of any automated systems, common issues such as reliability, trust, loss of situation awareness, and mental workload need to be considered" (Dempsey et al., 2018).	Dempsey et al. (2018); Kohler (2015); Rogers et al. (2019)
Perceived organisational support reduce	"job satisfaction may be reduced due to the fact that the introduction of automation is perceived as exclusively profit-oriented, while the benefits for the operator are minimal, non-existent, or negative" (Rogers et al., 2019).	Haas (2019); Rogers et al. (2019)
Social sphere		
Skill loss and Deskilling	"Deskilling relates to the automation creating a situation in which the operator does not exercise an important skill due to automation"(Rogers et al., 2019).	Dempsey et al. (2018); Knights and Scanlan (2019); Lööw et al. (2019); Lööw and Nygren (2019); Onifade et al. (2023); Rogers et al. (2019)
Cybersecurity and privacy concerns	"Cybersecurity must receive special attention. A wider level of connectivity between devices and sensors as well as between various business divisions is brought about by digital transformation. The risk of security breaches to the business could increase as a result. (Onifade et al., 2023)	Dempsey et al. (2018); Garcia-del-Real and Alcaráz (2024); Lööw et al. (2019); Onifade et al. (2023)
Inequality	"The fact that low-wage, less-skilled job roles are more likely to become automated relative to that of highly qualified employees increases inequality" (Moore et al., 2021)	Ali and Rehman (2020); Dempsey et al. (2018); Lööw (2022); Lööw et al. (2019); Moore et al. (2021)

Kohler (2015) utilised 3D scenes to create realistic and complex environments that help mine workers practise hazard identification. By engaging with these scenarios, miners become better at recognising potential hazards, increasing their overall safety awareness. In addition to safety training programs, emerging technologies like helmets equipped with environmental sensors monitor environmental parameters and provide real-time alerts, acting as constant guides that help workers quickly notice changes or hazardous conditions (Duarte et al., 2022; Haas, 2019). This ensures that workers are alert to changes that could introduce new risks and understanding the importance of maintaining a safe working environment.

3.3.2. *Psychological health and safety sphere*

Psychological health and safety is the second category, highlighting the positive effects of beneficial psychosocial work factors. Key emerging factors in this category include reduced cognitive demands, increased engagement in safety training, and decreased monotonous work.

By reducing the need for constant concentration and decreasing the mental effort required to complete complex tasks, the implementation of mining technologies has been found to lower cognitive demands and alleviate psychological stress. For instance, autonomous load, haul, dump operations allow for the teleoperation of the entire mining cycle, which is less intensive, and tiring compared to traditional methods that demand continuous focus (Paraszczak et al., 2015). In another study, a field trial of second-generation BEVs at Agnico Eagle Finland's Kittilä mine found that workers experienced a reduction in the mental effort required to perform tasks compared to existing diesel machines. This decrease in mental strain contributes to improved psychological well-being and job satisfaction (Halim et al., 2022).

The rise of emerging technologies is consistently reshaping safety training, leading to improved worker engagement and a more positive experience in safety training. An example can be VR-based training programs (e.g., Grabowski and Jankowski, 2015; Gürer et al., 2023). VR tools offer an interactive and active learning experience for trainees and provides realistic visual materials with an exploratory and exciting manner of instruction, which makes the training more engaging. In Zhang (2017), a head-mounted display-based VR training program designed for drilling scenario training was evaluated by 10 trainees. The results showed that the head-mounted display-based VR training system was a unique learning experience, highlighting its immersive, intuitive, and interactive features that allow for active participation and a near-reality experience.

Another key aspect of psychological health and safety is the reduction of monotonous tasks, which increases task variety and helps keep workers engaged and motivated. For example, teleoperation of mining equipment provides operators with the opportunity to switch tasks, reducing repetitive work and enhancing task diversity (Dempsey et al., 2018). Instead of performing a single task, such as repetitive lifting movements, operators can now engage in a variety of activities, including troubleshooting equipment, analysing data for efficiency improvements, and collaborating with team members to optimise operations. With smart systems, automation, and remote control taking over routine work, operators can focus on learning, creating, and valuing work tasks in a new working environment, and even can get the freedom to decide the location to work remotely (Lööw et al., 2019). By providing more varied and intellectually stimulating and challenging work tasks, emerging technologies can help improve job satisfaction and reduce the psychological burden of monotonous tasks.

3.3.3. *Social sphere*

In the social sphere, two key beneficial psychosocial work factors were identified: improved communication and information sharing, as well as enhanced workforce skills and diversity. Technologies such as automation tools, communication platforms, and knowledge management systems (e.g., Adjiski et al., 2019; Duarte et al., 2022) are transforming how workers interact and share information. These emerging technologies foster a collaborative work environment by connecting different departments and business units, leading to more cohesive and efficient operations. In addition, AI and satellite remote sensing could work together to establish collaboration and information sharing (Garcia-del-Real and Alcaráz, 2024). These emerging technologies lead to better-informed and more skilled workers who can quickly adapt to changes and make informed decisions. By promoting a culture of continuous learning and collaboration, these technologies help break down silos within organisations.

Skill shortages remain a critical challenge in the mining industry (Lööw et al., 2019). The integration of new machinery and emerging technologies presents an opportunity to address this issue by focusing on workforce upskilling and continuous training. By equipping employees with the essential technical skills to operate and maintain advanced technologies, organisations can reduce accidents caused by human error or unfamiliarity with new systems. For instance, VR-based training programs and automated hazard detection systems improve workers' competence, awareness and decision-making, directly contributing to a safer work environment. Operators trained to manage multiple automated systems can maintain better control over hazardous operations, reducing potential safety incidents (Paraszczak et al., 2015). Beyond individual skill development, diversity in the workforce plays a crucial role in strengthening workplace health and safety. The introduction of new technologies enables broader workforce participation by creating roles that are less physically demanding and more technologically oriented, attracting a wider demographic, including younger workers and women (Lööw, 2022; Moore et al., 2021). A diverse workforce approach problem-solving and risk assessment differently, leading to more comprehensive safety solutions (DeJoy, 2005). In addition, diversity contributes to a more inclusive work environment that fosters stronger teamwork, proactive safety compliance, and enhanced hazard awareness (Salas et al., 2020; Nasarasiddi, 2024). By embracing workforce skill development and diversity, the mining industry can establish a more resilient, inclusive, and safety-focused work environment. This approach can help reduce workplace hazards, enhance emergency response strategies, and create long-term safety improvements for all workers.

3.4. Effects on psychosocial work factors: Adverse factors

Emerging themes of adverse psychosocial work factors resulting from the implementation of mining technologies were also identified. Similar to the beneficial factors, they were also categorised into three spheres: physical health and safety, psychological health and safety, and the social sphere.

3.4.1. Physical health and safety sphere

Emerging technologies can also introduce ergonomic hazards if their design and implementation fail to consider human operators, potentially leading to situations where operators are required to maintain fixed body positions (Dempsey et al., 2018). For example, the LHD operator is intended to address ergonomic issues for mine workers. However, its sideways implementation forces workers to constantly move their heads back and forth, leading to neck and back problems (Paraszczak et al., 2015). Additionally, while emerging technologies such as weightlifting devices and handlers provide upper-body support, their design has been found to increase back tension for operators, leaving ergonomic hazards unresolved (Dempsey et al., 2018).

While technology projects in the mining industry have positively impacted work environments, they also introduce negative effects. For instance, mining equipment with isolated cabins can protect operators from dust exposure, but dust can still reduce visibility and interfere with sensors (Paraszczak et al., 2015). Although shifting work to control rooms or isolated cabins decreases overall exposure—resulting in fewer people being directly exposed to risks—not all operators can perform their tasks remotely. Remote operators may find it more challenging to follow practices that limit exposure on site. Furthermore, with reduced numbers of workers in the high-risk areas, it becomes harder to justify investments in improving the working environments onsite (Lööw et al., 2019). Additionally, some operators have noted that the ability to move and use their bodies positively impacts their work environment. However, with the introduction of automated technology, this beneficial physical activity may be lost, increasing the risks associated with sedentary work tasks (Lööw and Nygren, 2019).

Shiftwork-related physical fatigue is a significant concern in the mining industry, attributed to demanding shift schedules, long commutes, and heavy workloads. The introduction of emerging technologies, such as automation systems designed for continuous operation to maximise productivity, can exacerbate physical fatigue. These systems often require operators to perform real-time monitoring outside of typical working hours, including overnight, disrupting sleep patterns and circadian rhythms, leading to cumulative physical strain. Additionally, abnormal operational conditions may significantly increase workloads, potentially overwhelming operators (Rogers et al., 2019).

As emerging technologies introduce more intricate systems and processes, the safety protocols and procedures needed to manage them also become more complex. This increased complexity can exacerbate superficial safety compliance if not managed properly. Without sufficient safety training and a strong safety culture, safety management may focus more on completing tasks and fulfilling regulatory requirements, rather than proactively and genuinely addressing safety concerns. This will result in a superficial adherence to safety standards, which can leave critical risks unaddressed, safety competence compromised, ultimately undermining the effectiveness of safety management (Hu et al., 2020).

The implementation of emerging technologies in the mining industry has led to increased reliance on automation and digital systems. Although these advancements aim to enhance safety and efficiency, an over-reliance on technology can inadvertently intensify workplace risks. For instance, workers may become dependent on environmental sensors to detect hazards, as noted by Duncan and Stolarczyk (2015). While these sensors enhance safety, excessive reliance can diminish situational awareness, leading workers to overlook hazards—particularly if sensors malfunction or provide inaccurate data. Similarly, automation complacency can occur when operators trust automated processes without verifying their accuracy. Due to human attention span limitations, prolonged monitoring of automated systems can lead to vigilance fatigue, impairing an operator's ability to detect anomalies or early warning signs (Rogers et al., 2019). In high-risk scenarios, delayed responses due to excessive dependence on automation can escalate safety risks and operational inefficiencies.

Emerging technologies in the mining industry are heavily reliant on complex software and systems, which can be prone to instability and glitches, making software and system failures not uncommon. For instance, potential errors in AI algorithms could lead to false alarms or missed detections by sensors, and automated systems may fail unexpectedly (e.g., Baharfar et al., 2023; Mitra et al., 2022; Sidani et al., 2023). Such malfunctions can result in dangerous situations if not addressed promptly and effectively. Moreover, incidents can also occur when workers operate new technologies carelessly or without the necessary skills. For example, human operators might use automated systems without a full understanding of how automation controls the machinery, potentially leading to operation errors (Rogers et al., 2019). Improper use of mining machinery, such as haul trucks, loaders, and drilling equipment, can also contribute to accidents if not handled correctly (Sidani et al., 2023). Additionally, unforeseeable incidents may arise during technological integration, such as battery fires, electrical fires, and high-voltage hazards (Halim et al., 2022).

3.4.2. Psychological health and safety sphere

Isolation and loneliness have been identified as consequences of technologies that reduce human interaction. This is particularly evident in the shift towards remote control centres, where operators monitor and manage mining operations from distant locations rather than on-site (Johansson et al., 2018; Oltmanns and Petruska, 2023). While remote monitoring enhances efficiency and safety, it significantly reduces face-to-face interaction with colleagues (Bauerle et al., 2022; Lööw, 2022). Workers in these settings often spend long hours engaging primarily with machines and software, rather than collaborating with a physical team. Over time, this lack of direct human connection and a shared workplace environment can lead to feelings of loneliness, isolation, and detachment, potentially impacting job satisfaction and well-being (Lööw et al., 2019).

The implementation of emerging technologies often leads to a more structured work environment and streamlined processes by standardising operations and enhancing consistency. This increased structure can improve efficiency, as tasks are performed in a more organised and methodical manner. However, when work processes are pre-programmed by technologies such as AI, robotics, and automation, workers may find themselves following rigid protocols, restricting workers' autonomy, discretion, and creativity (Lööw, 2022). This shift may also alter individuals' relationship with work, as reduced job autonomy has been linked to negative health outcomes (Rogers et al., 2019; Zhang et al., 2019).

The risk of causing cognitive overload for workers during the implementation of mining technologies was also identified in our analysis. Emerging technologies often come with complex interfaces and operating procedures. For instance, automation might increase cognitive demands by requiring operators to monitor and manage intricate systems, or monitor multiple systems simultaneously, particularly if the technology is not intuitive or user-friendly (Dempsey et al., 2018). Moreover, AI predictive systems can generate vast amounts of data that miners need to interpret, requiring workers to learn and adapt to new ways of working, which can be mentally taxing and overwhelming.

Moreover, implementing new technologies in the mining industry can inadvertently impact workers perceived organisational support. When organisations adopt new technologies like automation to replace human labour, workers may perceive that the organisation values cost savings and efficiency over their well-being (Rogers et al., 2019). In this period of rapid transition, without adequate training or equipping, this process can be stressful and challenging. Workers might perceive a lack of organisational support if they do not receive sufficient resources or training.

3.4.3. Social sphere

In the social sphere, emerging adverse psychosocial work factors include potential skill loss and deskilling, cybersecurity and privacy concerns, and issues related to inequality.

As machines take over tasks that were traditionally performed by humans, there is a risk that operators will lose not only their knowledge of these tasks but also the nuanced efficiencies they developed through experience. Over time, reliance on technology can erode these practical skills, making it challenging for workers to revert to manual operations when needed (Dempsey et al., 2018). This loss of skill is compounded by the fact that operators may not engage in the critical thinking and decision-making processes once required in their roles, as automation increasingly handles these aspects. This deskilling can, in turn, bring a long-term impact on the socio-economy.

Cybersecurity and privacy issues are also a major concern. As the industry increasingly relies on data and networks to power advanced systems, these technologies become vulnerable to cyberattacks. Such attacks can have severe implications, potentially leading to the cyber-hijacking of BEVs and their use as weapons against various targets, thereby posing national security risks. Beyond the immediate threat of cyberattacks, privacy and data security concerns are also critical. The extensive data collected from vehicles and sensors, including detailed records of driving behaviour and operational metrics, can raise significant privacy issues (Dempsey et al., 2018; Garcia-del-Real and Alcaráz, 2024). Unauthorised access to this data could lead to exploitation or misuse, affecting both individuals and organisations.

The rise of emerging technologies can widen workforce inequalities, with significant implications for workplace health and safety. Automation disproportionately impacts low-wage, lower-skilled roles, as these positions are more likely to be replaced by machines than those held by highly qualified employees (Moore et al., 2021). This shift not only reduces employment opportunities for lower-skilled workers, but also is directly linked to higher stress levels, mental health challenges, and workplace safety risks (Mackenzie et al., 2013). Lower-skilled workers are often relegated to less challenging and lower-paying roles with limited access to training, restricting their transition to higher-skilled positions. This growing disparity creates systemic safety challenges. It can lead to lower morale, higher accident rates, and less proactive compliance with safety protocols (Lööw, 2022). Additionally, mental health strain caused by job insecurity can lead to fatigue, distraction, and impaired decision-making, all of which heighten the risk of workplace accidents (Richardsen et al., 2019; Forastieri, 2016). Ultimately, widening inequality in the workforce does not only affect economic stability but also exacerbates workplace safety hazards and overall worker health and well-being.

This review indicates the paradoxical effects of emerging technologies in the mining industry, simultaneously introducing both beneficial and adverse psychosocial work factors. These, in turn, have both positive and negative implications for workplace health and safety across the physical, psychological, and social spheres.

3.5. Mechanisms of change at work

Research on the evolving nature of work in the mining industry highlights how technological advancements are reshaping workplaces by transforming work organisation, environments, and tasks (Cheng et al., 2022; Babalola et al., 2023; Sorensen et al., 2021). Building on Cheng et al.'s (2022) model of emerging work changes, we examined five categories of workplace transformation identified in the reviewed literature: changes in how, what, when, where, and by whom work is done. For example, technologies such as automation are altering how tasks are performed—reducing human involvement in hazardous activities like drilling, blasting, and material transport. Consequently, workers' roles are shifting towards supervising and managing automated systems from safer locations. We propose that these fundamental changes serve as mechanisms driving variations in psychosocial work factors, leading to both positive and negative outcomes. Examples of mechanisms of change are shown in Table 9.

While these changes at work are inherently neutral, the benefits or drawbacks hinge on thoughtful management and integration. This requires strategic planning incorporating training and reskilling initiatives, integration guided by human-centric principles, and continuous evaluation with feedback mechanisms to ensure technology aligns with human factors. Perspectives on managing technology-driven change offer valuable insights into the future of work and workplace design, with the goal of maximising positive outcomes while managing potential negative impacts.

This review identified moderators influencing whether workplace changes lead to beneficial or adverse psychosocial work factors. These include employee training and upskilling (e.g. Ali and Rehman, 2020; Cao et al., 2019; Mensah et al., 2022), human-centred technology design (e.g. Boudreault, 2019; Dempsey et al., 2018), effective leadership (e.g. Moore et al., 2021; Johansson et al., 2018; Kohler, 2015; Lööw and Nygren, 2019), regulatory framework (e.g. Ali and Rehman, 2020; Cao et al., 2019; Garcia-del-Real and Alcaráz, 2024), and individual differences (e.g. Lööw and Nygren, 2019; Zhang et al., 2019). For instance, maximising the benefits of new automation systems requires comprehensive training and education programs. These programs ensure that workers acquire the necessary skills to operate and monitor complex automated systems effectively. Without such training, workers may struggle to adapt, increasing the risk of operational failures (Mensah et al., 2022). Furthermore, without ongoing safety training, over-reliance on automated systems can lead to complacency, where safety protocols are overlooked, potentially resulting in accidents if technologies fail (Duncan and Stolarczyk, 2015). In addition, the success of automated systems relies on strong organisational support and culture. If workers perceive that technology and profits are prioritised over their well-being, they may feel undervalued and disengaged (Rogers et al., 2019). Similarly, in the absence of employee support systems, remote operations and the reduction in team-based tasks can lead to isolation, negatively affecting mental health and job satisfaction (Bauerle et al., 2022; Lööw, 2022). Therefore, a human-centric approach to technology design is crucial for these automated systems to reduce hazards, rather than introducing new challenges.

4. Discussion and future research agenda

This study examines the use of technologies in mining workplaces and their impacts on psychosocial work factors. It also identifies

Table 9
Examples of change at work.

Change of work	Examples	Technology category	References
How	"The augmented miner uses augmented reality (AR) for integrating information from the digital to the physical world…through special glasses that send and receive live video, both parties would be able to see the problem—which can then be solved through instructions from the equipment manufacturer" (Lööw et al., 2019).	Augmented and Virtual Reality, Digital Twins	Moore et al. (2021); Aminossadati et al. (2014); Boudreault (2019); Johansson et al. (2018); Lööw et al. (2019); Lööw (2022); Adjiski et al. (2019); Duarte et al. (2022); Paraszczak et al. (2015); Jacobs et al. (2022); Santos et al. (2023); Sidani et al. (2023); Zhou et al. (2018); Marimuthu et al. (2023); Lööw (2022); Duncan and Stolarczyk (2015); Mitra et al. (2022);
	"Highly automated systems still need humans for supervision, adjustment, maintenance, expansion and improvement; the operator must intervene when the system fails or does not perform as expected" (Lööw, 2022).	Autonomous Equipment	
	"With this prototype system specially adapted for the needs of the underground mining industry that uses sensors attached to regular PPE clothing, including hard hats and safety vests, workers can now be monitored in real time, improving both productivity and safety" (Duarte et al., 2022).	Smart Sensors	
What	"By using the new Computer-Based Task-Training and VR, future operators will have an opportunity to observe the machine and processes in detail through the image or video format. This approach practically gives trainees more safety awareness of what they could expect to see and how to react while on their job duty" (Zujovic et al., 2021).	Augmented and Virtual Reality, Digital Twins	Boudreault (2019); Johansson et al. (2018); Paraszczak et al. (2015); Lööw (2022); Duncan and Stolarczyk (2015); Dempsey et al. (2018); Sen et al. (2020); Halim et al. (2022); Rogers et al. (2019); Kirsch et al. (2015); Onifade et al. (2023);
	"The short answer is generally four hours, unless you're working against gravity, in which case it is closer to three hours. The long answer is that it is a maximum of about six hours, but charging should be planned into the work activity" (Boudreault, 2019).	Autonomous Equipment	
	"Automating systems just because automation is available, or automating easy tasks leaving the more complex tasks for humans can lead to less-than-optimal automation, and is a result of poor function allocation" (Dempsey et al., 2018).	Integrated Remote Operation Centres	
When	"The procedure and automated processing allow for virtual outcrops to be available for mapping remotely, within the same day" (Creus et al., 2021).	Analytics AI/ML	Creus et al. (2021); Rogers et al. (2019); Ali and Rehman (2020); Onifade et al. (2023); Haas (2019)
	"CPDMs provide mineworkers with near real-time feedback about their level of respirable coal dust exposure through dust data output that is updated every 30 min" (Haas, 2019).	Smart Sensors	
Where	"Optic gas sensing has also been investigated, and this technology promises a remote, intrinsically safe, distributed solution" (Aminossadati et al., 2014).	Smart Sensors	Moore et al. (2021); Aminossadati et al. (2014); Paraszczak et al. (2015); Sidani et al. (2023); Lööw (2022); Duncan and Stolarczyk (2015); Lööw and Nygren (2019); Dempsey et al. (2018); Gürer et al. (2023); Grabowski and Jankowski (2015); Kiziroglou et al. (2017); Kapusta et al. (2020); Henriques and Malekian (2016); Oltmanns and Petruska (2023); Ali and Rehman (2020); Onifade et al. (2023); Zhang et al. (2019);
	"The location of the operator in relation to certain mining operations has also changed over time. In contemporary mining, remote controlled machinery can be used where there is 'risky mountain' instead of machinery piloted by an onboard operator. In cases where remote control is not applied, the operator works from an isolated cabin which generally protects against falling rock, poor air etc" (Lööw and Nygren, 2019).	Autonomous Equipment	
	"Virtual reality technology enables trainees to experience virtual scenes of the real underground mine environment in a safe and controllable environment at a very low cost, and the trainees can interact with preset objects in the scene to complete the corresponding training process" (Zhang et al., 2019).	Augmented and Virtual Reality, Digital Twins	
Who	"Tramming with a full bucket, dumping and return trip are done autonomously, the role of the operator is limited to supervision" (Paraszczak et al., 2015).	Autonomous Equipment	Aminossadati et al. (2014), Johansson et al. (2018); Paraszczak et al. (2015); Marimuthu et al. (2023); Kiziroglou et al. (2017); Creus et al. (2021); Sen et al. (2020); Rogers et al. (2019); Ali and Rehman (2020);
	"Humans are less exposed to hazardous materials or mining operations as they are replaced by robotic	Integrated Remote Operation Centres	

(continued on next page)

Table 9 (*continued*)

Change of work	Examples	Technology category	References
	systems" (Onifade et al., 2023).		Onifade et al. (2023);
	"AI would help to improve the autonomous resource exploration where AI-powered robots and rovers are able to autonomously explore celestial bodies, gather samples, and make real-time decisions based on environmental conditions. Therefore, minimising the need for human intervention in remote and hazardous environments." (Garcia-del-Real and Alcaráz, 2024)	Analytics AI/ML	Garcia-del-Real and Alcaráz (2024); Lööw et al. (2019)

research gaps and limitations, and proposes directions for future research, as shown in Table 10.

First, a key research gap is the lack of in-depth studies on technology implementation from the perspective of mining workers, who have firsthand experience with the emerging psychosocial work factors and safety hazards. Among the reviewed articles, only three used an interview-based approach to gather in-depth insights and feedback from the frontline workers (Haas, 2019; Lööw and Nygren, 2019; Santos et al., 2023): Lööw and Nygren (2019) explored how safety-related development have affected the accident frequency rate and safety at work, and Lucas et al. (2008) explored the effectiveness of the VR-based training program for conveyor belt safety. To address this gap, further research should prioritise worker-centred perspectives, using methodologies such as semi-structured interviews, focus groups, and diary studies. These methods can provide a nuanced understanding of workers' experiences, perceptions, attitudes and interactions during technological transitions. Additionally, a longitudinal quantitative approach to tracking worker satisfaction and engagement overtime can complement qualitative insights with statistical evidence to support a more comprehensive analysis.

Second, the mechanisms and interventions related to technological change remain underexplored. While most reviewed studies explained the impact of technology implementation, few clearly examined and articulated the underlying mechanisms of change, and further developed proactive measures to manage these transitions at work. This has created barriers to developing targeted inventions to mitigate the negative impacts and enhance the positive outcomes. Future studies should adopt a multilevel systems approach to explore how various levels—individual, team, organisational, technological—shape workers' experiences and interactions with new technologies and working environment. This will support the development and validation of interventions aimed at mitigating negative impacts and enhancing positive outcomes of technology implementations.

Third, the reviewed studies revealed a lack of well-established theoretical frameworks or the presence of fragmented theoretical perspectives. Among the reviewed studies, fifty-one out of sixty-two papers did not adopt a specific theoretical framework. This finding suggests that research on the impact of technology implementation on mining workers' health, safety and social welfare is still in its early developmental stage (Cheng et al., 2022), lacking widely established theoretical frameworks to guide a holistic understanding. This has led to fragmented insights and prevented the development of a coherent body of knowledge in the field. As a first step, future studies should explore existing theoretical frameworks from related disciplines (such as occupational health, psychology, engineering, and sociology) to assess their

Table 10
Potential future research directions and questions.

Existing research gaps	Research directions	Specific research questions
Lack of in-depth research from the worker's perspective on the technology implementation	• Research on the experiences, perceptions, and attitudes of workers regarding the implementation of new technologies in the mining industry	• How do workers perceive the implementation of new mining technologies in terms of their health, safety, job roles and responsibilities? • How do workers cope with the changes brought about by new technologies, and what support systems do they find most helpful?
Insufficient research on the mechanisms and interventions of technology-induced change	• Investigate how individual, team, organisational, and technological, and macro-level factors (e.g., regulatory environment, industry trends) shape worker outcomes. • Develop and validate interventions aimed at mitigating negative impacts and enhancing positive outcomes of technology implementations in the mining industry.	• In what ways do individual characteristics (e.g., age, experience, adaptability) influence the effects of technology-induced changes on miners' psychosocial well-being? • What role do industry-wide trends and regulatory policies play in shaping the effects of emerging technologies on worker outcomes in the mining industry? • What types of training programs are most effective in enhancing miners' adaptability and resilience to emerging technologies?
Lacking well-established theoretical frameworks or fragmented theoretical perspectives	• Validate existing theoretical frameworks from other fields to determine their applicability and effectiveness in addressing the multifaceted impacts of emerging mining technologies. • A potential to integrate multiple theoretical perspectives to attain a more thorough understanding of the intricacy of technological implications.	• How can interdisciplinary theoretical perspectives (e.g., combining ergonomics, occupational psychology, and organisational behaviour) be integrated to provide a comprehensive understanding of the impacts of emerging technologies on miner health and safety? • How can the integration of the interdisciplinary theories inform the development of interventions aimed at improving worker safety and well-being in technologically advanced mining environments?
Insufficient research on the long-term effects of digital advancements on social sustainability of the mining industry	• In-depth research on the long-term effects of implementing new mining technologies on social sustainability and providing practical guidance.	• What are the long-term effects of mining technology adoption on the balance between economic growth, environmental protection, and social sustainability? • How does the implementation of environmentally friendly technologies in mining operations contribute to the social well-being of surrounding communities over time?

applicability within the mining industry context. Additionally, future research should consider integrating multiple theoretical perspectives to attain a more thorough understanding of the intricate implications of technological change on worker health, safety, and social welfare in the mining sector. This will not only improve theoretical development, but also offer a broader and actionable understanding on how to address technological change.

Finally, there is insufficient research on the long-term effects of digital advancements on social sustainability of the mining industry. While immediate outcomes, such as reducing accident rates and improved safety training are vital, it is equally important to explore their lasting impact on social sustainability. Key questions include: How do new technologies impact job stability, worker satisfaction, and workplace culture over time? How do they influence the balance between economic growth, environmental protection, and social well-being in mining communities? Addressing these issues can provide valuable insights to promote long-term social benefits.

5. Contributions

5.1. Theoretical contributions

This study makes substantial theoretical contributions to the literature on mining technologies and their impact on psychosocial work factors. Existing evidence on the health and safety impacts of new technologies in mining remains fragmented, with the underlying mechanisms driving these varied outcomes still unclear. This uncertainty offers little guidance for practitioners on managing new technologies to optimise health and safety. Through a systematic analysis of sixty-two reviewed articles, we identified key categories and areas of technological impact in mining workplaces, highlighting their paradoxical effects and advancing the existing body of knowledge. Importantly, our study unifies fragmented perspectives by providing an integrated framework that addresses the emerging psychosocial work factors in the mining environments. It also identifies research gaps and limitations while proposing directions for future research. By establishing a strong foundation, this study supports ongoing research in this evolving field.

Second, our study suggests the underlying mechanisms of technological impact and technology-driven changes in the workplace. These fundamental changes in how, what, when, and where work is done, and by whom, serve as key mechanisms explaining the paradoxical outcomes in the mining workplace. Moreover, it highlights the fact that effects of technological advancements on workers depend on how these changes are managed and integrated. This integrative approach uncovers nuanced insights into the complex characteristics of digital advancements in the mining industry. It also highlights the need for multilevel analyses to examine the interdependencies among different factors at various levels in shaping work experiences. The findings will support the development of targeted interventions to mitigate negative impacts and enhance positive outcomes in the workplace.

5.2. Practical implications for the future of work in mining

Our research provides practical guidance for practitioners, decision-makers, and policymakers navigating digital innovations in the mining industry. The integrative framework introduced in this research helps employees and managers assess and manage the emerging psychosocial work factors associated with new technologies. It serves as a practical tool for evaluating technological change and its impact at both individual and organisational levels, enabling stakeholders to mitigate negative impacts and maximise benefits. More specifically, the following actionable recommendations based on this study are provided for practical implementation.

First, adapting to technological changes in mining requires continuous learning and professional development. Organisation managers should develop structured training and upskilling programs to enhance workers' technical expertise (such as operating autonomous equipment, data analytics) and soft skills (such as adaptability). These programs enable workers to interact effectively with new systems, mitigate risks, and improve safety compliance. Workers, in turn, should actively take part in the training programs, and they should also provide insights and feedback on new technologies to ensure their practicality and effectiveness in daily operations. Through this dual approach, organisations can better equip employees for a rapidly evolving workplace and facilitate successful adoption of new technologies.

Managers and leaders play a crucial role in integrating technology while maintaining workplace health, safety and productivity. Organisations should adopt a systematic approach for risk assessment and management to evaluate potential threats and benefits, enabling proactive interventions. Human-centred design principles should guide technology development. This can be achieved by involving frontline employees in the technology development stages, conducting usability testing, and minimising cognitive and physical strain for employees. Additionally, supportive leadership practices—fostering open communication, encouraging safety compliance, and empowering employees—help create a positive work environment, boost engagement, and improve productivity (Berhan, 2020; Sorensen et al., 2021; Zhang et al., 2020a, 2020b). By aligning technological integration with workforce readiness, managers can reduce resistance to change and enhance operational efficiency.

Furthermore, policymakers play an important role in developing and enforcing regulations that address psychosocial impacts of new mining technologies. Establishing industry-wide safety standards is essential to ensure responsible technology integration. Moreover, regular policy reviews, stakeholder consultations, and impact assessments can ensure that regulations remain effective in emerging workplace challenges and technological advancements.

6. Study limitations

While this literature review contributes significantly to both theoretical and practical aspects, it has certain limitations. This study provides a holistic overview of the paradoxical effects of technology implementation on psychosocial work factors; however, it did not offer quantitative insights on the implementation effects of various technology categories. Therefore, future research could address this gap by conducting meta-analyses to provide statistical evidence on the relationship between technology implementation and workplace outcomes. Additionally, while our study discusses both the benefits and potential threats of technology, it does not explore the unique characteristics of specific mining technologies, which is beyond its scope. For instance, AI-driven analytics and autonomous equipment have distinct attributes that may affect psychosocial work factors differently. Future research should examine how specific features like complexity and interoperability influence work environment and drive changes.

7. Conclusions

This literature review highlights the paradoxical and complex nature of mining technology implementation, where both positive and negative effects coexist on psychosocial work factors. It emphasises that technological advancements are inherently neutral, their impact depends on how these changes are managed and integrated into the workplace. Effective management and integration are essential to safeguarding psychosocial work factors, in turn health and safety outcomes. This requires strategic planning with training and reskilling initiatives, human-centric integration, and continuous evaluation through feedback mechanisms to ensure technology aligns with human needs. This perspective on managing technology-driven changes offer valuable insights into the future of work and sustainable workplace design. This approach aligns with the United Nations' Sustainable Development

Goals (SDG) mission to improve working conditions and promote decent work for all (United Nations, 2024).

CRediT authorship contribution statement

Keyao Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mengting (Rachel) Xia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Formal analysis, Data curation. **Tim Bentley:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

None.

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Data availability

Data will be made available on request.

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