Technological Advances in Mobile Equipment for Greenhouse Gas Emission Reduction in the Mining Industry: A Systematic Review

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ABSTRACT

The mining industry faces a critical challenge in reducing greenhouse gas (GHG) emissions, particularly those generated by mobile equipment. This systematic review examines recent technological advances and techniques applied to mining mobile equipment to mitigate GHG emissions. Effective strategies for GHG reduction are identified through a systematic analysis of objectives, methodologies, results, production impacts, gaps, and limitations in various studies. The urgency of meeting the industry's commitments under the Paris Agreement for net-zero emissions by 2050 underscores the importance of these advancements. Additionally, the review analyzes potential modifications and challenges in implementing these technologies to achieve sustainable mining practices. By synthesizing this knowledge, the study contributes to ongoing efforts to align mining operations with global climate goals, emphasizing the crucial role of mobile equipment in achieving a sustainable, low-carbon future for the mining sector.

1. Introduction

The mining industry, a cornerstone of global economic development, now faces the critical challenge of reducing greenhouse gas (GHG) emissions, particularly those generated by mobile equipment. This challenge is not merely a matter of environmental responsibility but a crucial necessity to meet global commitments under the Paris Agreement, which aims to achieve net-zero emissions by 2050 [1].

Currently, the mining sector accounts for approximately 4 - 7% of global GHG emissions, with carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) being the primary gases emitted [2]. These emissions are distributed across various activities: extraction and processing (50%), transportation (25%), and other operations such as drilling and blasting (25%) [3].

Historically, the industry relied on rudimentary technologies that were effective for mineral extraction but highly carbon intensive. The advent of the industrial revolution brought significant advances in heavy machinery, which increased productivity and led to a rise in GHG emissions. The reliance on fossil fuels to operate mobile equipment, such as haul trucks and excavators, became a symbol of industrialization and a major contributor to climate change [4].

In recent decades, growing concerns about climate change have driven the mining industry to seek innovative solutions. The motivation for reducing GHG emissions stems from regulatory pressures and the increasing recognition of climate change's environmental impact. As a result, major mining

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companies have pledged to achieve net-zero emissions by 2050, aligning their goals with global climate targets [3, 5].

One of the critical trends in the mining sector is the electrification of mobile equipment. Technologies such as electric haul trucks, catenary systems, and high-capacity batteries exemplify how advancements reduce mining operations' carbon footprint [6]. Additionally, implementing energy management systems and using artificial intelligence (AI) to optimize routes and minimize energy consumption demonstrate the sector's commitment to sustainability [7]. Digitalization and automation also play a significant role in enhancing operational efficiency and reducing emissions [8].

A simple way to measure the quantity of GHG emissions is through the use of emission factors, which quantify the emissions per unit of activity, such as kilograms of CO2 per litre of diesel consumed. These factors are outlined in guidelines provided by the Intergovernmental Panel on Climate Change (IPCC) [9] and the U.S. Environmental Protection Agency [2].

Despite these advances, the transition to a low-carbon future presents several challenges. Technical, economic, and operational barriers persist, limiting the widespread adoption of clean technologies. For instance, the initial investment in electric equipment can be prohibitive for some operations, and developing the necessary charging infrastructure is still in progress [10]. Furthermore, integrating these technologies into existing mining operations requires careful planning and significant adaptations to current processes [11].

This systematic review examines and analyzes the most recent technologies and techniques applied to mobile equipment in mining to mitigate GHG emissions. Effective strategies for GHG reduction are identified through a systematic analysis of various studies' objectives, methodologies, results, production impacts, gaps, and limitations. The urgency of meeting the commitments of the Paris Agreement underscores the importance of these technological advances. Furthermore, the review explores potential modifications and challenges in implementing these technologies to achieve sustainable mining practices. By synthesizing this knowledge, the study contributes to ongoing efforts to align mining operations with global climate goals, emphasizing the crucial role of mobile equipment in achieving a sustainable and low-carbon future for the mining sector [12].

2. Methodology

This systematic review examines recent technological advances and techniques applied to mobile equipment in mining to mitigate GHG emissions. The methodology follows a structured approach based on systematic literature review guidelines tailored to the context of mining engineering.

2.1. Research Questions

The review seeks to answer the following research questions:

1. What are the recent technological advances and techniques applied to mobile equipment in mining to mitigate GHG emissions?
2. How effective are these strategies in reducing GHG emissions?
3. What challenges and potential modifications are required to implement these technologies in mining operations?

2.2. Literature Search Strategy

A comprehensive literature search was conducted across several scientific databases, including Science Direct, Scopus, IEEE Xplore, MDPI, and Google Scholar. The search included papers published from the year 2000 up to June 2024. The search query was designed to capture relevant studies using the following combination of keywords:

- Keywords related to mobile equipment: "Mobile equipment", "Mining trucks", "Haul trucks".
- Keywords related to GHG emissions: "GHG emissions", "Greenhouse gas", "Carbon emissions".
- Keywords related to technological advancements: "Technological advancements", "Innovation", "Electrification", "Hybrid systems".
- Keywords related to sustainability: "Sustainable mining practices", "Net-zero emissions", "Paris Agreement", "Climate goals", "Carbon footprint mining", "Emissions reduction strategies".

2.3. Inclusion Criteria

The selection of studies for this review was based on the following criteria:

- Only peer-reviewed journal papers or conference proceedings were included.
- Publications from the year 2000 onwards.
- Written in English.
- Studies that specifically focus on the reduction of GHG emissions through technological advances in mobile equipment within the mining industry.

2.4. Exclusion Criteria

- Studies not related to the mining industry.
- Studies that address other aspects of mining operations not related to mobile equipment or GHG emissions reduction.
- Non-peer-reviewed journal, and conference papers.
- Articles not available in full text.

2.5. Data Extraction

Relevant data were extracted from the selected studies, including:

- Study objectives: What the study aimed to investigate.
- Methodologies used: Research methods and approaches used in the study.
- Results and findings: Key outcomes related to GHG emissions reduction.
- Impacts on production: Any reported impacts on mining operations and productivity.
- Gaps and limitations: Identified gaps in research and limitations of the study.

2.6. Selection and Filtering Process Diagram

Figure 1 illustrates the steps in the systematic review and provides a clear overview of the selection and filtering process.

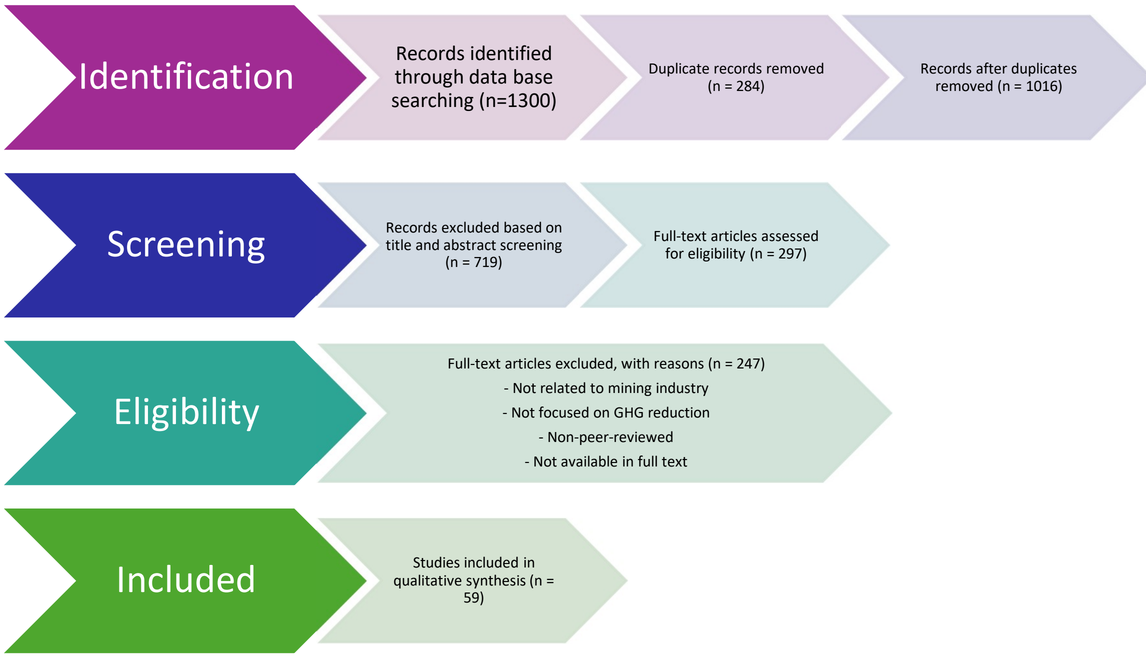

Figure 1. Diagram for Literature Selection and Filtering Process.

3. Results and Discussion

Mining is a carbon-intensive industry, significantly contributing to global GHG emissions. Finding effective strategies to reduce these emissions is essential to align the sector with the goals of the Paris Agreement and other international sustainability initiatives [1]. This study explores key factors contributing to GHG emissions in mining operations, as well as emerging methodologies and technologies that have the potential to mitigate these impacts.

The results section provides a detailed analysis of existing literature, highlighting factors influencing GHG emissions and their reduction strategies. Factors such as fuel type, energy efficiency, equipment electrification, operational practices, and the integration of renewable energy are crucial for developing a comprehensive approach to emission reduction in mining [13].

Additionally, complementary literature and methodological support are incorporated to provide a holistic view of current technologies and practices. This multidimensional approach is essential to capture the complexity of the problem, and the solutions needed for an effective transition to more sustainable mining operations. Integrating digitalization, automation, and implementing environmental policies and regulations are essential elements to promote sustainable practices and reduce GHG emissions in the mining industry [3].

Through a comprehensive analysis of recent publications, this section not only identifies emerging trends in emission reduction research but also evaluates the practical impact of various strategies in real mining operations. The findings underscore the importance of combining multiple approaches to achieve significant and sustainable reductions in GHG emissions.

3.1. Key Factors Contributing to GHG Emissions

The literature review identifies several key factors that significantly contribute to GHG emissions in mining operations. These factors are crucial for developing effective strategies to reduce emissions and improve efficiency in the mining industry. The factors identified in Table 1. Key Factors and GHG Emissions. provide a comprehensive understanding of the various elements influencing GHG emissions in mining operations.

Table 1. Key Factors and GHG Emissions.

Factor	Impact on GHG Emissions
Fuel Type [14], [15]	The type of fuel used in mining equipment directly impacts GHG emissions. Traditional diesel fuel produces higher emissions than alternatives like natural gas or hydrogen.
Energy Efficiency [13], [16]	Improving energy efficiency in mining processes reduces fuel consumption and GHG emissions.
Electrification of Equipment [6], [17], [18]	Switching to electric-powered equipment can significantly reduce GHG emissions associated with diesel fuel combustion.
Equipment Maintenance [19], [20]	Regular and high-quality maintenance of equipment ensures optimal performance and lower emissions.
Operational Practices [10], [12]	Efficient operational practices, including optimized vehicle dispatch and routing, can minimize idle times and reduce emissions.
Renewable Energy Integration [21], [22]	Integrating renewable energy sources, such as solar and wind, into mining operations can drastically reduce dependency on fossil fuels and GHG emissions.
Digitalization and Automation [23], [24], [25], [26]	Implementing IoT, sensors, and real-time data analytics can improve operational efficiency and emission monitoring, leading to lower GHG emissions.
Regulations and Policies [3], [5], [27], [28], [29], [30], [31]	Strict environmental regulations and policies can enforce emission reductions and promote sustainable practices in the mining industry.
Lifecycle Analysis [32], [33], [34], [35], [36]	Conducting lifecycle analyses of mining equipment and operations helps identify emission hotspots and opportunities for reductions.
Alternative Powertrains [15], [33], [37]	Utilizing alternative powertrains, such as hybrid and hydrogen fuel cells, can reduce emissions compared to conventional diesel engines.
Infrastructure for Charging and Refueling [17], [15]	Developing infrastructure for charging electric vehicles and refueling hydrogen-powered equipment is crucial for supporting low-emission technologies.

One of the primary factors influencing GHG emissions in mining is the type of fuel used in mining equipment. Traditional diesel fuel is known for its high carbon footprint. Studies by Cao et al. [14] and Leone [15] illustrate that switching from diesel to cleaner alternatives, such as natural gas or hydrogen, can drastically reduce emissions. Hydrogen, in particular, has the potential to reduce emissions by up to 90%, as its combustion produces only water vapour. This significant reduction was demonstrated through extensive emissions testing in operational mining settings, where the use of hydrogen led to markedly lower GHG outputs compared to diesel.

Complementing the shift in fuel type, improving energy efficiency within mining operations emerges as another critical strategy. Patterson et al. [13] and Saidur et al. [16] have shown that adopting energy-efficient technologies can reduce fuel consumption by 15-20%. This includes measures such as retrofitting machinery with high-efficiency motors, optimizing ventilation systems in underground mines, and implementing energy management systems. These improvements were achieved through comprehensive energy audits and performance optimizations, highlighting that reduced energy waste translates directly into lower emissions [16].

Building on the theme of efficiency, the electrification of mining equipment presents a highly effective method for emission reduction. Varaschin [6] and Bao et al. [17] provide robust evidence from case studies and lifecycle assessments that switching from diesel-powered to electric machinery can cut emissions by more than 50%. This is primarily because electric machinery eliminates direct emissions from diesel combustion. The studies monitored the performance and emissions of electric vehicles in real mining operations, revealing significant environmental benefits and long-term cost savings due to lower fuel and maintenance costs [6].

Similarly, integrating renewable energy sources into mining operations offers another transformative approach. Case studies where solar and wind energy implementation in mining projects reduced fossil fuel use by 40-50% have been documented. This integration was validated through real-time energy consumption data and emission tracking before and after adopting renewable energy sources, showing substantial environmental benefits and the feasibility of reducing GHG emissions in mining operations through renewable energy [21, 22].

Further enhancing the impact of these strategies, implementing digital technologies and automation can significantly optimize operational efficiency and reduce emissions. Yavari et al. [23], Avalos et al. [24], Asa'd and Levesque [25], and Awuah-Offei et al. [26] discuss the use of Internet of Things (IoT), sensors, and real-time data analytics to optimize mining operations. These technologies allow for immediate adjustments to operational parameters, reducing energy consumption and emissions. Pilot projects have shown that automated systems significantly improve operational efficiency by continuously monitoring and optimizing equipment performance, making mining operations more sustainable [23].

Among the strategies analyzed, integrating renewable energy and the electrification of mining equipment provide the most substantial benefits in reducing GHG emissions. These approaches address the primary sources of emissions and offer significant reductions. However, their effectiveness is greatly enhanced when combined with efficient operational practices, regular maintenance, supportive regulatory frameworks, digitalization, and lifecycle analysis. A comprehensive approach incorporating these factors is essential for achieving significant and sustainable emission reductions in the mining industry. The literature supports the potential of these strategies to transform mining operations into more sustainable and environmentally friendly activities.

3.2. Integration of Complementary Literature and Methodological Support

This section aims to incorporate complementary literature and methodological support that enhances the overall understanding of GHG emissions reduction in the mining industry. As shown in Figure 2, integrating four key themes provides a comprehensive view of the various strategies and technologies available. The review captures the full spectrum of current research by adopting this holistic approach.

Figure 2. Complementary Literature and Methodological Support.

The advancement of methodologies and evaluation frameworks is crucial for optimizing operations and reducing environmental impacts. Vis [38] focuses on optimizing fuel consumption for hauling mobile equipment through speed optimization using Simulated Annealing, demonstrating significant improvements in fuel efficiency and emission reductions. Complementing this, Kına [39] uses discrete-event simulation to model and optimize the microscopic fuel consumption of haulage trucks, offering a detailed methodology for minimizing environmental impact and operational costs. Both studies underscore the importance of detailed methodologies in achieving operational efficiency and sustainability. Further, Kazemi Ashtiani [40] introduces an integrated stochastic multi-objective simulation framework for fuel-efficient truck dispatching, addressing inherent uncertainties and ensuring reliable and sustainable outcomes.

Building on these methodologies, emerging technologies offer transformative potential in reducing GHG emissions. Yavari et al. [23] explore AI and IoT for real-time emissions monitoring in mining operations, demonstrating how these technologies provide precise data for timely interventions. Similarly, Feng et al. [41] compare various powertrain solutions for mining haul trucks, highlighting that electric and hydrogen fuel cell options significantly reduce operational costs and emissions. Jacobs [42] supports these findings by discussing the strategic integration of new technologies into mining operations, emphasizing the need for structured implementation plans to enhance both efficiency and sustainability. Moreover, Massonini Ngoma et al. [43] evaluate the impact of technological trends on climate change in Congo, underscoring the importance of adopting cutting-edge technologies to address environmental challenges. Widmer et al. [44] and Yip et al. [45] further highlight advancements in engineering solutions, such as extending battery life and hydrogen direct injection, which significantly contribute to sustainable mining operations.

In parallel to technological advancements, environmental policies and regulations are vital in shaping sustainable mining practices. Ulrich et al. [27] demonstrate how carbon pricing incentivizes the adoption of cleaner technologies and practices, aligning economic and environmental goals. Building on this, Wang et al. [46] emphasize the importance of regulatory frameworks in promoting sustainable fleet management practices, ensuring compliance with environmental policies to achieve greater efficiency and lower emissions. Additionally, Kittipongvises [47] underscores the potential of international mechanisms like the Clean Development Mechanism (CDM) in driving significant emissions reductions, highlighting the importance of global cooperation and adherence to international agreements.

To provide practical insights into these strategies and their real-world impact, specific case studies are invaluable. Widmer et al. [44] present a detailed case study on extending the battery life of hybrid mining trucks, demonstrating how engineering innovations can significantly improve performance and sustainability. Similarly, Carvalho et al. [35] offer crucial data on CO2 emission factors for lifecycle assessment of mining vehicles, which is fundamental for developing effective emission mitigation strategies. Furthermore, Issa et al. [22] discuss the opportunities and challenges of renewable energy and decarbonization in the Canadian mining industry, emphasizing the need for substantial investments in clean technologies and supportive policies to facilitate the energy transition.

By examining these diverse aspects, the review provides a holistic understanding of the current research landscape, highlighting significant achievements in GHG emission mitigation within the mining industry. This comprehensive approach ensures that all facets of emission reduction are addressed, fostering effective collaboration between industry stakeholders, governmental bodies, and the scientific community. Such an integrative effort is essential for advancing sustainable mining practices and achieving meaningful reductions in environmental impact.

3.3. Analysis of Publication Trends in Technological Advancements for GHG Emission Reduction in Mining

Figure 3 shows a marked increase in the number of research articles published in 2022 and 2023, indicating a growing focus on mitigating GHG emissions in the mining sector. This trend can be attributed to several key factors.

First, the Paris Agreement, signed in 2016, set ambitious long-term goals for reducing GHG emissions, which gradually translated into increased research and technological development over the subsequent years. The effects of these commitments became more pronounced in 2022 and 2023 as industries and researchers aligned their efforts to meet these global targets [1].

Second, the period has seen significant technological advancements, including developing battery-electric and fuel-cell hybrid mining trucks, integrating renewable energy sources, and implementing digital technologies such as IoT and AI for real-time monitoring and operational optimization. These innovations have spurred substantial academic and industry research to improve efficiency and reduce emissions [5].

Additionally, the COVID-19 pandemic accelerated the adoption of digital and sustainable practices. The disruption caused by the pandemic prompted industries to seek resilient and adaptive solutions, which included investing in sustainable technologies and practices. Researchers, adapting to new working conditions, were able to focus more on pressing issues such as GHG emissions, leading to a surge in publications during this period [6].

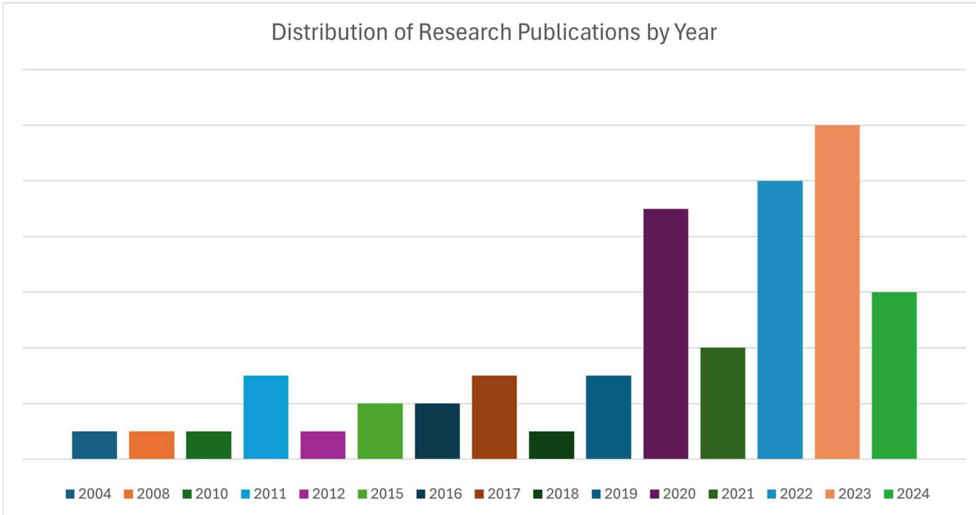

Figure 3. Distribution of Research Publications by Year.

Moreover, increased regulatory pressure and enhanced funding opportunities for sustainability projects have further driven research activities. Governments and private sectors have been providing substantial financial support for green technology initiatives, encouraging more studies and publications in the field of sustainable mining practices [7].

Overall, the combined impact of global environmental commitments, technological advancements, the COVID-19 pandemic, and increased regulatory and financial support has significantly contributed to the rise in research publications. This trend underscores the industry's shift towards sustainability and the critical role of engineering innovations in achieving these goals.

3.4. Final Thoughts

Among the key factors analyzed, the electrification of mining equipment is the most efficient strategy for reducing GHG emissions. Studies by Varaschin [6] and Bao et al. [17] indicate that switching from diesel-powered to electric machinery can reduce emissions by more than 50%, primarily due to eliminating direct emissions from diesel combustion. Additionally, integrating renewable energy sources in mining operations can further amplify these benefits, as demonstrated by Vergara-Zambrano et al. [21].

Considering the ambitious goal of achieving net zero emissions by 2050, current advancements and strategic implementations suggest that the mining industry is on the right track. However, meeting this target will require continuous innovation, substantial investments, and strict regulatory frameworks [3]. Despite significant progress, the full realization of net zero will depend on the widespread adoption of these technologies and practices across the industry.

The fluctuating costs of minerals also play a critical role in reducing GHG emissions. High mineral prices can provide mining companies the financial leverage to invest in sustainable technologies and practices. Conversely, low prices may restrict the ability to make such investments, potentially slowing down progress toward emission reduction goals [4].

Finally, climate change itself poses significant challenges to the mining industry. Rising temperatures and extreme weather events can disrupt mining operations, increase energy consumption, and impact infrastructure stability. These factors highlight the industry's urgent need to mitigate its environmental impact and adapt to the changing climate to ensure operational resilience and sustainability [48].

4. Conclusion

The mining industry is at a critical juncture, facing the imperative to reduce greenhouse gas emissions, particularly those generated by mobile equipment. This systematic review has identified significant technological advances and innovative strategies to mitigate these emissions. Key technologies such as the electrification of mining equipment, integration of renewable energy sources, and implementation of digitalization and automation have demonstrated substantial potential in reducing the carbon footprint of mining operations.

Achieving significant and sustainable reductions in GHG emissions in the mining industry requires a comprehensive approach that combines electrification, renewable energy integration, energy efficiency improvements, digitalization, and robust regulatory support. These strategies not only align with global climate goals but also enhance the sustainability and operational efficiency of mining activities.

The findings of this review underscore the critical role of mobile equipment in achieving a sustainable, low-carbon future for the mining industry. Adopting advanced technologies and innovative practices is essential to align mining operations with global climate goals. Furthermore, continuous research, development, and collaborative efforts among industry stakeholders are urgently needed to drive these advancements. This integrated approach is vital for ensuring the mining industry meets its environmental responsibilities while maintaining productivity and economic viability.

The mining sector can significantly reduce its GHG emissions by leveraging these technological advancements and adhering to stringent regulatory frameworks. This transition not only contributes to global efforts to combat climate change but also positions the industry as a leader in sustainable practices. Ultimately, the path to a low-carbon future in mining hinges on the widespread adoption of these technologies and the collective commitment of all stakeholders involved.

5. Future Work

Future research and development efforts should focus on several key areas to further advance the reduction of GHG emissions in the mining industry:

1. **Cost Reduction and Economic Viability:** Investigate ways to reduce the initial investment and operational costs associated with electrification and other advanced technologies. Economic models and incentives that promote adopting sustainable practices should be explored.
2. **Integration of Renewable Energy:** Continue exploring and expanding the integration of renewable energy sources into mining operations. Research should focus on optimizing the use of renewable energy to power mobile equipment and other mining processes.
3. **Advanced Digital Technologies:** Further develop and refine digital technologies such as IoT, AI, and machine learning for real-time monitoring, operational optimization, and

predictive maintenance. These technologies can significantly enhance efficiency and reduce emissions.

4. **Lifecycle Analysis:** Conduct comprehensive lifecycle analyses of new technologies and practices to identify emission hotspots and opportunities for further reductions. This will provide a holistic understanding of the environmental impact of mining operations.
5. **Policy and Regulatory Support:** Advocate for stringent environmental regulations and policies that enforce emission reductions and promote sustainable practices. Collaboration between industry, government, and academia is essential to drive these initiatives.
6. **Collaborative Research:** Encourage collaboration among mining companies, academic institutions, and technology providers. Sharing knowledge and resources can accelerate the development and adoption of innovative solutions.
7. **Expanded Literature Search:** To complement and strengthen this research, it is necessary to broaden the search for more articles and studies. Expanding the literature review will help identify additional technological advancements, strategies, and best practices that can further reduce GHG emissions in mining operations.

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