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Smart mining and emerging occupational health and safety risks in the mining industry: A literature review

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ABSTRACT

Advanced technologies, especially smart mining, enhance productivity and safety, reshaping traditional mining approaches. As technology integrates, challenges like disruptions and vulnerabilities emerge, urging careful planning and robust protective measures. The industry strives for a balance, leveraging benefits while addressing emerging challenges through proactive risk mitigation strategies prioritizing worker well-being.

This paper presents findings from a systematic literature review on smart mining and emerging occupational health and safety (OHS) risks using the PRISMA method. It employs a comprehensive research strategy, selecting four databases—Scopus, IEEE Xplore, ScienceDirect, and PubMed. The review is not restricted by timeframe and includes both English and French publications. Emphasis is placed on keywords like "safety and health" and "technology," examining 236 papers, with 32 selected for in-depth analysis following PRISMA guidelines.

This paper provides a comprehensive review of mining technologies, focusing on automation, Industry 4.0, and Industry 5.0. It explores Occupational Health and Safety (OHS) in two dimensions: how technologies contribute to OHS through monitoring, detection, control, and hazard reduction, and the impact of technology on miners' health and safety, examining both positive and negative aspects. A meta-analysis synthesizes findings across various parameters, including hazard types and technology types, providing a nuanced understanding of the relationship between technological advancements and miner well-being. The findings are categorized into eight groups, including accidents, risk management, ergonomics, chemical agents, physical agents, legislation, geological, and design, shedding light on the multifaceted nature of OHS concerns in the mining industry.

This paper provides a thorough review of mining technology, offering a comprehensive overview to help experts, practitioners, and affiliated organizations identify blind spots, gaps, and overlooked issues within the field. By expanding collective vision, this analysis serves as a valuable tool for scrutinizing existing knowledge and formulating strategic proposals to address concerns. It fosters a proactive approach to tackling challenges in the dynamic landscape of mining technology.

1 INTRODUCTION

The mining industry has evolved through four distinct phases over the past two centuries: Mechanical Mining (Mining 1.0) with steam engines, Mass Production Mines (Mines 2.0) using machinery, Automated Mines (Mines 3.0) with widespread automation, and Intelligent Mining (Mining 4.0) employing advanced technologies like remote-controlled vehicles. The next phase, Mining 5.0, aims to create a cyber-physical-social system (CPSS) through seamless integration of advanced technologies for enhanced efficiency and sustainability, known as smart mining [1].

The Institute of Advanced Mining Technology at RWTH Aachen University defines smart mining as the integration of mining machinery using information and communication technologies. This involves data exchange facilitated by the Industrial Internet of Things (IIoT) platform [2]. The definition highlights the essential elements of intelligent mining, encompassing automated equipment like excavators and conveyors, hardware such as sensors and drones, and software solutions including cloud platforms and remote management systems [2].

Advanced technology in mining brings various advantages such as enhanced productivity, decreased operating costs, and increased profitability [3], [4], and for OHS, it enhances the capability of managing risks inherent in mining operations. With advanced monitoring technologies, companies can better identify potential hazards and implement proactive measures to mitigate them, thus improving overall safety standards [5].

Integrated environmental monitoring systems in mining provide real-time tracking of hazardous agents, enhancing compliance with regulatory standards and safeguarding worker health [6].

Health monitoring systems detect worker health issues early by continuously tracking vital signs and exposure to hazards, ensuring well-being and timely intervention [7].

Advanced technology's benefits may be offset by drawbacks such as inadequate regulations, limited managerial awareness, insufficient risk assessment, emergence of new risks, increased workload and mental strain, internal collaboration challenges, ambiguity in responsibilities, and deficiencies in transparency and data protection [8].

The European Agency for Safety and Health at Work (EU-OSHA) defines emerging risks as any occupational risk that is both new and, on the rise, [9]. The International Risk Governance Council (IRGC) defines "emerging" risks as either new risks or familiar ones that arise in new or unfamiliar conditions. It focuses on systemic risks that transcend borders and economic sectors, impacting natural, technological, and social systems [10].

As Badri et al. assert, effectively managing risks in Industry 4.0 necessitates the adept identification of risk factors and ensuring a consistent availability of OHS experts [11].

This review underscores the vital need to comprehend the intersection of smart mining and occupational health and safety in the mining sector. It explores the benefits and drawbacks of smart mining technologies, offering guidance to stakeholders. By analyzing literature, it informs future research and policy decisions for a safer mining environment.

2. METHODOLOGY

The research followed the PRISMA Statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to guide the selection, analysis, and organization of articles [12].

The literature review examines articles spanning from the mid-20th century to the present, focusing on three main themes: "occupational health and safety," "mining industry," and "technology." Specific databases were selected to align with these themes: Pubmed for health and medical issues, IEEEXplore for electrical engineering and computer science, ScienceDirect for technical research on mining technology, and Scopus for multidisciplinary scientific and technical information.

Therefore, in the first phase, 236 articles were collected. The inclusion criteria encompassed articles related to:

- Industry Focus: This article specifically focused on the mining industry.
- Technology Scope: The technology scope included automation and mechanization, Mining 4.0 (e.g., digitalization, (Internet Of Things) IoT, (Artificial Intelligent) AI, cyber physics, big data, and mining 5.0.)
- Publication Date: No specific limitations were imposed on the publication date.
- Study Design: Various study designs, including research articles, case studies, and reviews, were accepted.

On the other hand, articles were excluded if they met specific criteria, including:

- Language: Articles in languages other than English and French were excluded.

- Publication Status: Book chapters, conference papers, theses, and unpublished working papers or reports were excluded.
- Specific Characteristics: Articles that did not exclusively focus on mining, OHS, and technology were excluded.
- The study focused solely on interventions or exposures within the OHS, mining, and technology nexus, excluding those beyond this scope, like mathematical software improvements or algorithmic enhancements for machine learning.
- OHS: This article specifically focuses on technology and its OHS. Consequently, topics related to public health, water management, and green & climate-smart (SIGCS) were intentionally excluded.

Using Microsoft Excel and Mendeley software, articles were recorded, and duplicate entries were identified and removed, resulting in 45 articles meeting inclusion criteria. After a thorough review of full texts, 13 articles were excluded due to various factors, leaving 32 articles meeting stringent criteria for the study.

3. RESULTS

3.1 Meta-Analysis: Unveiling Trends and Challenges in Mining

Despite aiming to cover a substantial portion of the field by focusing on major related databases, the study found no prominent journal for publishing notable articles on the subject. Typically, each journal only published one or two related articles. The findings in this study vividly illustrates the global distribution of article publications on the studied topic, showing China as the largest contributor, followed by the United States in second place. Australia ranks third, with other countries having smaller shares.

Preliminary studies on OHS, technology, and mining date back to 1999, with a lack of focused research until 2014. However, a noticeable upward trend in studies emerged from 2018, possibly reflecting renewed interest driven by emerging challenges, technological advancements, or regulatory shifts, peaking in 2023.

The hazard categories benefit from the categorization done by Baghaei et al., which focused on mining hazards. In this article, these hazards are categorized based on Canadian and international standards, regulations, and conventions as reference points [13]. In this way, the observed risk categories could be classified as risk management, ergonomic, chemical, and physical agents, accidents, legislation, design, and geological. Based on this categorization, the primary focus of the articles is on accidents which involve workplace conditions or processes resulting in injury or fatality [14], [15], [16], [17]. Examples include incidents related to roadway transportation [1], [18], related to heavy equipment causing harm to humans or equipment [19], explosives, fires[16], [20], and incidents within mining cages [21]. Following accidents, ergonomics emerges as the second most extensively studied subject, highlighting a significant disparity in attention [22], [23], [24]. Additionally, the categories of chemical agents [20], physical agents [25], and design [26] are depicted in subsequent places. Although geological concerns are included to a minor extent, more papers addressing these challenges may exist but may not necessarily directly pertain to OHS and are therefore not represented in this study. Nevertheless, this analysis helps identify existing gaps and challenges within these areas, contributing to a better understanding of the field. Figure 1 presents these results.

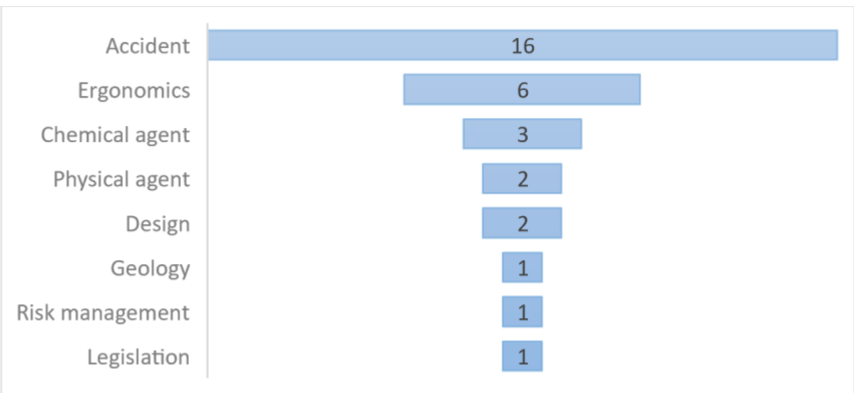

Figure 1. Classification and Distribution of emerging Risks

3.2 Benefits of Technology in Mining

Technology in mining has several positive effects on safety and efficiency. It enables early risk monitoring [27], reduces worker injuries [26], and enhances safety management [28]. Automation streamlines operations, reduces errors [29], and boosts productivity [30]. Advanced monitoring systems aid in real-time analysis [20], preventive maintenance [28], and emergency response [16], improving overall efficiency and safety [31], [32]. In sum, the integration of technology in mining operations not only improves safety protocols [30] and operational efficiency but also enhances overall productivity in the industry.

3.3 Challenges Presented by Technology in Mining

Technology in mining presents numerous challenges, including increased system failures [20], reliability issues [33], data quality concerns [16] , and skills gaps necessitating worker upskilling [29]. Additionally, integration difficulties with Virtual Reality (VR) and Augmented Reality (AR) tech in underground conditions [17]. Delays in identifying equipment abnormalities, compatibility issues between Operations Technology (OT) and Information Technology (IT) systems, and insecure remote access points compound these challenges [28]. Furthermore, resistance to change [34] and limitations in sensor precision [20] contribute to OHS risks, underscoring the need for standardized safety protocols [18] and comprehensive research to address these issues effectively. Disregarding human error or technology equipment error, each of the challenges outlined could potentially pose hazards in dangerous mining conditions.

3.4 Key Technologies in Mining

In mining, various technologies serve key functions. For example, Teleoperation and Simulation, like VR and Training Simulators, aid in remote control and training [35]. Monitoring and detection systems, such as Proximity Detection and Warning Systems (PDW) and Wireless Sensor Networks (WSN), enhance safety [36]. Data and Communication Technologies (DCT), IoT and Cloud Computing, enable real-time data analysis [37]. Sensors, such as Laser Scanners and Thermal Infrared Hyperspectral Sensors, provide critical information on conditions [38]. Miscellaneous tools like Arduino offer flexible solutions. These categories illustrate the diverse tech landscape driving mining innovation [39].

This study conducted a thorough analysis of articles focusing on new and emerging technologies in mining. Figure 1 illustrates the various technologies used in a Treemap format. Accurately delineating the contributions of each technology poses a challenge due to the varied focus of articles. Some articles concentrate on singular issues, while others pursue broader objectives, encompassing multiple technologies. However, given the comprehensive nature of our study, all technologies are considered collectively to identify overarching trends. The Treemap visualization provides a clear representation of each technology's proportional contribution, with size indicating its relative significance. Automation and mechanization were prominently featured, reflecting their central role in technological advancements. Additionally, IoT, GPS, digitalization, and virtual reality emerged as significant contributors, indicating their widespread adoption and relevance. Other technologies such as simulation, camera technology, and teleoperation were also noted for their importance in driving innovation.

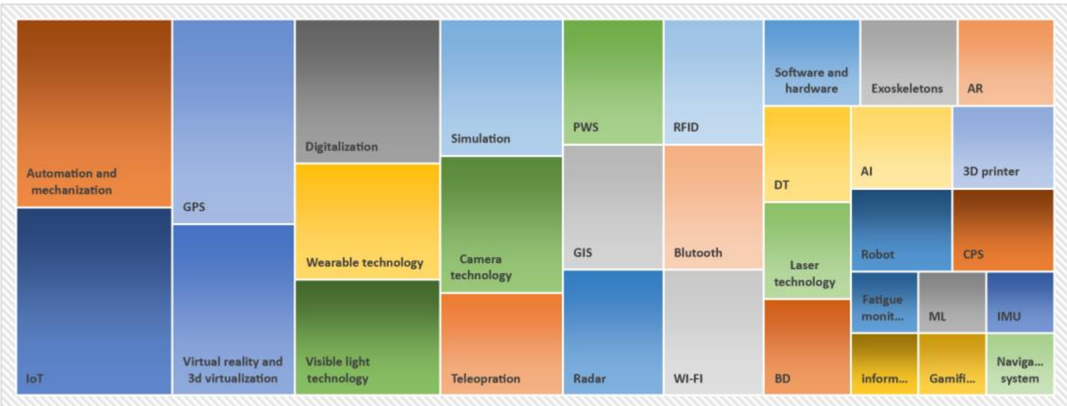

Figure 2. Visual representation of a broad range of utilized Technologies.

4. DISCUSSION

This article delves into the emerging technologies in the mining industry, particularly focusing on OHS. A comprehensive literature review was conducted to identify these advancements. With the advent of Industry 4.0 in 2011, initiated by Germany, there has been a gradual global adoption of advanced technologies, including automation and mechanization. This integration, coupled with the subsequent rise of Industry 5.0, has significantly increased the complexity of industrial operations.

This study aims to explore emerging technologies across three key phases: automation and mechanization, Industry 4.0, and the upcoming Industry 5.0. These phases represent foundational, advanced, and future stages of technological evolution. Automation and mechanization streamline basic tasks, while Industry 4.0 integrates cyber-physical systems and data-driven decision-making, revolutionizing industry processes [40]. Looking ahead, Industry 5.0 emphasizes human-machine collaboration and personalized industrial approaches, promising further transformation. This examination provides insights into the evolving landscape of industrial innovation, from past developments to future trends.

Automated and mechanized mining involves using technology to control machinery and processes with minimal human intervention, while mechanized mining uses machines to reduce human effort in tasks like breaking or moving rock. Automated systems are more advanced, often incorporating sensors and computer control for improved efficiency and safety [41]. In this study, only one paper was exclusively focused on mechanized mining [25].

Mining 4.0: It is characterized by the deployment of autonomous devices equipped with sensors and artificial intelligence (AI) capabilities [30]. These devices operate with predefined objectives within their decision-making space, utilizing AI to evaluate sensor data and independently make decisions regarding actuator control. Key technology objectives of Industry 4.0 include ruggedized sensors, machine-to-machine (M2M) communication, and the integration of artificial intelligence [42]. A significant portion of the papers discussed Industry 4.0 and its hybridization with automation and mechanization. It appears that with the integration of automation and mechanization through Industry 4.0, the distinction between these two sectors becomes increasingly blurred over time, posing challenges for their separate classification.

Mining 5.0: It goes beyond Industry 4.0, envisioning deeper integration of information and physical systems, leading to intricate Cyber-Physical-Social Systems (CPSS). These systems enable seamless collaboration between humans, machinery, and society, driven by virtual artificial systems. This transition marks an era of parallelization and heightened connectivity in the mining industry [1]. In this literature, only one paper appears to be related to Mining 5.0 integrated with OHS. It is foreseeable that the number of such articles will increase in the future [43].

In this study, it is evident that a significant portion of the papers focusing on emerging risks were related to the hybrid of Industry 4.0 and automation. It appears that the mining industry is deeply involved in integrating a hybrid of automation, mechanization, and Industry 4.0.

The integration of automation, data analytics, and IoT devices in smart mining brings both benefits and challenges. While automation reduces human exposure to hazardous environments, it introduces complexities in equipment reliability and control. Similarly, data analytics and IoT enhance safety but raise concerns about data security and privacy breaches. As smart mining technologies evolve, the potential for accidents increases due to reliance on autonomous vehicles and machinery. Ergonomic challenges arise as operations become more automated, necessitating careful design considerations to ensure worker comfort and safety.

Literature Gap and Future Research

While the review provides valuable insights into emerging technologies and their implications for OHS in the mining sector, several gaps warrant further investigation. Future work could focus on assessing the effectiveness of these technologies in real-world mining environments, considering factors such as usability, reliability, and worker acceptance. Additionally, there is a need for research into the long-term health effects of prolonged exposure to technology-driven work environments, as well as the socio-economic impacts of technological advancements on mining communities. Moreover, efforts should be directed towards developing standardized protocols and regulations for the safe implementation and operation of advanced technologies in mining operations. Collaborative initiatives between industry stakeholders, researchers, and regulatory bodies are essential to address these gaps and ensure the sustainable integration of technology while prioritizing worker safety and well-being.

5. CONCLUSION

This literature review provides insights into smart mining and emerging OHS risks, emphasizing the transformative role of automation, data analytics, and IoT in improving operational efficiency. However, it also highlights new challenges in ensuring worker safety in hazardous environments. The analysis identifies a significant focus on accidents and the importance of addressing workplace conditions and ergonomics. Despite disparities in attention among OHS risk categories, the review offers a comprehensive overview of current research. Moving forward, prioritizing worker safety requires ongoing research, collaboration, and investment in innovative solutions to address emerging risks and create a safer mining industry.

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