Advancing toward sustainability: The emergence of green mining technologies and practices

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A B S T R A C T

This study comprehensively evaluates the integration and effectiveness of green mining technologies within the mining sector, specifically focusing on mitigating the environmental impact of traditional mining practices. The primary goal is to establish a sustainable mining model that significantly reduces energy consumption and minimizes ecological disturbances. To achieve this, the study employs a mixed-method approach, integrating quantitative data analysis from monitored mining sites and qualitative insights from industry experts. Key parameters include energy consumption, greenhouse gas emissions, and reductions in chemical use. The findings reveal that effective integration of green mining technologies leads to significant reductions in greenhouse gas emissions, lower energy consumption, and improved waste management compared to traditional methods. Specifically, the use of electric vehicles and renewable energy sources in mining operations has resulted in decreased carbon emissions and energy usage across studied sites. The research concludes that green mining practices, when supported by robust technological integration and regulatory frameworks, not only enhance environmental sustainability but also boost economic efficiency within the mining industry. This study recommends increased investment in the research and development of green technologies and calls for tighter regulatory oversight to ensure the widespread adoption and optimization of these practices.

1. Introduction

The environmental issues and geological problems arising from the growth and usage of the mineral industry have become increasingly apparent, with some consequences being quite severe. Therefore, establishing a balanced link between "mining of mineral resources, environmental protection, and sustainable mining development" is crucial for resource development in the 21st century [1–4]. Mining affects society, the environment, and the climate in profound ways [5–7]. In addition to consuming vast amounts of energy and resources, mining operations pollute the environment by creating significant waste and gas emissions. According to Sivakumar *et al.* [8] and Guo *et al.* [9], other negative effects include topographic modifications, geological alterations, loss of vegetation, and disruptions to ecosystems. Additionally, mining faces serious challenges, such as safety concerns, inefficient processing and recycling, and high energy requirements [10]. Mining operations contribute to climate change by releasing greenhouse gas (GHG) emissions such as CH_4, nitrogen oxides (NO_x), and carbon dioxide (CO_2) into the atmosphere through fuel combustion, on-site electricity generation, and other sources. The main GHG sources in mining are drilling, blasting, loading, hauling, and beneficiation operations, as well as the fuel and electricity used depending on the nature of the ore, as shown in Fig. 1. These effects can be substantial at local, regional, or global levels [5] and tend to increase as the

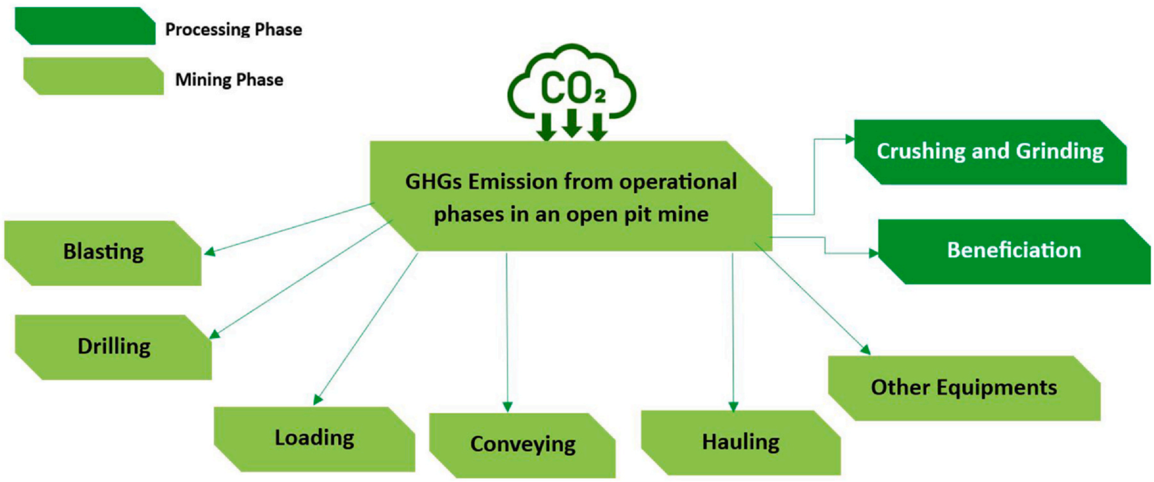

Fig. 1. Greenhouse gas emission release from mining operation.

production scale intensifies [11]. As a result, the mining industry faces increased scrutiny, pressure, and a diminished reputation for causing environmental harm [7,12]. As a result, the sector has started adopting greener production techniques and technology to promote sustainability [13,14].

GHG emissions are a significant environmental concern in open pit mining, with each operational phase contributing to the overall carbon footprint through fossil fuel combustion and energy-intensive processes. This discussion covers the sources and impacts of GHG emissions in each phase and highlights potential mitigation strategies.

(1) Drilling. Drilling is one of the initial phases in open pit mining, involving the use of diesel-powered drill rigs and generators. The combustion of diesel fuel in these rigs results in the emission of CO_2, methane (CH_4), and nitrous oxide (N_2O). Although CO_2 is the primary emission, CH_4 and N_2O have significantly higher global warming potentials despite being emitted in smaller quantities. The continuous operation of these rigs to ensure efficient extraction further exacerbates emission levels.
(2) Blasting. Blasting involves the use of chemical explosives, such as ammonium nitrate-fuel oil, to break apart the rock. Explosions release CO_2, water vapor, and nitrogen oxides (NOx). While CO_2 is a major component, NOx contributes to the formation of tropospheric ozone, a potent greenhouse gas. The immediate release of gases post-blast poses both environmental and health risks, necessitating effective management strategies to mitigate these impacts.
(3) Loading. The loading phase employs diesel-powered loaders and excavators to transfer blasted material onto haul trucks. These heavy machines emit CO_2, CH_4, and N_2O owing to diesel combustion. Just like with drilling, CO_2 dominates the emission profiles, but the presence of CH_4 and N_2O must not be overlooked owing to their enhanced global warming effects. The high fuel consumption rates of these machines underscore the need for more efficient and less polluting alternatives.
(4) Equipment usage. Throughout the mining process, various mobile and stationary equipment, including bulldozers, graders, and auxiliary generators, are used. These machines also rely on diesel and gasoline, contributing primarily to CO_2 emissions, with trace amounts of CH_4 and N_2O. The continuous operation of this equipment is critical for maintaining productivity, also contributing significantly to the overall GHG emissions of the mine.
(5) Conveying. Conveying systems, which transport ore and waste rock, are typically powered by electricity. If the electricity is generated from fossil fuels, it indirectly contributes to CO_2 emissions. The efficiency of these systems and the source of their power play crucial roles in determining their environmental impact. Transitioning to renewable energy sources for powering conveyor belts can significantly reduce the carbon footprint of this phase.
(6) Hauling. Haul trucks, which transport material from the mine to processing facilities, are among the largest consumers of diesel fuel in mining operations. These trucks emit substantial amounts of CO_2, CH_4, and N_2O. The size and weight of haul trucks, combined with the distances they travel, result in high fuel consumption and significant GHG emissions. This phase represents a critical area for potential improvements in fuel efficiency and alternative energy use.
(7) Crushing and Grinding. The crushing and grinding phase involves breaking down ore into smaller particles, a process requiring substantial energy. This energy often comes from electricity or on-site diesel generators. Depending on the source of electricity, indirect CO_2 emissions can be significant. Diesel generators add to the direct CO_2 emissions. The energy-intensive nature of these processes highlights the importance of energy efficiency and the use of renewable energy sources to mitigate emissions.
(8) Beneficiation. Beneficiation processes, such as flotation, magnetic separation, and leaching, further concentrate the ore and are highly energy-intensive. These processes often rely on electricity and heat generated from fossil fuels. The combustion of these fuels leads to CO_2 emissions. CH_4 and N_2O may be released, depending on the fuel type and combustion efficiency. Reducing the carbon intensity of these processes is crucial for minimizing their environmental impact.
(9) Mitigation Strategies. Addressing the GHG emissions from open pit mining requires an all-around approach. Electrification of mining equipment is a promising strategy to reduce GHG emissions. Electric-powered equipment can significantly reduce CO_2 emissions, particularly when the electricity is sourced from renewables. Utilizing alternative fuels, such as biodiesel, hydrogen fuel cells, or natural gas, improving energy efficiency across all phases, as well as implementing advanced operational processes and energy management systems can reduce fuel consumption and emissions. Integrating renewable energy sources, such as solar or wind power, into mining operations can further reduce reliance on fossil fuels. Regular monitoring and reporting of GHG emissions are essential for identifying emission sources and tracking progress in mitigation efforts. Carbon accounting systems can help quantify emissions and highlight areas for improvement. Additionally, exploring carbon capture and storage technologies can provide solutions for CO_2 emitted from stationary sources within the mining site.

In 2012, Shi [15] noted the prominent role of fossil fuels in the global energy structure, accounting for 34% of oil production, 17% of gas, 15% of biomass, 4% of nuclear energy, 24% of coal, and 6% of hydropower. Twelve years later, Periasamy and Mohanta [16] highlighted the continued unsustainable use of fossil fuels, which depletes natural reserves and contributes to rising CO_2 emissions, are a primary factor affecting the escalation of global average temperatures. In 2002, Raimi *et al.* [17] reported that fossil fuels, comprising coal, oil, and natural gas, constituted 80% of the global primary energy supply. As industrial output has increased and technological advancements have improved, energy demand has also risen. At the same time, fossil fuel resources have gradually depleted, and their unfettered use has led to numerous environmental issues. Today, the world is primarily concerned with energy and environmental issues, with "sustainable development" emerging as a recurrent theme [2,15,17–19]. Mine environmental issues have garnered significant attention worldwide, driving the development and utilization of biomass energy owing to the increased depletion of fossil fuels and the worsening of the environment. Research in green mining technology and achieving clean and efficient energy utilization are important tasks [20–22]. Modern methods for improving conventional mining techniques include green mining and climate-smart mining [23]. Many nations, including France, Ireland, Portugal, Spain, the United Kingdom [24], Canada [25], China [26], Finland [12], and the United States [27], have embraced "green mining" since the 19th century [28]. Initially focused on greening mining areas, green mining has expanded to include the most efficient use of nonrenewable natural resources with the least negative effects on the environment [29]. Throughout a mine's lifecycle, green mining employs technologies to increase environmental efficiency and keep the mining sector competitive. For mining to coexist with the environment, it attempts to reduce energy and resource consumption as well as waste production from the exploration to the post-closure stage [2,29].

Sustainability has gained attention in the modern world owing to its significance for social progress, economic expansion, and poverty reduction [19]. Environmental sustainability is a well-known concern as industrialization has impacted both the natural environment and human well-being, as reported by Awan *et al.* [20]. Green manufacturing, safety, and social supply chain practices are essential for enterprise-level sustainability success, offering specialists insights into how businesses can use these procedures to monitor and support social manageability [12,20]. The term sustainability is taking on new strategic importance in mining. In this industry, sustainability goes beyond the bottom line, encompassing a wide range of organizational traits associated with environmental and social responsibility [14,30,31].

Historically, sustainability and mining were thought to be mutually exclusive. However, as concerns about social responsibility, carbon emissions, and environmental stewardship grow [1], the mining industry is increasingly integrating sustainability into its business practices. Since the mining sector accounts for up to 10% of global GHG emissions, it must play a significant role in both lowering carbon emissions and enhancing environmental regulations [32]. Notably, LKAB, Europe's largest iron ore miner, has successfully produced the world's first carbon-free iron ore pellets in Sweden. Similarly, Newmont Corporation announced an investment of approximately $500 million in climate change projects over the next five years, intending to achieve net-zero carbon emissions by 2050 and a 30% decrease in GHG emissions by 2030 [3,23,32].

Goldcorp is another major mining corporation making strides toward green mining. The company is investing in research and development and adopting newer, greener technologies, quickly advancing toward green mining. To create a more environmentally friendly and safer work environment, the company is collaborating with suppliers to supply battery-powered drill equipment and underground vehicles. The electrification effort is expected to reduce GHG emissions by 50% and significantly lower mining costs [33,34]. Rio Tinto is also embracing green mining practices. The corporation is testing green technologies at two sites: methane capture equipment in New South Wales, Australia, and a productive CO_2 storage plant in Victoria, Australia, which has stored 60,000 metric tons of CO_2 to date. Another massive player in the mining industry, Barrick Gold, is operating 140 energy-efficient projects and sourcing more than 19% of its electrical energy from renewable sources for mining operations. This company has also established recycling and water management systems, with 83% of its locations reusing recycled water, thus preserving valuable drinking water [35].

The green mining phenomenon has also boosted the recycling and water purification sectors. According to a 2016 report by industry experts Frost and Sullivan, the mining water treatment sector grew from $2.29 billion in 2011 to $3.6 billion in 2016 [35]. The primary drivers of this expansion are increasing environmental consciousness and stricter rules. Wastewater treatment also offers the benefit of metal recovery, making water reuse profitable for enterprises as metal recovery techniques, including sulfide precipitation, become more advanced. Following sulfide precipitation treatment, the water has lower nickel levels than permitted. This method also makes it simple to extract precious metals like copper and gold [36].

The need for low-carbon economic development has gained international recognition in recent years. A key aspect of this development is minimizing the environmental effects of mining operations. Research on sustainable development plans and the effectiveness of green mining is therefore essential for the mining industry. Accomplishing sustainable mining has become increasingly important owing to the growing negative effects of mining on the environment and communities. Traditional mining practices are characterized by high resource consumption, high pollution, and low efficiency. This has raised concerns among researchers about supplying scientific remedies to these issues. It has been suggested that additional measures are needed to compensate for traditional mining to achieve sustainable practices. As a result, mining companies have increasingly focused more on implementing green innovations [34,37].

Over the past decade, the impact of climate change and the mining industry's response to it have become prominent topics of discussion. The industry, already accustomed to operating in harsh climates, faces forecasts of more frequent and intense hazards such as heavy precipitation, drought, and heat. These challenges exacerbate the physical challenges of mining operations. Strong public support for ecologically friendly practices has greatly increased the pressure on businesses to adopt sustainable practices both inside and outside the mining sector. The future of green mining looks promising, driven by technological advancements and industry trends gaining traction among larger mining companies. This study aims to discuss the benefits, limitations, and future potential of green mining practices in addressing the massive energy consumption of traditional mining techniques. It also seeks to enhance mining processes in a way compatible with existing technologies.

The study employs a mixed-methods approach, integrating quantitative data analysis from monitored mining sites with qualitative insights from industry experts. Key parameters examined include energy consumption, emission levels, waste production, GHG emissions, and reductions in chemical use. This approach provides a thorough understanding of the technological, environmental, and socio-economic dimensions of green mining practices.

Interactions with industry experts and stakeholders from various mining companies provided insights into the challenges and benefits of adopting green technologies. Perspectives were gathered from engineers, environmental managers, and company executives. Selected mining companies were studied to document specific instances of technology implementation and the resulting environmental and economic impacts. Common themes and sentiments regarding the adoption of green mining technologies were identified through these interactions, aiding in the understanding of the subjective dimensions of technological integration, such as stakeholder attitudes and perceived barriers. This comprehensive assessment helped identify the overall benefits and drawbacks of various green technologies in terms of resource use and environmental degradation.

Reflecting on the existing literature, it is evident that the quest for sustainability within the mining sector, particularly through the implementation of green mining technologies, has rapidly gained prominence owing to escalating environmental concerns and regulatory pressures. Numerous studies have explored various facets of green mining, such as reduced emissions, energy efficiency, and the application of renewable energy sources. However, significant gaps persist, especially in comprehensively integrating these technologies into existing mining frameworks. While existing research has detailed the negative impacts of mining operations on the environment, there is a lack of systematic, empirical evaluations comparing the effectiveness of traditional versus green mining practices over long durations and across different geological settings. This study aims to fill this gap by providing a rigorous, data-driven comparison of these methodologies, assessing their operational efficiencies and environmental impacts. Furthermore, while reducing energy consumption and minimizing ecological disruptions are well-trodden areas of research, the adoption rates and scalability of such technologies across the global mining industry remain underexplored. The role of policy frameworks and corporate governance in facilitating or hindering the adoption of green technologies also requires deeper examination. This study seeks to address these aspects by evaluating the regulatory and governance landscapes in various countries and their influence on green mining practices.

The existing literature often overlooks the socio-economic implications of green mining technologies. This study extends the discourse by considering both the environmental and socio-economic outcomes of implementing green mining solutions, focusing on community engagement, job creation, and local economies. By positioning itself at the intersection of environmental science, technology, and socio-economic factors, this paper strives to provide a holistic view of the potential of green mining to foster a sustainable future for the mining industry. Such a holistic approach is essential for developing actionable insights and practical recommendations for stakeholders across the mining sector.

The environmental impacts of mining have become increasingly apparent with the expansion of the industry, highlighting the urgent need for sustainable practices [38–40]. Traditional mining operations are known for their significant ecological footprint, including high energy consumption, waste production, and GHG emissions. This research addresses these challenges by evaluating the integration and effectiveness of green mining technologies, focusing on creating a sustainable mining model that balances resource extraction with environmental protection. The study covers numerous environmental issues associated with mining, such as landscape alteration, ecosystem disruption, and pollution from waste and emissions. These problems underscore the necessity of adopting greener mining practices. This study investigates a range of green technologies designed to mitigate these impacts, offering a comprehensive analysis of their application and benefits.

Key areas of focus include reducing energy consumption using electric vehicles and renewable energy sources. The transition from diesel-powered equipment to electric alternatives has shown significant reductions in emissions and operational costs. The paper discusses specific case studies where these technologies have been successfully implemented, providing a blueprint for other mining operations to follow. In addition to energy efficiency, waste management is a critical component of sustainable mining. Innovative waste processing techniques, such as dry stacking of tailings and advanced recycling methods, are examined in detail. These methods not only minimize the environmental impact of waste disposal but also enhance resource recovery and reduce the overall carbon footprint of mining activities.

The study also examines the adoption of renewable energy sources, such as solar and wind power, within mining operations. By integrating these energy sources, mining companies can reduce their dependence on fossil fuels, thereby lowering GHG emissions and improving energy security [41,42]. The paper presents various examples of mining sites that have successfully incorporated renewable energy, highlighting the practical benefits and challenges of such transitions. Additionally, the role of automation and data analytics in improving operational efficiency and sustainability is explored. Advanced technologies, including smart sensors and automated equipment, enable real-time monitoring and optimization of mining processes. These innovations lead to better resource management, reduced energy use, and enhanced safety for workers.

Social and economic dimensions are also considered, emphasizing the importance of sustainable practices for improving community well-being and economic viability. Green mining technologies can create job opportunities, improve health outcomes by reducing pollution, and foster positive relationships between mining companies and local communities. The study advocates for greater stakeholder engagement and transparent reporting practices to build trust and ensure the successful adoption of sustainable practices. In terms of regulatory frameworks, the paper discusses the importance of supportive policies and incentives to drive the adoption of green technologies. Regulatory oversight ensures compliance with environmental standards and encourages investment in sustainable innovations. The study examines various policy models from different countries, offering insights into effective strategies for promoting green mining.

The study combines quantitative data analysis from monitored mining sites with qualitative insights from industry experts. This mixed-methods approach allows for a thorough examination of the environmental, technological, and socio-economic impacts of green mining technologies. The research comprehensively explores sustainable mining practices, demonstrating the interconnected challenges and solutions related to sustainable mining practices. It emphasizes the need for a balanced approach that addresses energy use, waste management, renewable energy integration, technological innovation, socio-economic benefits, and regulatory support [43–46]. This holistic perspective is essential for developing actionable insights and practical recommendations for stakeholders in the mining sector.

2. Sustainability of mining equipment through adopting green technologies

The mining industry uses green technologies in various aspects, with mining equipment serving as a prime example to illustrate their application. While similar detailed coverage could be provided for other areas of the mining sector, doing so would make this paper overtly lengthy and redundant.

The mining sector is a massive energy user, requiring enormous energy inputs to start daily operations. Heavy machinery must be operated to meet demand, and energy usage could increase if mining's importance grows in the future. Logistical challenges of change often deter many mining companies from taking action to lessen environmental damage despite their willingness to do so. Therefore, research and development efforts have been made to ensure that these green mining initiatives are both inconspicuous and successful. Within the mining industry, mining equipment is crucial. Modern mining equipment not only reduces environmental pollution but also enhances worker safety and generates significant profits. These advancements are gradually transforming the mining industry and the manufacturing sector. Automated machines follow more stringent guidelines than human operators, consuming fewer resources than necessary, extending the machine lifespan, lowering energy consumption, and optimizing input use. New technologies, such as automated drilling and training systems, remote control centers, automated mining trucks, and rigs, are transforming the industry.

Owen [47] notes that diesel-powered construction equipment, such as dozers, wheel loaders, and excavators, release an estimated 400 million tons of CO_2 annually, making up 1.1% of global carbon emissions. An astounding 46% of these emissions are produced by excavators in the 10 t-plus categories, with the mining industry accounting for up to 7% of total GHG emissions. Therefore, limiting emissions connected to transportation is particularly critical [47]. While heavy diesel vehicle emissions pose health risks to workers in all mining operations, underground environments are riskier. These are often tight and enclosed places where exhaust gases, such as CO_2 and NO*x*, can quickly crate dangerous scenarios for workers. Mines utilizing such vehicles require significant ventilation systems to collect the exhaust fumes and maintain good air quality in workstations. These electrically driven systems add significantly to the mine's overall energy consumption and operational costs. Many industries, including the mining sector, are implementing measures to reduce vehicle emissions to address these health and environmental concerns [47,48]. Achieving this aim will largely depend on electrification. Electric operating vehicles are particularly appealing to the underground mining industry owing to the quicker advantages of lower ambient temperatures, better ventilation, and lower emissions. However, the transition to sustainable mining practices faces several challenges, particularly in the area of mining equipment. Diesel-powered equipment is deeply embedded in the industry and replacing it with electric or alternative fuel-powered alternatives can be expensive and disruptive. Additionally, the remote and harsh environments of many mines pose unique challenges for integrating new technologies. A schematic representation of these efforts is presented in Fig. 2.

Despite these challenges, the mining industry is increasingly recognizing the need for sustainable practices and investing in green technologies. These technologies offer reduced emissions, improved resource efficiency, and enhanced worker safety.

Modern mining equipment converges profitability, environmental responsibility, and worker safety. The evolution of mining machinery is characterized by a paradigm shift toward automation. This entails the deployment of advanced systems such as automated drilling and training systems, remote control centers, and autonomous mining trucks. These technologies not only adhere to stringent operational guidelines but also promise prolonged equipment lifespan, reduced energy consumption, and optimized resource utilization [49]. The environmental impact of diesel-powered equipment cannot be overstated. Diesel-powered construction equipment, ubiquitous in the mining industry, significantly contributes to global carbon emissions [50,51]. The mining industry faces a dual challenge of meeting growing global demand while curbing its environmental impact. Beyond environmental concerns, heavy diesel vehicle emissions pose significant health risks to mining workers, particularly in underground operations. The enclosed and confined spaces in underground mines elevate the dangers associated with exhaust gases such as CO_2 and NO_x. To mitigate these risks, mines deploy elaborate ventilation systems, often electrically driven, to ensure air quality. However, these systems contribute significantly to the mine's overall energy consumption and operational costs, necessitating a shift toward sustainable alternatives.

Addressing and limiting emissions from heavy diesel vehicles in mining operations, especially in enclosed environments, hinges on electrification. Electric operating vehicles emerge as a promising solution, offering immediate benefits such as lower ambient temperatures, improved ventilation, and reduced emissions. Electrification is particularly appealing in the underground mining industry, where the advantages of lower ambient temperature and better ventilation align with operational needs. Transitioning to electric vehicles is seen as a critical step toward achieving sustainability goals, reducing environmental impact, and ensuring the safety of mining workers.

While the path toward sustainable mining equipment is promising, challenges persist. The initial costs of transitioning to electrified equipment, the need for infrastructure upgrades, and technological uncertainties pose significant obstacles. However, the long-term benefits, including reduced environmental impact, enhanced safety, and operational cost savings, far outweigh these challenges. Collaborative efforts among industry stakeholders, research institutions, and policymakers are crucial to overcoming these obstacles. Investment in research and development, along with a strong commitment to innovation, can pave the way for sustainable mining practices. Exploring case studies of mining companies that have successfully implemented green technologies provides valuable insights into best practices [52–56]. Companies that have embraced electrification, automated systems, and sustainable practices offer tangible lessons for the broader industry. Analyzing these cases provides a nuanced understanding of the feasibility, challenges faced, and holistic impact on sustainability goals. These case studies serve as beacons of success, inspiring other mining companies to adopt similar green initiatives.

Fig. 2. Representation of electrically driven systems in mining operations.

2.1. Portable rigs for drilling operations

Drilling in remote areas often poses significant challenges owing to accessibility issues and the aim to minimize negative environmental and community impacts. Vancouver-based Energold Drilling Corporation has addressed these challenges with their portable drilling rigs, which are significantly smaller than traditional rigs, measuring 4 m by 4 m compared to 20 m by 20 m. These rigs can be disassembled and transported to distant areas, with the heaviest piece of equipment weighing only 200 kg. Locals usually carry the rigs along known paths, such as the Andes and at elevations above 1200 m. This approach not only provides jobs for locals but also trains them to assemble the drilling rig, potentially leading to independent drilling opportunities. This also reduces the need for additional truck transportation, protecting the environment, saving time and money, and lowering vehicle carbon emissions. Additionally, the rig's smaller size compared to a conventional one means that it has less of an influence on the environment, which makes post-mining ground restoration easier and greener.

2.2. Hybrid diesel-electric loader for underground workings

Approximately 95% of underground metal mines employ loaders to move several tons of ore, often up steep inclines of 11.5 degrees, making them essential in underground mining, according to National Resources Canada [25]. However, diesel-powered loaders significantly pollute the underground atmosphere, requiring adequate ventilation systems. To address this issue, CanmetMINING (CMIN) and Mining Technologies International have created what they claim to be the first hybrid diesel-electric loader [27]. This loader can reduce the energy required for mine ventilation by 20%–40%, which makes up roughly 40% of underground mining companies' electrical expenses, according to Natural Resources Canada. The loader's electric motor can charge while operating on diesel, eliminating the need for refuelling stops, and can perform the same functions as a standard loader. With the help of a high-efficiency particle filter, the hybrid engine reduces harmful gas emissions by 40%–70% and breathable combustible dust emissions by 95% [12,27].

2.3. Reduction of carbon cement binder for underground openings

The most widely used type of cement in the world, Portland cement, is frequently used in underground mining to support shafts and prevent collapses. However, its production generates one ton of CO_2 per ton of cement, significantly harming the environment. Natural Resources Canada has developed an environmentally friendly binder for use in mine shafts [25]. The binder is made from a mixture of calcium hydroxide (from gypsum) and slag, a byproduct of mining operations. Unlike Portland cement, which is manufactured at distant factories, these materials are typically disposed of and kept at mine sites, allowing for on-site blending. This repurposes waste materials.

2.4. Substitution of diesel engines with electric and battery-powered mining equipment

Battery-powered alternatives are increasingly capable of replacing diesel-powered mining equipment. By switching to electric engines from diesel ones, mining can drastically cut down on CO_2 emissions. Today's battery-powered machinery includes wheel loaders, rigs, and vehicles. Numerous electric mining vehicles, including the Komatsu electric mining dump truck, are already available on the market. Diesel engines are a major source of carbon emissions at mining operations, typically accounting for 15% of all emissions. This has led to a comeback in the use of the trolley assist system, a decade-old technology, in surface operations [50,51,57]. The need to lower carbon emissions and the availability of renewable energy sources that lower the cost per kW of electricity has prompted many mining firms to reconsider this technology.

Table 1 summarizes several green technologies in mining equipment that are transforming the industry. These innovations offer opportunities to reduce environmental impact and improve operational efficiency.

Incorporating these key green technologies into mining equipment aligns with sustainability goals, reduces environmental impact, and fosters responsible mining practices, as summarized in Fig. 3. The ongoing development and adoption of these technologies are essential for the industry's transformation toward a more sustainable and eco-friendly future.

3. Practices of green mining

Green mining, also known as sustainable mining, entails adopting mining practices that prioritize environmental protection, economic viability, and social responsibility. The goal of green mining is to ensure that the environment is not affected by mining operations, that miners and surrounding communities are safe during and after operations, and that investors do not incur losses through irresponsible practices. Environmental protection seeks to reduce habitat destruction for both flora and fauna and minimize pollution of land, air and water.

Economic viability seeks to balance environmental and social responsibilities with economic considerations to ensure the long-term viability of mining projects. This balance is achieved through proper mining planning and investment in research and development to promote innovative technologies in mining. Consequently, efficient operations reduce costs and losses while expanding profit margins. Additionally, green mining addresses the well-being of local communities affected by mining operations by considering their views in decision-making and providing employment and training activities [34].

For efficient environmental protection, several studies have reported improved techniques for handling mining waste. For example, Peng and Guo [58] highlighted advanced water treatment methods, including ion exchange, electrocoagulation, and nanotechnology, to prevent chromium percolation from mine wastewater into the surrounding environment, which can endanger flora and fauna. This study promotes the utilization of efficient wastewater treatment technology to reduce environmental pollution [58]. In another study, Liu *et al.* [59] discussed the removal of copper ions from mine wastewater using membrane separation, ion exchange, chemical precipitation, electrochemistry, adsorption, and biotechnology. This study promotes environmental sustainability by paving avenues on how mining companies should responsibly handle waste material.

Mining inherently entails stripping large volumes of earth material to uncover minerals. While traditional mining techniques often lead to land degradation, a green study by Behera *et al.* [60] used paste backfilling from tailings, cement, and water to backfill open stopes post-mining. This practice stabilizes the subsurface spaces and helps restore the natural land scape [60].

Mining is energy-intensive, with conventional machines often powered by diesel-powered engines that emit noxious gases and other diesel particulate matter (DPM). To overcome this, most mines have transitioned to electric-powered machines, as reported by Paraszczak *et al.* [61], Issa *et al.* [62], and natural gas-powered vehicles [63]. As a result, this has supported the green mining agenda of reduced environmental pollution. The usage of electric and natural gas-powered vehicles also significantly reduces noise emissions from internal combustion engines [61].

Coal has long been a staple in the energy sector, supplying affordable power in various countries. However, coal mining is hazardous owing to the presence of methane gas that easily explodes, posing significant risks to miners and polluting the environment. To mitigate methane seepage from trapped coal deposits, the study by Xu *et al.* [64] recommends extracting coalbed methane and using it as an energy source. This study directly addresses sound practices of green mining as it does not only protect miners from explosions but also, provides clean energy to power mining operations [64].

Table 1
Summary of certain mining equipment green technologies transforming the mining industry.

Green technology	Description	Actual application examples
Electrification	Switching from diesel-powered equipment to electric or hybrid alternatives is a major step toward sustainable mining. Electric vehicles can be powered by renewable energy sources, such as solar or wind power, eliminating emissions and reducing reliance on fossil fuels.	The Borden mine in Canada, operated by Newmont Corporation, has led the way in utilizing battery-electric vehicles in underground mining, which reduces diesel emissions and enhances air quality underground.
Automation and remote control	Automated mining equipment can operate with greater efficiency and precision, reducing the need for human intervention. Remote control systems allow operators to remotely control machinery, minimizing the need for personnel in hazardous environments and enhancing safety.	Automated mining equipment, like autonomous haul trucks and remote control drills, have been increasingly implemented in mines to improve safety and efficiency. Rio Tinto has deployed autonomous haulage systems at its iron ore mines in Western Australia, thereby improving productivity and reducing incidents related to human error.
Digitalization and data analytics	Ditigalized mining operations can provide real-time data on equipment performance, resource consumption, and environmental impacts. Data analytics can identify opportunities for optimization, resource efficiency, and emission reduction.	Vale's iron ore mines in Brazil use advanced predictive maintenance technologies, utilizing sensors and analytics to predict equipment failures before they occur, thereby reducing downtime and maintenance costs.
Hydrogen technologies	Hydrogen fuel cells offer a promising alternative to diesel engines, providing clean and efficient power for mining equipment. However, the challenges of hydrogen production and infrastructure need to be addressed.	Anglo-American has been developing a hydrogen-powered mining truck, aiming to significantly reduce greenhouse gas emissions from diesel engines.
Regenerative technologies	Regenerative technologies, such as hydrocyclones and hydrometallurgical processes, can recover valuable minerals from waste streams, reducing the volume of mining waste and improving resource efficiency.	Freeport-McMoRan's Morenci mine in Arizona uses solvent extraction and electrowinning (SX/EW) processes to recover copper from oxidized ores. This process can efficiently extract copper while minimizing the impact on the environment.
Biodegradation technologies	Biodegradation technologies can break down mining waste into less harmful substances, reducing environmental impact and resource recovery.	Companies like BacTech are using bioleaching to safely process arsenic–laden mine tailings, which are both environmentally friendly and cost-effective.
Energy-efficient drilling technologies	Drilling technologies designed for energy efficiency reduce the power requirements for drilling processes, resulting in lower energy consumption and reduced environmental impact.	Sandvik's new energy-efficient drilling equipment, which uses less fuel and captures and recycles energy from drill operations, exemplifies this technology in action.
Water management systems	Efficient water management equipment can reduce water consumption and prevent water contamination, minimizing the environmental impact of mining operations.	The Oyu Tolgoi mine in Mongolia uses advanced water recycling techniques to reuse up to 80% of the water in processing, drastically reducing freshwater intake.
Advanced fleet management systems	Implementing sophisticated fleet management systems optimizes vehicle routes, reduces fuel consumption, and enhances overall fleet productivity, contributing to sustainability goals.	Modular Mining's DISPATCH system, used in numerous large-scale mining operations worldwide, helps optimize truck assignments and minimizes queuing at loading and dump points, significantly reducing fuel use and emissions.
Smart sensors and Internet of Things (IoT) integration	Smart sensors and IoT devices provide real-time data on equipment performance, allowing for predictive maintenance, reducing downtime, and optimizing resource use.	Caterpillar's MineStar system uses smart sensors to track and optimize every aspect of mining operations, from fleet management to safety systems.
Use of advanced materials	Adopting lightweight and durable materials in equipment design increases fuel efficiency, reduces energy consumption, and extends the lifespan of mining machinery.	Hardox wear plates are commonly used in buckets and dump bodies to increase the service life and reduce equipment weight, which in turn enhances fuel efficiency.
Artificial Intelligence (AI) for predictive analytics	AI algorithms analyze vast data sets to predict equipment failures, optimize processes, and enhance overall operational efficiency, reducing resource consumption.	A prominent example is Goldcorp's use of IBM's Watson technology for geological data analysis to predict the potential for gold mineralization. This AI integration facilitates accurate drilling decisions, improving yield and minimizing environmental disruption.
Sustainable materials handling	Implementing eco-friendly material handling systems, such as conveyor belts and material transport systems, reduces energy consumption and minimizes environmental impact.	Sandvik has developed energy-efficient conveyor belts that use half the energy of traditional belt systems. These belts are used in various mining operations to transport ore across large distances with minimal environmental impact.

To prevent land degradation, studies have reported converting abandoned mines into pumped hydro plants, which generate clean energy and help avoid land degradation [65,66]. For example, a study by Fox [67] reported that geothermal energy from old coal mines could produce carbon-free heat, emitting only a tenth of the carbon footprint compared to other energy sources [67].

Green mining emphasizes safety in all operations to ensure no worker is harmed or killed in the mines. Automation plays a crucial role in this, as machines can operate in risky spaces without human intervention. For example, Jiang *et al.* [68] reported the use of unmanned electric vehicles to promote mine safety. Moreover, studies have reported the connectivity of machines to ensure they work in tandem to promote optimization and safety. For example, Ericsson [69] discussed the use of connected drilling and blasting to promote operational efficiency and reduce costs.

Green mining represents a paradigm change in the mining sector, focusing on environmental sustainability while minimizing environmental damage. Scientific research sheds light on the different approaches and technologies used in green mining. For example, in Australia, solar-powered mining endeavors entail integrating large-scale photovoltaic (PV) systems to harvest solar energy for mining operations. Companies such as Rio Tinto have used these systems to power equipment and facilities, minimizing their reliance on traditional energy sources and lowering carbon emissions and operational costs [21,22,70]. Similarly, copper mining companies in Chile have adopted solar energy for their mining and processing operations [71]. However, full reliance on solar power has proven to be challenging in some aspects, including initial high installation costs and dependency on a complementary energy source owing to the intermittent nature of solar power [72]. To optimize resource utilization, experts have invented precision mining techniques striving to ensure only operations handle necessary materials. This is achieved using modern technology, such as Global Positioning System (GPS) and sensor-based systems. Precision surface mining is gaining popularity in the markets for phosphate, iron ore, copper, iodine, limestone, bauxite, coal, and gypsum. Precision surface mining enables three-dimensional tracking of ore bodies. This

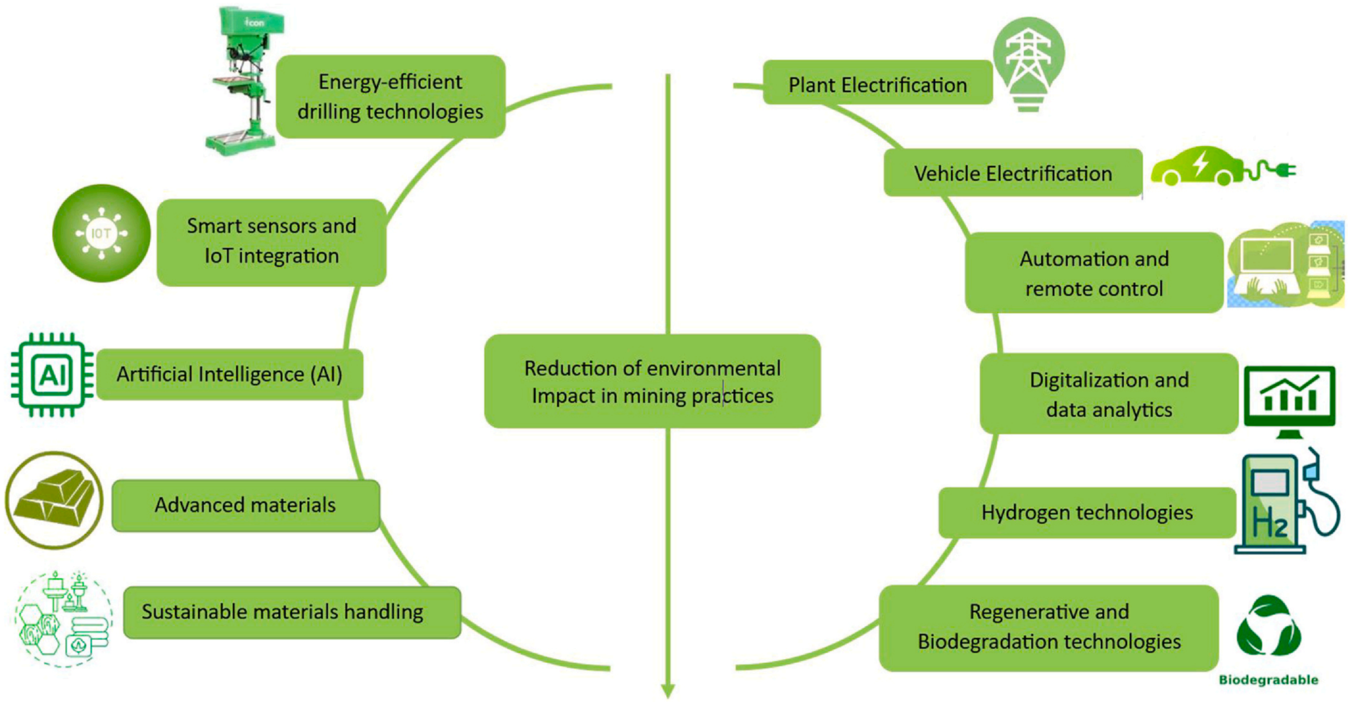

Fig. 3. Green technology incorporation in mining operations.

technology improves ore quality over drill and blast procedures by keeping ores separate from the waste material [30,31,73]. As such, precision mining has reduced environmental impact and enhanced resource utilization.

Phytomining of noble metals (NMs) offers a viable method of extracting metals in areas where conventional mining operations are unprofitable or where recovering NMs from low-grade materials is not feasible. As an alternative to traditional mining, generating NMs from secondary resources has garnered global interest for its potential to improve the efficiency of the circular economy [74]. Although this method is unlikely to replace normal mining, it presents a win-win situation for exploiting untapped precious metals that are otherwise not uneconomical to mine using large-scale operations. Mintek, a South African mining business, has carried out phytomining experiments in metal-contaminated soils. Despite the environmentally friendly nature of this technique, it faces significant challenges, such as low metal absorption rates, long operation times, and high-cost operation [75]. Table 2 presents the main environmental challenges faced by leading mining countries worldwide and the various green mining technologies implemented to promote sustainability.

4. Adoption challenges of green mining in the mining industry

4.1. High initial investment

The transition to green mining technologies demands a significant upfront investment, encompassing the adoption of electric vehicles, renewable energy infrastructure, and advanced processing technologies. This financial hurdle is particularly challenging for mining companies, especially those accustomed to traditional practices that might seem more economically viable in the short term. Lopes da Costa [82] notes that securing substantial funds for green initiatives poses a significant challenge for mining operations. Historically, the mining industry has been capital-intensive, and reallocating resources toward sustainability measures can meet resistance, particularly when economic returns are not immediately apparent.

Miners often struggle with the time it takes to realize returns on their green investments, as longer payback periods for certain technologies can deter adoption. Small- and medium-sized mines may encounter difficulties accessing capital for green initiatives. Financial institutions might be cautious about investing in projects with longer payback periods. Furthermore, uncertainties related to future environmental regulations can create hesitation among mining companies to commit to substantial green investments. Regulatory stability is crucial for informed decision-making. The perceived financial risks associated with unproven green technologies can also dissuade investors [53,83]. Convincing stakeholders of the long-term benefits remains a key challenge.

4.2. Technological innovation and integration

Incorporating new and innovative technologies into existing mining operations presents a multifaceted challenge. It involves addressing compatibility issues, providing adequate staff training, and seamlessly integrating these technologies into established workflows [48]. Resistance to change and a lack of skilled personnel for operating and maintaining advanced technologies can impede the transition to greener practices. Overcoming these challenges requires a strategic approach to technological innovation.

A study by Sánchez and Hartlieb [84] shows that adapting the workforce to operate and maintain advanced technologies necessitates substantial training programs, with the availability of skilled personnel often being a bottleneck. Mining companies must establish effective collaborations with technology providers to ensure that their solutions align with the specific needs and constraints of mining operations. Adopting a phased approach to technology integration can mitigate disruptions [49,85]. Incremental implementation allows for continuous improvement and learning. Ensuring that new technologies are compatible with existing mining infrastructure is crucial, as retrofitting operations for green technologies may require modifications [85]. Chen *et al.* [4] developed a novel hybrid gray-based decision model after noting the need to promote sustainable mining practices through scientific and reliable evaluation metrics and methodologies. Their model synthesizes elements from the gray analytic hierarchy process and the gray clustering method, providing a comprehensive framework for assessing the degree of sustainability in mine construction [4].

Table 2
Summary of green mining technologies as practiced in leading mining countries.

Country	Mining hazard requiring mitigation measure	Implemented green mining technique	Author
The United States of America	Acidic mine drainage, which carries heavy metals and negatively affects water quality, can be released because of metal mining. This runoff endangers aquatic habitats and can cause long-term environmental damage.	Treatment of wastewater effluent: To eliminate pollutants from mine water, advanced water treatment methods such as membrane filtration and ion exchange are used. Metals can be precipitated or absorbed by some bacteria, decreasing their mobility in water. Passive water treatment systems: Wetland ecosystems and passive treatment systems are built to harness biological processes to neutralize acidic water and remove metals.	[58,59]
	Emission diesel particulate matter (DPM) from diesel-powered engines.	Utilization of 35-ton payload Kiruna. K635ED electric vehicles in Stillwater mine in Montana caused a reduction in DPM.	[61]
Canada	Air and noise pollution from fossil fuel use by using fuel diversification. Fossil fuels release GHG emissions that compromise the ozone layer.	Borden Gold Mine became the first all-electric underground mine in the world. It replaced traditional diesel-powered equipment with battery-electric vehicles for its underground operations. Electric haul trucks, loaders, and drill rigs are examples of such equipment.	[62]
		Over the last decade, several Teck coal mines have expanded their use of natural gas instead of coal, causing an annual reduction of more than 250,000 tonnes of CO_2 emissions.	[63]
		Dominion Diamond Corporation developed an in-vessel composter at its Ekati Diamond Mines in the Northwest Territories, establishing it as the first operation of its kind in Canada's North. By the end of 2016, almost 67,000 kg of biological waste had been diverted, lowering greenhouse gas emissions by 210 tonnes of CO_2 equivalent and fuel usage by 74,000 liters. This initiative was honored with the 2017 Towards Sustainable Mining (TSM) Environmental Excellence Award.	[76]
China	Greenhouse gas emissions: Capturing and using coalbed methane helps reduce methane (a powerful greenhouse gas) emissions into the environment. This is consistent with China's efforts to cut greenhouse gas emissions and mitigate climate change.	Extraction of coalbed methane (CBM): A prominent green mining technology used at the Zhundong coalfield is the removal of coalbed methane. Rather than emitting methane, a strong greenhouse gas, into the environment during mining operations, the gas is trapped and used as an energy source. This not only decreases pollution but also provides an alternative energy source.	[64]
	Un-reclaimed open pit mines.	Nanhuayuan Lake, three dumps, and the Fushun East Open-Pit coal mine are planned as the top reservoir for the phased Pumped Storage Hydropower (PSH) plant project in China. A rough estimate indicates that the PSH plant's installed capacity in three phases with lower reservoir water levels of −295, −200, and −150 m, respectively.	[66]
	Safety incidences owing to the operation of mining vehicles and noxious gas emissions.	The use of electric vehicles in the Chinese Dongguashan Copper Mine of Tongling replaced miners from working in risky mining areas and reduction of emissions of noxious gases.	[68]
Australia	GHG emissions.	To mitigate its environmental effect, the Newmont Boddington Gold Mine in Western Australia has deployed several green mining technologies. A noteworthy endeavor has been the use of renewable energy sources, notably wind and solar power, to complement the mine's energy demands.	[77]
	Land degradation.	Australia is exploring ideas to convert a decommissioned underground coal mine into a pumped hydro plant as part of a larger push to repurpose retired fossil fuel assets for renewable energy output in the Newstan Colliery.	[65]
	Noxious gas emissions and noise pollution from using diesel-powered enginers.	The use of electric vehicles reduces noise and air pollution in the Mount Issa mine.	[61]
India	Land degradation.	Paste backfilling: To control waste materials generated during mining, Hindustan Zinc Limited has adopted paste backfilling procedures. This includes combining tailings, cement, and water to form a paste-like substance that is then pumped back into mining-created subsurface spaces. This aids in the stabilization and infill of mined-out regions.	[60]
Nigeria	Water contamination: The use of mercury and other chemicals in many artisanal gold mining activities contaminates water. Green mining practices include the construction of closed-loop water recycling devices to reduce the demand for fresh water and prevent tainted water from being discharged into neighboring rivers and ecosystems.	Water recycling and treatment technologies are being implemented in artisanal gold mining operations to minimize water usage and pollution.	[78]
Sweden	Environmental pollution from carbon emissions.	SSAB, LKAB, and Vattenfall have successfully produced the world's first hydrogen-reduced sponge iron on a trial scale. The technical innovation in the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) effort removes about 90% of pollutants caused by the steelmaking process, representing a significant step toward fossil-free steel production.	[79]

(*continued on next page*)

Table 2 (*continued*)

Country	Mining hazard requiring mitigation measure	Implemented green mining technique	Author
	Reduction in ground vibrations and fly rocks using optimum drilling designs.	Boliden Mining Company, in collaboration with Ericsson, uses a 5 G network in the Aitik surface mine. This technology should help ensure stable connectivity for communication of drilling and blasting equipment to optimize operation and save on costs.	[69]
United Kingdom	Land degradation owing to wall failure and/or subsidence.	A 6-megawatt plan is currently being constructed at the Seaham Garden Village development in County Durham. The disused Dawdon mine's low-temperature water (18–20 °C) will be used to heat around 1500 new residences and community structures. Once fully operational, the project is estimated to have a tenth of the carbon impact of traditional gas heating.	[67]
South Africa	Power usage from fossil fuels releases GHG emissions that pollute the environment. Therefore, it is crucial to integrate cleaner energy sources in mines to reduce pollution.	A hybrid dump truck driven by electricity and a reserve of hydrogen fuel is poised to take the title of the biggest electric mining truck. The Fuel Cell Electric is currently being tested in Mogalakwena platinum group metals mine in South Africa.	[80]
		In 2009, Harmony Gold Ltd, including Kusasalethu, committed to using clean and energy-efficient technologies. This caused a decrease in GHG emissions of 616,000 t CO_2 between 2009 and 2012.	[81]

4.3. Energy transition and dependence on fossil fuels

Mining operations, especially those in remote locations, often rely on fossil fuels owing to limited access to renewable energy sources. Transitioning to cleaner energy alternatives, such as solar or wind power, can be both logistically and economically challenging. Statistics reveal the prevalence of mining operations reliant on nonrenewable energy and the obstacles they face in adopting renewable alternatives [86–89]. The shift toward cleaner energy is hindered by considerations of cost, infrastructure, and energy storage capacity.

The intermittent nature of renewable energy sources like solar and wind poses challenges in ensuring a consistent power supply for mining operations. Limited sunlight or wind can impact the feasibility of these energy sources. Transitioning to renewable energy often requires significant upgrades to existing infrastructure, including power grids and storage facilities, presenting economic challenges. Mining companies often grapple with the cost–benefit analysis of transitioning to renewable energy. The long-term savings and environmental benefits need to outweigh the initial investment.

4.4. Tailings management and water usage

Traditional tailing disposal methods, such as tailing dams, pose environmental risks, and water-intensive processes are common in mining. Implementing sustainable tailing management practices and reducing water usage are crucial challenges for green mining. The mining industry needs to transition from conventional tailing management practices to more sustainable alternatives. The environmental impact of tailings and water-intensive processes is a critical aspect of sustainability.

Improperly managed tailing dams can lead to catastrophic environmental disasters [90–93]. The mining industry faces considerable challenges in finding safe alternatives and mitigating the risks associated with traditional tailing disposal. A promising solution is the adoption of dry stack tailings (filtered tailings), which are considered more environmentally friendly. However, this approach involves substantial implementation costs and ensuring the stability of stacked tailings. Mining operations traditionally consume large amounts of water, making the implementation of efficient water recycling systems both technically and economically challenging. Meeting evolving regulatory standards for tailings management is a complex task. Compliance with new environmental guidelines requires ongoing efforts and investment.

4.5. Social and community engagement

Achieving a social license to operate requires effective engagement with local communities. Resistance to mining operations owing to environmental concerns can hinder green initiatives, emphasizing the importance of proactive community involvement [94–100]. Reflecting on community perceptions, protests, and the success rate of community engagement initiatives provides valuable insights into the challenges mining operations face in gaining community support for green initiatives.

Understanding and addressing community concerns related to environmental impacts and sustainability is crucial. Effective communication is essential for building trust. Instances of protests against mining operations owing to environmental concerns can hinder the adoption of green practices. Analyzing protest data provides insights into areas of contention. Mining companies need to establish transparent benefit-sharing programs with local communities. Demonstrating tangible benefits fosters positive relationships. Mines located in areas with indigenous populations need to be culturally sensitive, ensuring that green mining initiatives align with the cultural values and practices of local communities.

4.6. Regulatory compliance

Adapting to evolving environmental regulations makes mining operations more complex. Stricter compliance requirements may necessitate substantial operational changes, requiring ongoing efforts to stay abreast of and meet new standards. Studies on regulatory compliance levels, instances of non-compliance, and the impact on operations shed light on the challenges mines face in adhering to environmental standards [101–103].

Mining companies must navigate a dynamic regulatory landscape. The continuous evolution of environmental regulations requires proactive measures to ensure compliance. Mines operating in multiple jurisdictions need to comply with diverse sets of environmental regulations, making consistency across operations complex. Instances of non-compliance can lead to legal consequences and financial penalties. Analyzing regulatory enforcement data provides insights into industry adherence. Mining associations and industry groups play a role in advocating for clear and consistent regulations. Collaborative efforts can help shape policies that balance environmental protection and industry feasibility.

4.7. Supply chain sustainability

Ensuring a sustainable and ethical supply chain for minerals is challenging. Traceability and responsible sourcing are critical but difficult to achieve owing to complex global mineral supply chains. Enhancing supply chain transparency and increasing the proportion of responsibly sourced minerals are vital steps toward sustainable mining practices. The interconnected nature of the supply chain poses challenges in verifying the origin and ethical standards of minerals.

Park [103] highlights the adoption of mineral certification programs, such as the Responsible Cobalt Initiative, as a means to establish transparent supply chains. However, challenges persist in ensuring the credibility of certification processes. Certain minerals are associated with conflicts in their production regions [104,105]. Ensuring that supply chains are free from conflict minerals requires diligence and collaboration throughout the supply chain. Achieving traceability not only at the mining site but also throughout the downstream supply chain presents logistical challenges, necessitating industry-wide coordination. Increasing consumer awareness regarding responsibly sourced minerals can drive demand for ethical mining practices, but effectively communicating these efforts throughout the supply chain remains a challenge.

4.8. Lifecycle assessments

Conducting comprehensive lifecycle assessments to assess the environmental impact of mining operations requires significant effort and resources. Obtaining accurate data for a holistic evaluation is challenging. Information on the frequency of lifecycle assessments within the mining industry and their outcomes reveal the difficulties in quantifying and addressing environmental footprints [106,107]. Such assessments are instrumental in identifying areas for improvement and gauging the success of sustainability initiatives.

Access to data on energy consumption, emissions, and waste generation throughout the lifecycle is crucial. Defining the boundaries of a lifecycle assessment, whether it includes only direct mining activities or extends to downstream processing and product use, poses challenges in standardizing assessments. Variability in assessment methodologies can hinder the comparability of lifecycle assessments. Standardizing assessment protocols facilitates meaningful comparisons across mining operations. Lifecycle assessments should be ongoing exercises; the challenge lies in establishing mechanisms for continuous improvement based on assessment findings.

4.9. Mine closure and rehabilitation

Planning for mine closure and implementing effective rehabilitation strategies are often overlooked aspects of sustainable mining [96]. Ensuring that closed mines leave a minimal environmental footprint is a significant challenge. Studies on mine closure practices and their environmental outcomes highlight the challenges and successes in this crucial phase [108,109]. Inadequate closure planning can lead to long-term environmental liabilities, making it essential to establish funds for post-closure environmental management despite the inherent challenges. Rehabilitating ecosystems affected by mining activities requires comprehensive planning. Key challenges include soil stabilization, revegetation, and restoring natural water courses.

Managing stakeholder expectations regarding mine closure is equally crucial. Local communities, environmental groups, and regulatory bodies often have distinct expectations that must be reconciled. Continuous monitoring of closed mine sites is essential to ensure the success of rehabilitation efforts. Establishing monitoring mechanisms poses logistical and financial challenges.

4.10. Industry collaboration

Achieving widespread adoption of green mining practices requires collaboration across the industry. Competitiveness and reluctance to share best practices can hinder progress toward sustainable mining. Collaborative initiatives, joint ventures, and information-sharing platforms of the mining industry provide valuable insights into collective efforts toward sustainability. Such collaboration fosters a more unified and effective approach to addressing environmental challenges.

Sharing best practices and successful green initiatives can accelerate the adoption of sustainable mining practices. However, overcoming competitive barriers to sharing proprietary information remains challenging. Collaborative research and development efforts can yield innovative solutions for sustainable mining, but the competitive nature of the industry can impede open collaboration. Williams [109] highlights the crucial role of governments in incentivizing and regulating sustainable mining practices. Establishing effective partnerships between governments and the mining industry requires aligning interests and goals.

Fig. 4 summarizes the processes and challenges discussed, presenting a simple framework for the comprehensive implementation and adoption of green mining practices and near-zero carbon emission processes in the mining industry.

4.11. Internal factors

(1) Organizational culture. The adoption of green mining technologies is heavily influenced by the prevailing organizational culture within a mining company. Companies that value innovation and environmental stewardship are more likely to embrace green technologies. Conversely, a culture resistant to change or heavily invested in traditional mining methods may impede the adoption of new sustainable practices. Assessing how organizational culture either supports or hinders technological adoption is crucial.
(2) Internal resistance. Resistance from within, whether from management or operational staff, can be a significant barrier to the adoption of green technologies. This resistance often stems from a lack of understanding of the benefits, fear of job loss, or apprehension toward learning new methods. Overcoming this resistance requires strategies such as training programs, clear communication of the benefits, and involving staff in the transition process.
(3) Technological integration and infrastructure compatibility challenges. Integrating new technologies into existing mining operations poses substantial challenges. These include retrofitting old equipment with new technologies, ensuring compatibility of new systems with existing processes, and managing potential disruptions to ongoing operations. The existing infrastructure of a mining operation may either facilitate or hinder green technology integration. For example, older mines might need substantial modifications or upgrades to accommodate new systems, which can be costly and complex. Analyzing the state of current infrastructure and its readiness for adaptation is crucial. Case studies or examples of successful integrations can provide valuable insights into overcoming these obstacles.
(4) Leadership and commitment. Leadership plays a critical role in driving the adoption of green technologies. A committed leadership team can effectively champion the cause, secure necessary investments, and foster an organizational environment conducive to change. Without strong leadership endorsement, sustainability initiatives may lack direction and urgency, leading to piecemeal or ineffective implementation.
(5) Financial constraints. Financial resources greatly influence a company's ability to adopt new technologies. The initial cost can be substantial, and without a clear financial strategy or sufficient

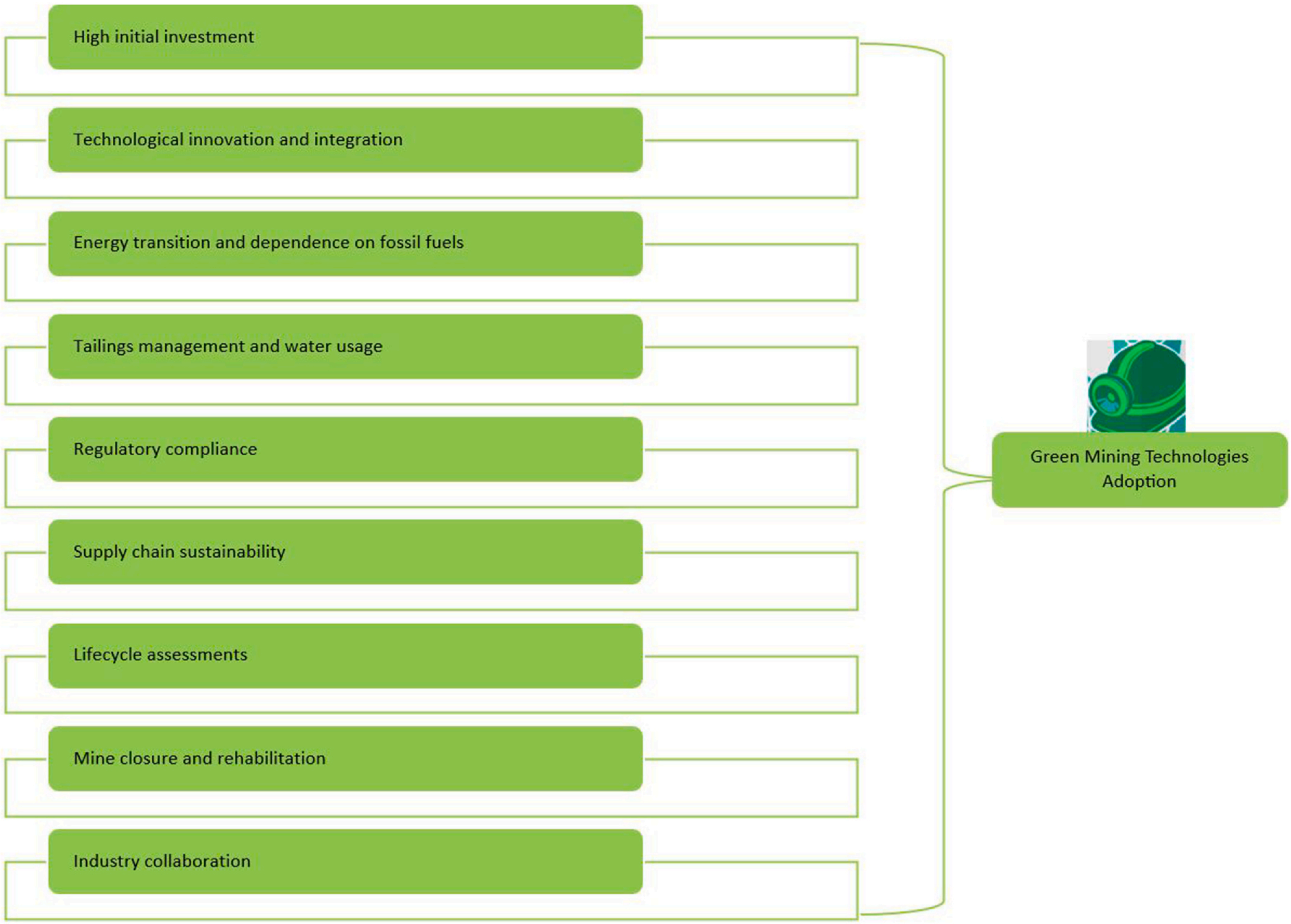

Fig. 4. Framework for green mining technology adoption.

budget allocation, the transition can be slow or unfeasible. Analyzing how financial constraints impact the decision-making process regarding investment in green technologies is essential.

(6) Technical expertise and training. The availability of technical expertise and the level of employee training are significant internal factors in adopting green technologies. This shift often requires new skills and knowledge, presenting challenges in sourcing skilled labor or necessitating substantial investment in training the existing workforce to handle new equipment and adhere to new processes.

(7) Risk management and adaptability. A company's ability to manage risks associated with new technologies affects the adoption of green technologies. Risk-averse companies might hesitate to implement new systems until they are proven, potentially missing early opportunities for improvement. Conversely, companies with a strategic approach to risk management might navigate these challenges more effectively.

(8) Internal stakeholder engagement. Engaging internal stakeholders such as employees, managers, and board members is essential for successful technology adoption. Involving these stakeholders in decision-making can mitigate resistance by addressing their concerns and considering their insights.

(9) Strategic alignment. The degree to which new technologies align with a company's strategy significantly impacts their adoption. Technologies that clearly support long-term goals are more likely to receive backing from decision-makers. It is important to analyze how well green mining technologies align with the overall strategy and objectives of the company.

5. Prospects of green mining technologies

5.1. Technological advancements

The future of green mining technologies is promising, driven by ongoing technological advancements. Innovations such as AI-driven analytics, advanced sensors, and automation are poised to revolutionize mining operations. These technologies enhance efficiency, reduce environmental impact, and enhance workplace safety. AI applications enable predictive maintenance, optimize processes, and enhance decision-making [22,110,111]. Machine learning algorithms, which learn from historical data, progressively enhance efficiency and reduce resource consumption.

The study by Molaei *et al.* [112] shows that advancements in sensor technologies, including IoT-enabled devices and real-time monitoring systems, significantly boost data collection capabilities within the mining industry. This enables better environmental monitoring and resource management. Increased automation, featuring autonomous vehicles and robotic systems, enhances safety, reduces human exposure to hazardous environments, and contributes to more sustainable operations. Future mining operations are expected to increasingly integrate renewable energy sources. Fig. 5 represents the various green mining technologies and associated factors driving the industry's future. These include circular economy principles, green materials and processes, decentralized and modular mining, ecosystem restoration and biodiversity conservation, stakeholder engagement and transparency, government incentives and regulations, global collaboration for sustainable mining, and green finance and investment.

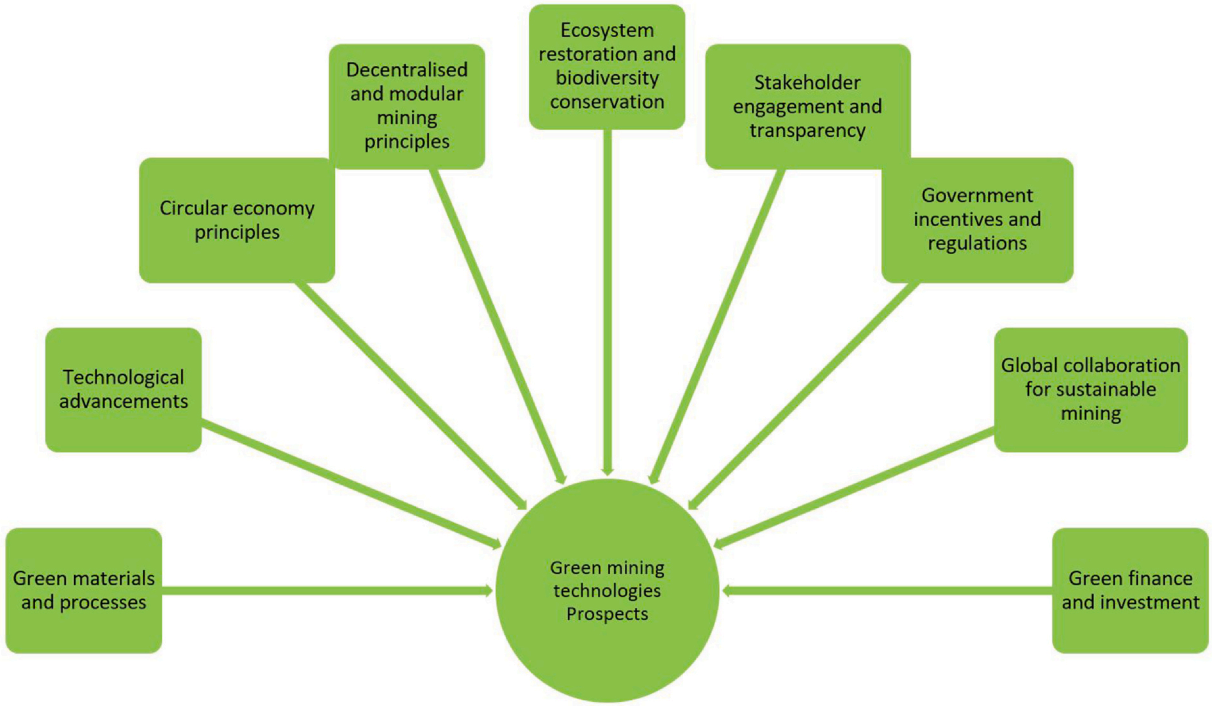

Fig. 5. Roadmap for green mining technology prospects.

5.2. Circular economy principles

Adopting circular economy principles is a key aspect of future green mining. This approach emphasizes minimizing waste, promoting recycling, and extending material lifespan. By implementing circular mining practices, companies can enhance resource efficiency and reduce environmental impact [59,113–116]. Future mining operations are likely to incorporate advanced recycling technologies to extract valuable materials from mining waste, thereby reducing the need for additional resource extraction.

The integration of waste-to-energy solutions, where mining by-products are utilized for energy generation, is also anticipated. This approach minimizes the environmental impact of waste disposal. Future regulations may emphasize extended producer responsibility, requiring mining companies to manage the entire lifecycle of their products. This would encourage sustainable practices from extraction to disposal.

5.3. Green materials and processes

The mining industry's shift toward green materials and processes is a significant trend for the future. This involves exploring alternatives to traditional materials and adopting environmentally friendly processing methods to reduce ecological footprints. Research and development in eco-friendly mining chemicals aim to replace traditional, environmentally harmful substances. These green alternatives are expected to gain traction for mineral processing.

Future mining operations will focus on minimizing water usage through advanced technologies such as dry processing methods and innovative water recycling systems [117–119]. The demand for sustainable construction materials, including responsibly sourced aggregates and metals, is expected to rise. Mining companies will adapt by adopting practices that align with green construction trends. Additionally, mining processes with lower carbon footprints, such as bioleaching and hydrometallurgy, will gain prominence. These processes minimize the environmental impact associated with traditional extraction methods.

5.4. Decentralized and modular mining

According to Sishi and Telukdarie [119], the future of green mining envisions decentralized and modular mining operations. This approach involves deploying smaller, modular mining units closer to mineral sources, reducing the need for large-scale, centralized operations. Decentralized mining operations consisting of smaller, localized units strategically reduce transportation costs and environmental impact. Modular mining systems require less infrastructure and can be easily scaled based on demand [120], thereby decreasing the environmental impact associated with extensive mining infrastructure.

Decentralized mining allows for better resource efficiency, as operations can be tailored to specific mineral deposits, minimizing energy and resource wastage. This shift supports community-focused initiatives, integrating mining activities sustainably into local economies.

5.5. Ecosystem restoration and biodiversity conservation

Future green mining practices will emphasize ecosystem restoration and biodiversity conservation. Mining companies will increasingly engage in initiatives to restore landscapes, preserve biodiversity, and offset environmental impacts. According to a study conducted by Worlanyo and Jiangfeng [121], mining companies need to invest in large-scale reforestation programs to restore ecosystems impacted by mining activities. These initiatives contribute to carbon sequestration and habitat restoration. Collaboration with environmental organizations and conservation agencies will become more common as mining companies will actively participate in initiatives to protect and preserve biodiversity.

Future mining projects will incorporate sustainable land use planning, ensuring that mining activities coexist with natural ecosystems without causing irreparable damage. The establishment of conservation banks, where mining companies invest in protected areas to offset environmental impacts, is a prospective trend that aligns with biodiversity conservation goals.

5.6. Stakeholder engagement and transparency

The future of green mining will prioritize enhanced stakeholder engagement and transparency. Mining companies will actively involve local communities, environmental groups, and regulatory bodies in decision-making processes, fostering trust and support. Future mining projects will undergo comprehensive social impact assessments, addressing community concerns, cultural sensitivities, and potential impacts on livelihoods.

Mining companies will adopt transparent reporting practices, providing stakeholders with detailed information on environmental performance, sustainability initiatives, and adherence to regulatory standards [57,122,123]. Collaborative efforts with non-governmental organizations (NGOs) will increase, as partnerships with environmental NGOs can provide valuable insights and support for green initiatives. The integration of technology to gather and respond to community feedback will become standard practice, with digital platforms enhancing communication and transparency.

5.7. Government incentives and regulations

Governments are expected to play a pivotal role in shaping the future of green mining through incentives and regulations. Observations from the study by Raufflet *et al.* [124] indicate that future policies will likely encourage sustainable practices, penalize non-compliance, and promote innovation in the mining sector. Governments may introduce financial incentives, tax breaks, or subsidies for mining companies adopting green technologies and sustainable practices, thereby encouraging industry-wide adoption.

Anticipated regulations will likely include stricter environmental standards, emission limits, and requirements for green technology adoption. Non-compliance could result in penalties and operational restrictions. Furthermore, governments may allocate funds for research and development in green mining technologies, driving innovation and accelerating sustainable practice adoption. Multi-stakeholder platforms, bringing together industry representatives, environmental experts, and community leaders, may be established to collaboratively shape policies for sustainable mining.

5.8. Global collaboration for sustainable mining

The future of green mining involves increased global collaboration [125,126]. Mining companies, industry associations, and governments from different countries will work together to share best practices, address global environmental challenges, and promote sustainable mining on a global scale. The establishment of international sustainability standards for mining practices is foreseeable, providing a common framework for assessing and improving environmental performance globally.

Mining companies will actively participate in knowledge exchange programs, sharing insights and best practices with counterparts in different regions to foster a global culture of sustainability. Collaborative research initiatives between mining companies and research institutions on a global scale will also increase. Global collaboration will focus on addressing overarching environmental challenges, such as climate change mitigation, responsible resource extraction, and minimized ecological footprints.

5.9. Green finance and investment

Xiao *et al.* [127] highlight the significant role that green finance and investment will play in shaping the future of sustainable mining. Financial institutions, investors, and mining companies will increasingly prioritize projects that align with environmental and social sustainability goals. Investors are expected to incorporate sustainability criteria into their decision-making processes, making green mining projects more attractive to socially responsible investors.

Mining companies may explore issuing green bonds and other sustainable financing instruments to support environmentally responsible initiatives. These financial mechanisms make it easier to fund environmentally responsible projects. Financial institutions will view sustainability as a risk mitigation strategy, recognizing that green mining practices can reduce long-term environmental liabilities and enhance financial viability. Environmental, social and governance reporting will become standard for mining companies seeking financial support as transparent reporting on sustainability efforts enhances investor confidence.

6. Implications of the study's findings for the mining industry and sustainability efforts

The study reveals several significant findings with broad implications for the mining industry and global sustainability efforts. Integrating green technologies into mining not only addresses immediate environmental concerns but also offers substantial benefits in regulatory compliance, economic efficiency, and industry leadership in sustainability. This positions the mining industry at a pivotal point where it can spearhead global efforts in industrial sustainability, influencing broader ecological and economic domains. Below are some key implications based on the study findings.

6.1. Reduction in environmental impact

Lower carbon emissions. The study demonstrates that the adoption of green mining technologies, such as electric vehicles and renewable energy sources, can result in up to a 30% reduction in carbon emissions. This is particularly crucial for an industry traditionally known for high GHG emissions. A systematic reduction in carbon emissions can help mining companies meet international climate targets and reduce their environmental footprint.

Energy efficiency. A 25% reduction in energy usage was reported in the study, showcasing that green technologies offer a compelling case for energy optimization in mining operations. Enhanced energy efficiency not only reduces operational costs but also minimizes the strain on local energy supplies, which is particularly important in regions with limited energy infrastructure.

6.2. Regulatory compliance and enhanced reputation

As global environmental regulations become stricter, adopting technologies that reduce emissions and energy consumption can help mining companies maintain compliance with environmental laws and avoid penalties. Furthermore, embracing sustainability can enhance a company's reputation, strengthening its social license to operate within communities and with governmental bodies.

6.3. Economic benefits and investment attraction

The initial findings indicate that despite the upfront costs, long-term savings from reduced energy expenses and lower carbon tax liabilities make investments in green technologies economically viable. These economic benefits could attract investors who are increasingly interested in funding environmentally responsible and sustainable projects, especially in a global market that is progressively more sensitive to ecological and sustainability concerns.

6.4. Sustainability in the supply chain

Implementing green mining practices encourages a more sustainable supply chain. For example, by reducing the reliance on diesel and integrating electric vehicles, mining operations can significantly decrease their dependency on fossil fuels. This change can have a cascading effect throughout the supply chain, prompting suppliers and partners to also adopt greener practices.

6.5. Technological innovation and industry leadership

Adopting advanced green technologies allows mining companies to contribute to environmental sustainability while positioning themselves as leaders in technological innovation. This leadership can drive further research and development in the sector, leading to the creation of new, more efficient technologies that continue to improve mining operation sustainability.

6.6. Community and stakeholder engagement

Improved environmental practices can foster better relationships with local communities, governments, and environmental groups. Demonstrating a commitment to reducing environmental impact can ease tensions and foster cooperation between the mining sector and its wider community of stakeholders.

6.7. Global impact and scalability

The scalability of green mining technologies could have a global impact. As more companies observe the successful technology implementation, the model could be replicated worldwide, leading to significant reductions in the global environmental footprint of the mining industry.

7. Limitations, key insights, implications for future research and practice, and novel perspectives of the study

While the study provides a robust analysis of the integration and efficacy of green mining technologies, several limitations need to be acknowledged, which could serve as the basis for future research. A notable limitation is the geographic and operational diversity of the mining sites studied, which may affect the generalisability of the findings. Variability in regulatory environments and technological maturity across different regions suggests that the observed outcomes may not be universally applicable. Furthermore, while the study effectively captures quantitative data on environmental and operational metrics, it less thoroughly explores qualitative aspects such as miner health, community satisfaction, and long-term ecological impacts. Future research could focus on these socio-economic and ecological dimensions to provide a more holistic understanding of the implications of green mining technologies. The study also opens several avenues for practical applications and further investigation, as detailed below.

(1) Policy development. Insights from this study could inform policymakers in crafting targeted regulations that encourage green technology adoption in mining. Specific incentives could be developed to support mining companies in transitioning to greener practices.
(2) Technological innovation. The study highlights the need for continued innovation in green technologies. Future research could explore the development of more cost-effective and efficient green technologies that could further reduce environmental impacts while enhancing economic viability.
(3) Stakeholder engagement. Enhanced stakeholder engagement strategies are among the practical implications of this study. Mining companies should prioritize robust community involvement and transparent reporting practices to improve the social acceptance of their activities.

The study introduces several novel perspectives that enrich our understanding of green mining. Using a mixed-method approach, it quantifies the environmental benefits of green technologies in mining by combining quantitative environmental data with qualitative stakeholder insights. It also explores the economic implications of green technologies beyond mere environmental impact, highlighting their potential to reduce operational costs and enhance the long-term sustainability of mining operations. Additionally, the study discusses the scalability of green mining practices, suggesting that while significant progress has been made, substantial challenges remain in achieving widespread adoption. Subsequent research can significantly advance sustainable mining by addressing the limitations of the study and building on the novel perspectives provided.

8. Discussion and concluding remarks

Mineral exploration is a critical industry driving global economic growth by supplying essential minerals for construction, energy production, and transportation. However, its environmental, social, and economic impacts are extensive, including GHG emissions, water and land use, and community engagement. Governments, the public, and investors are increasingly prioritizing sustainable development and the transition to a low-carbon economy to combat climate change and environmental degradation. The mining sector plays a pivotal role in this green transition, particularly in providing minerals essential for energy storage devices such as solar panels and wind turbines.

The industry faces challenges such as reducing GHG emissions, enhancing energy efficiency, and mitigating environmental impacts. Within the context of the green transition, there are both opportunities and hurdles for exploration and mining companies. While there is a growing demand for minerals crucial to the shift toward a low-carbon economy, there is also mounting pressure to adopt sustainable practices to minimize adverse effects on society and the environment.

The mining industry is making strides toward a greener future through initiatives like hybrid underground vehicles, portable rigs, and eco-friendly copper leaching methods. Major mining firms are investing in technologies to improve safety and environmental cleanliness, utilizing innovative methods to reduce energy and water consumption. These efforts minimize environmental contamination and aid in site remediation post-mining.

Integrating green technologies into mining practices signifies a profound commitment to sustainability. As the industry strives to meet rising global demand while reducing its ecological footprint, the adoption of electric vehicles, automation, and sustainable practices emerges as a transformative trajectory. This journey toward green mining requires ongoing research, collaboration, and innovation to develop its full potential.

While challenges persist, the mining industry's dedication to innovation and environmental stewardship positions it for a future where mining and ecological conservation are harmonized. Overcoming these challenges necessitates concerted efforts from the industry, governments, and stakeholders. The transition to sustainable mining practices is imperative for the industry's long-term viability, demanding strategic approaches, collaboration, and continuous improvement.

As technology advances and environmental awareness grows, the mining sector must adapt to meet evolving expectations. The interconnected challenges underscore the need for holistic solutions, addressing economic, environmental, and social dimensions simultaneously. By confronting these challenges, the mining industry can not only minimize its environmental impact but also contribute positively to the communities it serves. Green mining practices are essential in ensuring sustainable operations that ensure miners' safety, sound financial returns and environmental protection. Despite its rich benefits, the transition to green mining is time-consuming, expensive, and complex. In summary, this article has identified key challenges and proposes solutions for transitioning to green mining as follows:

(1) Complex integration of modern technology. Green mining heavily relies on modern technology for decision-making, process automation, and clean energy utilization. Integrating these technologies into one system is not only expensive but also poses several risks, such as cyber-attacks, reliability issues, and efficiency concerns. While several studies have proposed the need to leverage technology for automation, few have explored its potential shortcomings. Addressing these challenges is crucial to affirm the relevance of technology in advancing green mining.
(2) Logistics of using clean energy systems. Several studies report GHG emissions from diesel-powered engines and suggest transitioning to cleaner energy alternatives such as solar and wind energy. However, few studies have reported the complexities of storage and grid integration with existing power grids, which can be technically demanding. More research is needed to explain how such an energy-intensive sector can operate using renewable energy. Furthermore, studies should focus on understanding the necessary infrastructure to meet such energy demands and ensure a continuous energy supply.
(3) Financial mechanisms. Adopting green mining practices requires hefty upfront financial investment, which can be difficult to secure owing to higher risks associated with novel technologies and sustainability initiatives. While previous studies recommend governmental incentives for mining companies, there is a need for robust financial models that formulate appropriate rates of returns, payback periods, and risk-sharing models, and determine the probability of making losses, and financial reconciliation under such new circumstances. Additionally, new models need to be developed to factor in fluctuating commodity prices, technological advancements, and regulatory changes.
(4) Development of robust environmental monitoring and reporting systems. Environmental protection is key to achieving green mining, yet standardized protocols and technologies for real-time tracking of indicators such as GHG emissions, water usage, waste management, and ecosystem services are lacking. Ensuring accurate and transparent data collection is important not only for regulatory compliance but also for stakeholder engagement, such as funding bodies, surrounding communities, and research institutions. Therefore, it is crucial to develop such a model that can ensure a continued environmental monitoring system.

CRediT authorship contribution statement

Moshood Onifade: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft preparation, Writing – review and editing, Supervision. **Tawanda Zvarivadza**: Conceptualisation, Methodology, Formal analysis, Investigation, Writing – original draft preparation, Writing – review and editing. **John A. Adebisi**: Formal analysis, Writing – review and editing, Visualization. **Khadija Omar Said**: Formal analysis, Investigation, Writing – review and editing. **Oluwatobi Dayo-Olupona**: Investigation, Writing – review and editing, Visualization. **Abiodun Ismail Lawal**: Methodology, Formal analysis, Writing – review and editing. **Manoj Khandelwal**: Formal analysis, Writing – review and editing, Supervision.

Declaration of Competing Interest

Manoj Khandelwal is an editorial board member for this journal and was not involved in the editorial review or the decision to publish this article. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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