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Reducing Carbon Footprint in Mining: Current Sustainable Practices and Future Directions

Bunyamin Cicek*

Hitit University, Technical Sciences Vocational School, Türkiye

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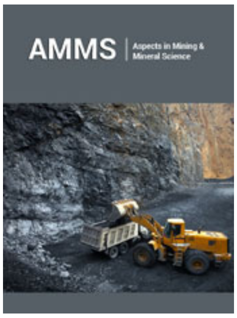

***Corresponding author:** Bunyamin Cicek, Hitit University, Technical Sciences Vocational School, Corum, Türkiye

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Abstract

The mining industry is one of the largest contributors to global energy consumption and carbon emissions, making sustainability a critical focus for its future. This review explores current practices and emerging technologies aimed at reducing the sector's carbon footprint. Key advancements include the adoption of energy-efficient equipment, integration of renewable energy sources, and implementation of Carbon Capture and Storage (CCS) technologies. Innovations in waste management, circular economy models, and digitalization-such as IoT-based monitoring systems and digital twin technology-are transforming operational efficiency and environmental performance. Despite these advancements, challenges such as high implementation costs and technical limitations persist. The review highlights the importance of policy support, industry investments, and collaborative approaches to drive widespread adoption of sustainable practices. Looking forward, technologies like hydrogen-powered machinery and biomineralization hold promise for achieving carbon-neutral mining operations, marking a pivotal shift toward environmental sustainability and long-term viability in the sector.

Keywords: Carbon footprint reduction; Sustainable mining practices; Renewable energy integration; Carbon capture and storage (CCS); Energy efficiency in mining

Introduction

The mining industry's significant environmental impact has led to increased focus on sustainable practices and green technologies. Recent studies highlight the importance of integrating renewable energy sources and electric vehicles in mining operations to reduce greenhouse gas emissions and energy consumption [1]. Decarbonization strategies for the mining sector include on-site power supply, improved processing technology, and carbon capture and storage [2,3]. The adoption of renewable energy in mining not only reduces carbon footprint but also presents opportunities for economic diversification in resource-rich countries [4]. However, challenges persist, including tailings dam failures, deforestation, and acid mine drainage. To achieve sustainability, the mining industry must minimize resource and energy consumption throughout all stages, from exploration to post-closure [5]. Implementing these sustainable practices requires supportive policy environments, technological innovation, and a systemic approach to address environmental, social, and economic responsibilities in the mining sector.

Energy Efficiency and Renewable Energy Use

The mining industry is increasingly adopting green technologies and practices to reduce its environmental impact and enhance sustainability [1]. Electric mining equipment and renewable energy sources, particularly solar and wind, are being integrated into mining operations to decrease carbon emissions and energy consumption [1,4]. Digital technologies, such as automation, artificial intelligence, and the Internet of Things, are reshaping the mining sector, offering potential for improved energy efficiency and decarbonization [6]. The electrification of mining operations, combined with renewable energy-powered microgrids, presents opportunities for more efficient, sustainable, and safer mining practices in both underground and open-pit settings [7]. While these technological advancements provide environmental and economic benefits, their successful implementation requires substantial investment, collaboration between stakeholders, and supportive policy environments [4,7].

Carbon Capture and Storage (CCS) Technologies

CCS technologies are crucial for mitigating climate change and reducing CO_2 emissions from various sources, including the mining industry [8]. Mineral carbonation, both in situ and ex situ, is emerging as a promising CCS option, particularly for smaller emitters where geological sequestration is not viable [9]. However, high costs and technical challenges remain significant barriers to widespread adoption, with current costs ranging from $50 to $300 per tCO_2 sequestered for ex situ mineral carbonation [9]. The mining industry presents unique opportunities for integrating CCS through mineral carbonation of alkaline mine wastes and coal-fired power station by-products, which can be used in mine site rehabilitation [10]. Despite its potential, CCS deployment has not yet reached the scale anticipated a decade ago, necessitating further research and development to address technical, commercial, and political barriers [11].

Waste Management and Circular Economy

Mining waste management plays a crucial role in reducing environmental impacts and promoting sustainability in the mining industry. Recycling mining waste for use in construction, particularly as concrete aggregates, offers significant environmental and economic benefits [12,13]. This practice aligns with circular economy principles, minimizing resource extraction and waste disposal while creating value from mine waste [14]. Implementing circular economy elements in mining regions, such as developing Eco-Industrial Parks, can foster industrial symbiosis and enhance waste recycling and recovery [15]. Proactive management of mining waste throughout a mine's lifecycle can provide environmental benefits and generate value, as demonstrated in the Mount Morgan mine case study [14]. By repurposing mining waste as construction materials, the industry can reduce its ecological footprint, conserve resources, and contribute to sustainable development goals in both mining and construction sectors [12,13].

Reducing Carbon Footprint through Digitalization and Data Analytics

The mining industry is undergoing significant digital transformation, with technologies like Digital Twins, IoT, and big data analytics driving operational efficiency and sustainability. Digital Twins enable virtual modeling of mining processes, optimizing resource utilization, reducing downtime, and improving productivity [16,17]. This technology has shown potential to increase EBITDA by 21% and free cash flow by 96% in empirical studies [16]. IoT-based sensors and real-time monitoring systems help prevent energy waste, optimize equipment usage, and enhance safety in mining operations [18]. The integration of these technologies addresses challenges such as resource scarcity, quality degradation, and rising energy costs [17]. Industrial applications of Digital Twins in mining span various categories, including collaborative decision-making, data analysis, design, management, monitoring, and operational efficiency [19].

Future Directions and New Technologies

Innovation is crucial for the mining industry to improve efficiency, reduce costs, and address environmental concerns [20]. The industry is undergoing digital transformation and exploring new technologies to tackle challenges like lower ore grades and deeper deposits [20]. Implementing innovative processes can enhance both productivity and environmental performance [21]. Microbial processes offer promising solutions for carbon dioxide removal and metal recovery from mine tailings, potentially transforming the industry towards sustainability [22]. Microorganisms can be utilized to precipitate metals from industrial leachates and acid mine drainage, improving metal recovery efficiency while reducing environmental risks [20,23]. These bio-processes could help "green up" the mining industry by minimizing leachable metals in tailings storage dams and enhancing overall metal recovery [20,23]. Embracing these innovative technologies is essential for the mining industry to address future challenges and achieve environmental sustainability goals.

Conclusion

Sustainable practices to reduce carbon footprint in the mining sector provide environmental and economic benefits. However, strong policy support and industry investments are required for these technologies to become mainstream. In the future, carbon neutral mining operations could become a new standard for the industry and play an important role in achieving environmental sustainability goals.

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