ENVIRONMENTALLY SUSTAINABLE MINING

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Sustainability science and solution, master's thesis

2025

BENJAMIN OKYERE

Examiners: Professor Mika Horttanainen

Dr. Mariam Abdulkareem, DSc

ABSTRACT

LAPPEENRANTA–LAHTI UNIVERSITY OF TECHNOLOGY LUT

Degree Programme of Environmental Technology

Master's Programme in Sustainability Science and Solution

Benjamin Okyere

ENVIRONMENTALLY SUSTAINABLE MINING

Master`s Thesis

2025

49 pages, 1 figure and 2 table

Examiners:

Professor Mika Horttanainen and Dr. Mariam Abdulkareem, DSc

Keywords: Sustainable mining, pollution control and waste management.

The increasing demand for natural resources has intensified pressure on the mining sector to adopt more sustainable practices. This study examines global sustainable mining approaches, with a specific focus on pollution control, energy efficiency, and waste management. Using a systematic literature review of 16 studies published between 2015 and 2025, thematic analysis revealed that technologies such as automation, closed-loop water systems, and artificial intelligence significantly reduce environmental impacts. However, adoption is hindered by weak policy enforcement, limited financial resources, and strategic misalignment. Drawing from Finnish case studies, the research identifies robust regulatory frameworks and industry innovations that have driven more sustainable outcomes. The study recommends strengthening environmental regulations, investing in green technologies, and promoting stakeholder engagement and circular economy models to facilitate more sustainable mining globally.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisors for their support and constructive feedback throughout the course of this study. I am also thankful to the academic staff and administrative team at Lappeenranta–Lahti University of Technology LUT for providing the resources and environment needed to complete this thesis.

Special thanks to my family and friends for their invaluable support and encouragement.

SYMBOLS AND ABBREVIATIONS

ESG – Environmental, Social and Governance

SDG – Sustainable Development Goals

LCA – Life Cycle Assessment

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses

EU – European Union

EIA – Environmental Impact Assessment

CWA – Clean Water Act

CAA – Clean Air Act

Table of Contents

ABSTRACT 2
ACKNOWLEDGEMENTS 3
SYMBOLS AND ABBREVIATIONS 4
1. Introduction 7
1.1. Objectives and Research Questions 8
1.2. Significance of study 9
2. An Overview of the Global Mining Industry 11
2.1. The Finnish Mining Industry 14
3. Methodology 18
3.1. Research Design 18
3.2. Data Sources and Search Terms 19
3.3. Inclusion and Exclusion Criteria 21
3.4. Bias 22
3.5. Data Extraction 23
3.6. Data Analysis 25
4. Thematic Analysis 26
4.1. General Findings 26
4.2. What techniques are mostly used to minimize air, water, and soil pollution during mining operations? 31
4.2.1. Procedural Interventions 31
4.2.2. Regulatory Interventions 32
4.2.3. Technological Interventions 32
4.3. How effective are these tools in reducing environmental impacts? 33
4.3.1. Effectiveness of Environmental Management Tools and Interventions 34
4.4. What challenges hinder the implementation of sustainable mining practices, and what potential solutions can address these challenges? 35
4.4.1. Challenges and Barriers to Sustainable Mining 35
4.5. Which case studies from Finnish mines demonstrate successful pollution reduction strategies? 36
4.5.1. Environmental Sustainability in Finnish Mining 36

5. Conclusion 38
6. Recommendations 39
References 40

List of Figures

Figure 1: PRISMA Flowchart 24

List of Tables

Table 1: Data Source Queries 20
Table 2: Primary Findings 27

1. Introduction

The rising importance of environmental, social, and governance (ESG) frameworks, alongside a surge in eco-conscious advocacy from significant internal and external stakeholders, has altered corporate priorities across various industries in recent years (Li et al., 2021). This shift is particularly pronounced in sectors with high resource consumption, intricate value chains, and substantial environmental impacts (Daugaard, 2019). The mining industry exemplifies such a sector, yet its practices have often been associated with issues like biodiversity loss, large-scale land degradation, water pollution, and socioeconomic challenges (Witchalls, 2024). For years, companies in this field have navigated the delicate balance between economic benefits and the social and environmental costs of extraction. However, with the current shift in the global business environment, these firms face mounting pressure from key stakeholders to adopt sustainable mining practices within their operations (Tost et al., 2018). This need is not only regulatory but also an ethical and strategic requirement for many companies in the sector.

Exploring this area of literature is a valuable endeavour, as it clarifies the current direction of sustainable mining practices and offers tools for evaluating their effectiveness and identifying potential implementation gaps. Nevertheless, the existing literature presents a mixed perspective on sustainable mining practices. In his influential paper, Kirsch (2009) claimed that sustainable mining is simply a corporate oxymoron used by companies to deflect criticism and hide harm while prioritising profits and economic growth over environmental responsibility. In contrast, more recent authors assert that sustainable mining practices can effectively enhance operations within the industry. Monteiro et al. (2019) identified sustainable mining as a crucial means of achieving the 17th sustainable development goal (SDG) by fostering jobs, income, and environmental enhancements. Likewise, Asr et al. (2019) suggest that integrating sustainable development principles throughout the mining life cycle can yield projects that are environmentally sustainable, economically viable, and socially responsible within the sector.

Within the Eurozone, Finland's role in the mining sector cannot be disputed. The country boasts a rich natural resource base, with substantial deposits of gold, copper, chromium, zinc and cobalt to boot. This makes the country an essential player in Europe's strategic objective for achieving

mineral self-sufficiency and boasting economic sovereignty in the global resource market. It therefore stands to reason that issues pertaining to sustainable mining will be of critical concern to the country's key policy-making bodies. Similarly, countries like the Netherlands, Poland and Norway are all strategically positioned to leverage their vast natural resource base to expand their market influence and meet Europe's ever-increasing resource needs for both residential and industrial purposes.

The EU has made substantial pledges towards reducing the bloc's net greenhouse gas emissions by 90% by 2040 relative to 1990 (European Commission, 2023). Thus, generating insights into pathways that key players within the mining industry can take to promote sustainability. Similar parallels are shared among the world's most resource-rich regions. For example, countries like Canada, Australia, Saudi Arabia, China and Chile are all embarking on substantial overhauls of their traditional mining dynamics to accommodate their newfound ecological concerns. Thus, issues relating to sustainability within extractive industries have far-reaching global implications that require prompt redress if international ecological accords such as the Paris Agreement are to be realised.

Accordingly, this study seeks to comprehensively review sustainable mining practices by evaluating pollution control, energy efficiency and waste management through the lenses of the theoretical and empirical literature, providing a systematic approach to evaluating the environmental impacts of mining operations from resource extraction to waste management and site rehabilitation. By identifying areas for improvement, LCA helps mining companies enhance sustainability efforts, optimise resource use, and minimise negative environmental and social effects (Segura-Salazar et al., 2019). Additionally, this study will examine how these strategic interventions influence circular economy principles within the specified contexts.

1.1. Objectives and Research Questions

This study primarily aims to investigate environmentally sustainable mining practices by identifying and assessing techniques that reduce air, water, and soil pollution in mining operations. It will analyse case studies from mines that have effectively implemented pollution reduction

strategies and achieved their sustainability targets. Furthermore, the study will investigate the use of energy-efficient technologies and renewable energy sources in mining, assessing their effect on operational efficiency. Finally, it will explore methods for minimising, recycling, and repurposing mining waste.

The overarching goal of this research is to explore sustainable mining practices globally by identifying and evaluating techniques that improve operational efficiency while minimising environmental impact. The study will identify, examine, and explore practised sustainable mining strategies across different regions. Specifically, the study aims to answer the following questions:

- What techniques are mostly used to minimise air, water, and soil pollution during mining operations?
- How effective are these tools in reducing environmental impacts?
- What challenges hinder the implementation of sustainable mining practices, and what potential solutions can address these challenges?
- Which case studies from Finnish mines demonstrate successful pollution reduction strategies?

1.2. Significance of study

This research holds immense potential for all key stakeholders in the mining sector. The generated insights will be a critical step towards enhancing the sustainability efforts of policymakers, mining companies and environmental advocacy groups. This study will also provide primary policy-making bodies with the needed empirical evidence for evaluating the current state of sustainable mining practices within their jurisdiction and assessing their progress towards achieving the climate goals set by the European Commission and other international economic collectives. Considering the strategic position of the mining sector within the Eurozone, the European Union's ambitious commitment to reducing greenhouse gas substantially by 2040 is contingent on the ability of key players within the sector to adopt sustainable practices. Thus, cognisance of effective pollution control measures, energy-efficient mechanisms and robust waste management

technologies is paramount. Accordingly, the insights generated from this study will provide a strong foundation for informing the relevant decision-makers in crafting effective regulations, sustainability frameworks and incentive structures for promoting environmental stewardship and socio-economic resilience within the international mining sector.

Given the parallels the Finnish mining sector shares with those of other European countries and global markets, it is well within range to argue that extractive industries within the region will benefit from this study by gaining a deeper understanding of the implications of sustainable mining practices within a real-world context. Critically assessing case studies of Finnish mines that have successfully implemented sustainability measures will enable other firms within the region to benchmark their operations against industry leaders which have adopted efficient pollution control, energy efficiency and waste management mechanisms. Other international contexts will also be explored to critically examine the global perspectives inherent in sustainable mining and unearth the requisite insights for formulating policies that address ecological concerns within the industry.

All said, from an academic viewpoint, this research will contribute to the ongoing discourse of sustainable mining practices in advanced economies. It addresses gaps in assessing this stream of literature within the context of the global mining industry. By assessing the techniques used in the circular economy, pollution control, energy efficiency and waste management, this research provides an essential avenue for providing invaluable theoretical and empirical insights that contribute to the epistemology of sustainable resource management, further advancing the scholarly appreciation of the interplay that exists between economic activity and environmental sustainability in high-impact industries like mining.

2. An Overview of the Global Mining Industry

Mining refers to the extraction of key subterranean resources such as metals, minerals, and fossil fuels. It serves as a crucial mechanism for producing essential geographical materials required to sustain everyday life and power industries (Ismail et al., 2021). Thus, it is no surprise that this sector is a fundamental facet of virtually every contemporary economy, providing the necessary resources to facilitate the operations of numerous downstream industries, such as manufacturing, energy production, technology, and construction (Hresc et al., 2018). Global mining activity can be polarised into two broad categories: small-scale mining (largely labour-intensive with informal mining practices and limited regulation but yielding substantial economic impacts within countries, mainly prevalent in emerging economies with a large natural resource base) and large-scale/industrial mining (capital-intensive mining operations driven largely by multinational corporations) (Kemp & Owen, 2019). These activities can be further broken down based on extraction method, resource type, and industrial subdivision.

The overall mining industry can be polarised into two main segments: metallic mineral mining and industrial mineral mining. Metallic mineral mining focuses on the extraction of valuable metals such as cobalt, copper, lithium, gold and zinc (Liu et al., 2022). This segment is imperative to the value chains of industries like renewable energy, electronics and automotive manufacturing. Additionally, these metals are used to produce high-performance, speciality alloys that are used in advanced industries such as aerospace engineering and construction (Mitra, 2018). On the other hand, industrial mineral mining focuses on the extraction of non-metallic minerals such as quartz, limestone, phosphate, and feldspar (Kolala and Dokowe, 2021). These outputs are essential for the manufacturing of products such as cement, glass, ceramics and even fertiliser, supporting sectors like agriculture and chemical manufacturing (Von Der Goltz and Barnwal, 2018).

In mining, extraction methods generally refer to the techniques employed in retrieving rare-earth metals or other geological materials from the subterranean deposits. One of these methods is surface mining. Here, minerals are retrieved near the Earth's surface. For example, strip mining involves removing large strips of rock to reveal the underlying mineral deposits. Miners tend to use this method when mineral deposits are in horizontal beds close to the surface (Patra et al.,

2016). Examples of mined resources that use this method are coal and lignite. Open pit mining, on the other hand, involves the creation of a large, terraced pit which is used to gain access to ore deposits, located relatively close to the surface (Altiti et al., 2021). Miners tend to use this method when mineral deposits are distributed vertically and widely. This makes it extremely difficult to access using underground tunnels. Thus, open pits serve a critical purpose. They are used to create successive layers or benches, which allow the safe and efficient retrieval of ore while limiting the cost implications of the mining project (Shestakov & Zuenko, 2024).

Underground mining is used to extract minerals from deep beneath the Earth's surface. This process involves creating extensive tunnel systems and sophisticated shafts that allow miners to reach mineral deposits too impractical to retrieve with surface mining methods (Ghorbani et al., 2022). To utilise this method, miners must drill, use explosives for blasting, and transport the extracted materials to the surface for processing. Other extraction techniques include placer mining, which involves extracting alluvial deposits using water, and solution mining, which retrieves water-soluble minerals by dissolving them and pumping the resulting solution to the surface.

Global mining operations can also be classified based on the resources they extract. For example, the oil and gas industry focus on the exploration, discovery, and extraction of crude oil and natural gas from underground reservoirs (Nourelfath et al., 2022). This sector plays a critical role in fuelling key industries such as production and manufacturing. The major global players within the oil and gas industry are ExxonMobil, BP, Shell, and Saudi Aramco, all of whom operate extensive production networks around the world.

With coal mining, emphasis is placed on the retrieval of coal deposits from subterranean sources. These resources are used primarily for fuel generation and are mined using near-surface techniques such as strip mining (Williams & Nikijuluw, 2020). Key players within this industry include Peabody Energy, Glencore and China Shenhua Energy Company. Non-metallic mineral mining, on the other hand, involves the extraction of non-metallic minerals such as potash, gravel and limestone (Korczak et al., 2022). Understandably, this industry generates essential inputs for industries such as agriculture and construction. The dominant global players in this sector are LafargeHolcim and HeidelbergCement.

It is therefore not surprising that mining generates a considerable amount of value in the global economy. The sector not only contributes immensely to the gross domestic product (GDP) of national economies, but it is also an invaluable source of employment, infrastructural development and raw material production. As a result, many core industries are dependent on the operations and sustainability of the extractive sector. According to Escamilla (2024), it contributes approximately $1.9 trillion to the global economy annually. This underscores its significant role in supporting contemporary industries and fuelling economic development. In the world's biggest economy, the United States, mining accounted for an estimated 1.4% of total GDP in 2023 (Nanchalal, 2024), while its northern neighbour, Canada, generated $109 billion from its minerals and metals sector, representing 6% of its total GDP (Government of Canada, 2025).

In resource-endowed developing countries, the economic impact of mining is more pronounced. According to Ali (2024), it often accounts for, on average, 10 – 20% of national GDP, and goes up to 50% of total exports, especially in sub-Saharan African countries. Thus, the sector is an indispensable driver for both economic growth and sustainability, providing local governments with essential sources of foreign exchange earnings, employment and market influence (Karakaya & Nuur, 2018). Moreover, mining these natural resources and their eventual sale helps the government generate revenue through both direct and indirect taxes, as well as royalties and licensing fees. Together, these funding avenues provide the pecuniary resources for financing national development projects in essential areas like education, health and infrastructure.

Employment is yet another critical dimension that is continually being sustained through the operations of key actors in the mining industry. From mining operations that create direct jobs in exploration, extraction, and processing, to the indirect jobs created by the economic partnerships between the extractive industry and the transportation, manufacturing and construction sectors (Gräser, 2024), mining plays an essential role in sustaining the livelihoods of millions of people around the world. According to Mining Visuals (2024), among the leading employers in the sector are Coal India (248,550 employees), Glencore (150,000 employees), and Anglo American (105,000 employees). In North America, Canada to be precise, the minerals and metals sector directly employed approximately 420,000 people in 2022 and indirectly supported an additional 274,000 jobs, making its total impact on employment 694,000 jobs (Government of Canada, 2024). Similarly, in developing countries, the mining sector happens to be one of the largest sources of

formal employment, supporting both local economies and broader social development through healthcare, education and infrastructure investments.

2.1. The Finnish Mining Industry

Finland's large natural resource base makes it a significant player in the European markets. From expansive forest-based industries to rich mineral deposits, Finland boasts a diverse range of natural resources which have contributed immensely to its economic profile both domestically and internationally (Kivinen et al., 2017). In terms of mineral resources, nickel, copper, cobalt, lithium, zinc, and gold are among the most prominent minerals extracted in Finland (Eilu et al., 2020). These minerals are essential inputs for various high-tech industries, including electric vehicle (EV) battery production, renewable energy and advanced manufacturing. As Europe slowly transitions to more sustainable energy solutions, Finland has emerged as a major contributor to the critical raw materials required for actualising the objectives of the Paris Agreement and other climate change/sustainable energy treaties in the region (Child et al., 2020). Moreover, the euphoric rise in EV production across the world's most advanced economies has spurred a concomitant increase in demand for certain rare earth minerals, such as lithium, placing the Finnish mining sector in a rather auspicious position within the global EV market (Degen, 2023).

Unsurprisingly, the country has produced some of the biggest names within the sector. Boliden Kevitsa, located in the northern region of Finland, is one of the country's largest open pit mines, producing significant quantities of gold, platinum group metals and nickel (Boliden Kevitsa, 2025). Terrafame is yet another major player within the Finnish mining sector. The firm operates one of the world's most efficient bio-heap leaching mines (Terrafame, 2025). Among the firm's major outputs are nickel, cobalt, zinc, and copper. More recently, the Keliber Lithium Hydroxide Project is set to become a key producer of lithium hydroxide in the Eurozone region, providing much-needed support to the ever-growing demand for battery materials, particularly for EVs and renewable energy storage solutions (European Investment Bank, 2024).

The need for sustainability emerges as a result of environmental concerns associated with mining activities. These include, but are not limited to, land degradation, biodiversity loss, and water

contamination. Historically, mining scandals have generated immensely negative and long-term consequences for a wide range of stakeholders. A notable example is the Hpakant Jade Mine Disaster in Myanmar. On August 13, 2023, a landslide occurred at the mining site in Kachin State, Myanmar (RFA Burmese, 2025). The disaster caused the deaths of at least 32, with many others reported missing. According to reports, the landslide was caused by the collapse of mining waste piles, which is a common hazard within the region due to the prominence of unregulated mining practices (Chay et al., 2023).

Similarly, the Çöpler Gold Mine Collapse is yet another example of the adverse effects of inadequate safety measures and environmental mismanagement in the mining industry. This tragedy, which occurred in February 2024 in Erzincan Province, Turkey, resulted in a massive landslide of heap leach material, which killed nine miners (Kneen, 2024). The ensuing investigations revealed that negligence in monitoring structural integrity due to lax regulatory oversight was the principal cause of the disaster. Environmental groups also voiced concerns over the incessant disposal of mining chemicals in nearby water bodies, which continue to threaten the lives and livelihoods of many of the residents in the region (Petley and Petley, 2024).

Finland has a long history of enforcing strict environmental regulations and laws to ensure sustainable practices within its domestic mining industry while minimising ecological damage. As a result, the country has managed to build an extensive legal framework that governs all mining activities. The Mining Act (2011) happens to be one of the most comprehensive pieces of legislation that governs the mining sector. It focuses on balancing mineral extraction with environmental sustainability as well as social responsibility. The act outlines definitive regulations for environmental protection, exploration, permitting and mine closure, ensuring that all practices follow predefined provisions and are conducted in a responsible and transparent manner (Food and Agriculture Organisation, 2020). A core aspect of the Mining Act is its emphasis on environmental impact assessments, requiring mining companies to thoroughly assess and mitigate any potential ecological risks before obtaining the relevant permits. The act also has stipulations on financial liability, ensuring that all mining operators have provisioned sufficient funds for post-mining rehabilitation and waste management.

Next, the Environmental Protection Act (2014) details the regulatory framework for preventing and minimising environmental harm caused by industrial activities, including mining operations.

The act sets strict rules on issues pertaining to emissions, water protection, waste management and ecological sustainability, ensuring that industries within the country operate within environmentally acceptable limits (Food and Agriculture Organisation, 2025). Similarly, this act requires mining operations to conduct extensive environmental impact assessments (EIAs) before permits are issued. It also mandates the ongoing monitoring of air and water quality in and around mining sites, as well as the implementation of the best available techniques (BAT) to minimise pollution and resource depletion in the country. Overall, the Environmental Protection Act strengthens Finland's commitment to sustainable mining and industrial practices.

Buttressing the aforementioned acts, the European Union (EU) mining waste directive seeks to regulate extractive waste management to minimise its environmental impact and ensure the responsible disposal of mining waste across member states. The EU Mining Waste Directive (2006/21/EC) details guidelines for the storage, safe handling and treatment of waste materials generated by mining operations and activities in the Eurozone region (IEA, 2024). This includes tailings, waste rock and processing residues. A defining provision in this directive is the requirement for waste management plans (WMPs) for all licensed mining projects in the region. This obligates all companies within this field of endeavour to outline detailed strategies for waste prevention, disposal and treatment. It also establishes pathways for strict ecological monitoring and reporting obligations, ensuring that all mining activities comply with defined water and soil contamination limits, land rehabilitation measures and biodiversity protection standards.

In a similar vein, the Finnish Biodiversity Strategy and Action Plan is a national policy document that aims to enhance and protect Finnish biodiversity by ensuring the sustainable use of natural resources, including those within the mining sector (State Treasury Republic of Finland, 2024). This action plan is in alignment with the EU Biodiversity Strategy and the UN Convention on Biological Diversity, ensuring Finland remains consistent in its ecological conservation goals (European Union, 2025). The action plan's primary objective is to reduce industries' ecological footprint by implementing robust measures to restore degraded habitats, promote ecosystem resilience and protect endangered species.

Finally, the Finnish Environment Institute acts as an independent regulatory and research body responsible for monitoring and assessing Finland's environmental policies. The Institute's role is indispensable in the collection and analysis of critical environmental data, the execution of impact

assessments and the development of strategies for sustainable resource management (Green Deal, 2024). Moreover, the Institute provides scientific expertise and policy recommendations to government agencies, playing an active role in shaping environmental laws and sustainability initiatives.

3. Methodology

This chapter focuses on presenting the research methodology the researcher will employ to realise the stated research objectives. This chapter will delve into key aspects of the research design as well as outline the data sources that will be explored throughout the study. The chapter concludes with the data collection and analysis techniques this research will adopt.

3.1. Research Design

The role of a research design is to detail the plan or blueprint that the researcher will leverage in realising the research objectives. It provides guidance in the systematic execution of the research methodology. Additionally, it serves as a strategic framework that ensures alignment between all core facets of the research: research background, objectives, questions, chosen methodology, and methods employed. This enables the researcher to effectively realise the stated goals of the study, achieving the requisite goals efficiently and reliably.

In the present study, a systematic literature review is employed as the primary research design. This design involves a replicable and structured orientation for aggregating, choosing, assessing and synthesising the extant literature on sustainable mining practices globally (Simsek et al., 2021). Through a systematic literature review, the researcher can adopt rigorous and transparent methods for not only enhancing objectivity and reducing bias but also improving the comprehensiveness and reliability of the findings generated through this scientific inquiry. This approach allows the researcher to consolidate the existing knowledge on the subject matter of interest and identify gaps that may exist in the epistemology (Pati & Lorusso, 2017), providing a detailed understanding of pollution control, energy efficiency and waste management strategies utilised within the global mining contexts.

3.2. Data Sources and Search Terms

The quality and relevance of the literature selected for a systematic review is arguably the most important determinant of the whole credibility, reliability and academic robustness of this scholarly endeavour. Within the domain of the present research inquiry, the core focus was to critically assess sustainable mining practices globally. Accordingly, the researcher employed high-quality, peer-reviewed and methodologically sound sources to facilitate the realisation of the stated research objectives. Ensuring comprehensiveness was of critical concern. Thus, academic databases were used as the primary sources of literature, providing the research access to a wide variety of journals and articles that are closely related to the research objectives.

The primary database that was employed for this review was Google Scholar. This was used due to its extensive index of scholarly material produced from a wide variety of disciplines. Moreover, it is a free resource with a user-friendly interface. This provided a highly effective starting point for identifying key literature related to sustainable mining, environmental impact control, resource efficiency and life cycle assessment (LCA) applications.

Alongside Google Scholar, several highly specialized and widely used academic databases such as SpringerLink, Emerald, ScienceDirect, and Taylor & Francis were consulted to enhance the rigour and depth of the review. ScienceDirect provided literature that focused on environmental technologies and life cycle analysis frameworks. SpringerLink was an effective database in accessing peer-reviewed papers on mining innovations and sustainability reporting. Emerald contributed to finding important content on corporate environmental responsibility and governance, while Taylor & Francis offered interdisciplinary perspectives on sustainability and net-zero transitions. Collectively, these sources ensured the systematic literature review was deeply rooted in contemporary and authoritative literature. Although the employed databases were diverse and varied, the data extraction processes were identical.

To complement the peer-reviewed sources and ensure a comprehensive grasp of the subject matter, grey literature was included in the study, which is literature produced outside of conventional academic publishing channels The sole aim here was to capture insights generated from government policy papers, environmental agency reports, industry reports and recent development publications that have not yet been published in academic journals. This grey literature was

accessed through the Google web search engine. Grey literature played an immeasurable role in improving the relevance and timeliness of this review, reflecting real-world implementation of sustainability policies in Finland and abroad.

Table 1: Data Source Queries

Database/Source	**Queries**
Emerald	Sustainable mining practices, resource efficiency, pollution control in mining, global mining sector sustainability, corporate social responsibility, corporate environmental responsibility, mining governance, ESG in mining, environmental sustainability in extractive industries.
ScienceDirect	Life cycle assessment in mining, resource efficiency in mining, mining waste management, energy-efficient mining technologies, water and air pollution in mining, sustainable mineral extraction, Finnish mining sector, renewable energy adoption, environmental impact of mining.
SpringerLink	Life cycle assessment, sustainable development in mining, circular economy in mining, environmental technologies in extractive industries, renewable energy adoption, Finnish mining sector, energy efficiency in mining, air and water pollution in mining, energy transition in the resource sector.
Google Scholar	International mining sector, life cycle assessment in mining, mining life cycle analysis, environmental impact of mining, energy efficiency and pollution mitigation in mining, renewable energy adoption, Finnish mining regulations, pollution reduction technologies in the extractive sector, ESG frameworks in mining.

Francis and Taylor	Mining sustainability, mining and environmental policy, renewable energy adoption, Finnish mining sector, energy-efficient technologies in mining, mining waste management, clean energy in extractive industries, ESG in mining, international corporate environmental regulations, LCA application in mining, sustainable mining practices in Finland.
Google	LCA applications in mining, global mining sector, Finnish mining regulation, energy efficiency, pollution mitigation and waste management in mining, EU mining regulations, sustainable mining practices, renewable energy adoption, ESG in mining.

The researcher combined some of these terms using the Boolean operators such as AND, OR, and NOT, to help streamline and refine the realised results. It also helped in identifying literature that were more closely related to the primary objectives of the study. The structured use of these terms ensured both breadth and specificity, providing a more robust and diverse body of literature to inform the study's findings and analysis.

3.3. Inclusion and Exclusion Criteria

In any systematic literature review, establishing clear inclusion and exclusion criteria is essential for the identification, selection and assessment of the collated literature. This process is a prerequisite for ensuring that only high-quality, contextually relevant sources are considered for evaluation. This, in turn, improves the credibility, coherence and academic integrity of the research. The inclusion criteria were centred around peer-reviewed journal articles, reputable industry reports, government policy documents, and empirical studies that focus on the relevant themes of this research: sustainable mining practices, LCA, the global mining sector and environmental management. In terms of the temporal frame of reference, only publications released between March 2015 and March 2025 are included. This timeframe adequately captures a key inflexion point in sustainability policy formulation and implementation as it marks the post-

Paris Agreement period in which climate policy advancements became increasingly prominent within the mining industry and other related sectors.

Conversely, the exclusion criteria removed literature that was outdated or captured from non-peer-reviewed sources. Additionally, opinion pieces and studies unrelated to environmental sustainability or the global mining sector were omitted from the analysis. The researcher ensured that studies or literature that lacked adequate methodological transparency or failed to engage the primary themes of pollution control, energy efficiency or waste management in mining were excluded from the review. Doing so allowed the researcher to ensure that the final body of literature directly supported the research objectives and provided a strong foundation for insightful analysis.

3.4. Bias

Bias is unavoidable in interpretivist research, especially in qualitative studies such as systematic literature reviews, due to the subjective nature of data interpretation, the recognition of multiple realities shaped by lived experiences and the influence of the researcher's worldview on the study's outcome (Smith & Noble, 2014). While bias cannot be entirely eradicated, it can be minimised through the incorporation of qualitative rigour interventions. In the present study, two forms of bias were identified and pre-emptively addressed: review design bias and synthesis bias.

Review design bias describes the limitations that emerge during the preliminary planning and structuring phases of the literature review. These include poorly formulated research questions, inadequately defined inclusion and exclusion criteria, and limited keyword scope. All these limitations can diminish the credibility of the research and unintentionally restrict the diversity and relevance of the gleaned insights (Page et al., 2016). To address this, the researcher ensured that the research design was carefully formulated, and all methodological processes were detailed and justified. Additionally, a wide range of keywords were employed, well-rounded research questions were formulated and flexible, yet focused inclusion and exclusion parameters were outlined.

On the other hand, synthesis bias focuses on the distortion of findings during the data analysis phase of a systematic literature review. It describes the over- or underemphasis of evidence to suit

a researcher's preconceived notions about the research inquiry (Hasanoff et al., 2023). This form of bias was reduced by carefully organizing and analysing information. Different opinions were fairly considered and then combined into one clear and consistent explanation or integrated into a streamlined and congruent research narrative.

By addressing these potential sources of bias and employing established quality assurance techniques to limit them, the researcher ensured that the findings generated through this study were credible, objective and methodologically robust.

3.5. Data Extraction

The data extraction stage of the research was a critical step in realising the study's objectives. It involved the meticulous process of identifying, collating, structuring and evaluating key pieces of information from a selected body of literature that aligned with the overarching themes of the present study. After executing the search queries, a total of 351 publications were identified. However, after the inclusion and exclusion criteria were applied, 16 highly relevant and credible publications were analysed. This refinement goes to show the nature of systematic literature reviews, in which broad preliminary searches often yield an expansive base of literature, which is then intentionally filtered to ensure that only thematically relevant content and materials are analysed. The extraction process took 1.5 months. The assigned timeframe gave the opportunity to conduct a thorough screening of the compiled database and evaluate each piece of literature based on the relevant objectives of the study.

To enhance transparency and methodological soundness, the PRISMA framework was employed for the study. This model aided the researcher throughout the selection and extraction process. PRISMA, which stands for Preferred Reporting Items for Systematic Reviews and Meta-Analysis, comprises four main stages: identification, screening, eligibility, and inclusion (Wirani et al., 2024). The first stage involved the deletion of duplicate studies and literature. In this stage, the abstracts of the identified studies were screened to determine relevance. At the eligibility phase, the researcher evaluated the full-text versions of the shortlisted studies and examined them based on the formulated inclusion and exclusion criteria. Finally, in the inclusion phase, literature that

fulfilled all the relevance parameters was selected from in-depth thematic analysis. Employing this approach ensured that the identified biases were reduced, and the selection process remained replicable and transparent.

The flowchart of the PRISMA framework is summarised in the figure below.

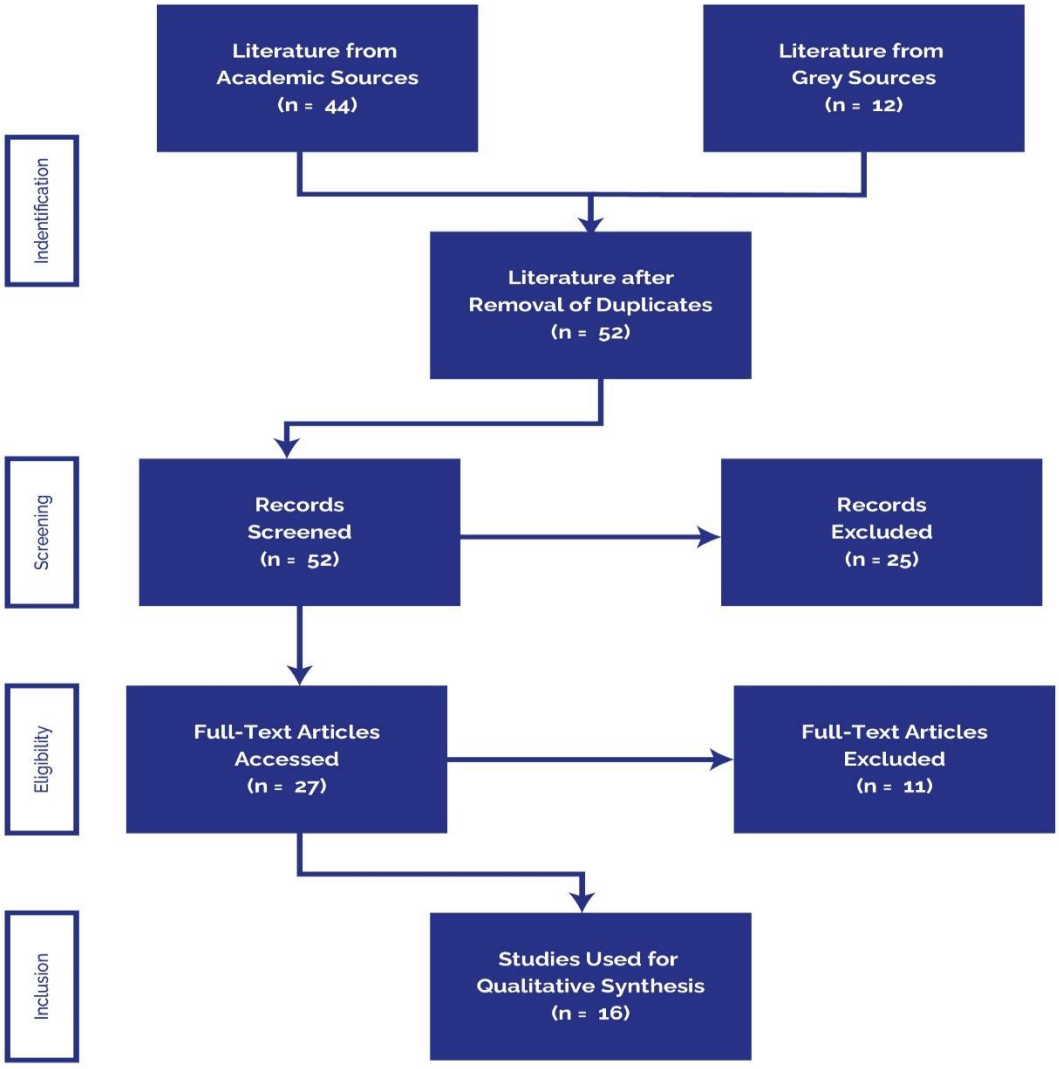

Figure 1: PRISMA Flowchart

3.6. Data Analysis

In this study, thematic analysis served as the primary tool for realising the research objectives. This approach involved a multifaceted process designed to uncover recurring themes within the extracted dataset. The analysis began with an initial phase of familiarisation, where the researcher repeatedly reviewed the selected literature to gain an in-depth understanding of the content and make notes on relevant observations. Next was the digital coding process, which grouped key observations into preliminary themes based on commonalities and conceptual relevance. The emerging themes were then refined and reviewed to ensure that they were in alignment with the research objectives and were coherent with the broader discourse on sustainable mining. Finally, the themes were synthesised into a cogent research narrative that critically examined the findings based on the overarching objective of the study.

4. Thematic Analysis

Thematic analysis was the main method used for data analysis to achieve the study's overall goals. This approach provided a solid framework for systematically identifying, organising, and evaluating the key patterns derived from the literature review. Consequently, the sections that follow will present the primary findings and insights obtained. The results will be detailed according to the four primary research questions of the study. The researcher aimed to evaluate the techniques currently employed to reduce air, water, and soil pollution in global mining operations; the efficacy of these methods in mitigating environmental impacts; the challenges that impede the implementation of sustainable mining practices; and potential solutions to address these challenges, alongside case studies from Finnish mines that showcase successful pollution reduction strategies.

4.1. General Findings

The systematic literature review provided a wealth of information on the subject matter. Analysis generated highly relevant insights into the key trends in global sustainable mining and the challenges hindering this movement from realising its full potential. Furthermore, the researcher managed to assess specific developments in this field of endeavour within the context of the Finnish mining industry. The broad themes assessed in this phase of the research were pollution mitigation techniques and strategies in mining, effectiveness of environmental management tools, barriers to sustainable mining practice, strategies for overcoming implementation challenges, and case studies of best practices (lessons from Finland). These issues will be discussed further in the coming sections

Table 2: Primary Findings

No.	Author and Year	Major Findings
1.	Monteiro et al. (2019)	Sustainable mining is a critical component in priming countries with the tools to achieve the 17 Sustainable Development Goals. It provides avenues for poverty reduction, job creation and environmental improvements, but requires significant investments in inclusive education, gender equality and climate change mitigation
2.	Tost et al. (2018)	The key factors that are required to ensure the realisation of environmental sustainability within the mining sector are centred around the regulatory interventions produced by the Paris Agreement, considerations surrounding natural capital and the implications of strong sustainability on conventional business models in the industry
3.	Amegboleza and Ülkü (2025)	The primary limiting factors that are precluding the implementation of sustainable energy systems in the global mining industry are the high costs of these novel technologies and the logistical issues they pose. However, global regulatory alignment, financial mechanisms and technological innovations can be employed to surmount these challenges
4.	Antwi et al. (2022)	Adopting green supply chain practices can be a catalyst for boosting sustainable performance of mining firms specifically in developing countries. These translate into significant economic, social and environmental benefits at both the micro and macro levels.

5.	Blinova et al. (2022)	To enhance sustainable development and corporate sustainability, mining companies must effectively manage their ESG factors while keeping a circular business model at the heart of their operations. This will, in turn, enhance their contributions to sustainable development goals and optimise their environmental performance.
6.	Wan and Ni (2020)	The prevalence of pollution in mining operations globally, highlights the needs for the employment of sustainable water management systems such as strip filling for coal mining, to prevent groundwater and surface water damage, and to address negative social and ecological externalities.
7.	Aznar-Sánchez et al. (2019)	The domain of sustainable mining research has grown tremendously from 1998 to 2017, with researchers focusing primarily on the development of pathways for reducing fossil energy use and promoting renewable sources, with the core emphasis on achieving clean production in new mining environments
8.	Ben-Awuah et al. (2016)	When comparing the financial implications of open pit and underground mining, the researchers found that open pit mining generates higher levels of net present value than the alternative extraction method. However, underground mining generates a better return on investment due to the investment requirements of both methods.
9.	Kalisz et al. (2021)	Waste management is of critical concern, especially in the metal ores, coal, oil and natural gas industries. Mining waste management can be enhanced by prioritising recycling. This ensures that by-products from mining are treated as a resource as opposed to waste, contributing to the circular economy principles and meeting environmental expectations

10.	Ericsson and Löf (2020)	Extractive dependency continues to rise in emerging economies. In 2018, mining of coal and metals was one of the largest economic contributors in low—to middle-income countries, with African countries being the principal beneficiaries. The discovery of new oil and gas fields further entrenched the dependency on these natural resources.
11.	Zhang et al. (2023)	Mines in emerging economies generate considerable socio-economic benefits. However, care must be taken to ensure that their eco-environmental impact is minimal. The Hetai mine in South China has generated significant socio-economic wealth (approximately 12,565.45 million yuan) since its inception. This is compounded by the Huangnikeng gold deposits that further highlight the potential of this mine.
12.	Dikgwatlhe and Mulenga (2022)	The mining sector is one of the most essential avenues of employment in developing countries. In South Africa, the sector is one of the largest sources of direct and indirect employment. Its expansion has led to an improvement in the quality of life and increased migration to the country.
13.	Kinnunen et al. (2020)	Closed water loops provide an effective way for improving the sustainability of mines, specifically with ore sorting and tailings valorisation. This technology can be leveraged to improve the environmental, economic, and social outcomes of mines while reducing operational waste and enhancing resource utilisation
14	Ali and Frimpong (2020)	Machine learning, artificial intelligence and process automation provide essential pathways for revolutionising the mining industry by improving the efficiency, effectiveness, and safety of mining operations, thereby leading these organisations to a more sustainable future.

15	Ren and West (2022)	Policy interventions are key to the realisation of sustainability goals. The Clean Water Act (CWA) has significantly reduced water pollution in the United States, leading to expansions in residential construction and human population along major water bodies. Its benefits have far exceeded its government costs by at least fourfold
16	Berberoglu et al. (2024)	There are several challenges mines face as they progress towards their sustainability goals. However, for the Turkish mining sector, the main challenge confronting its sustainability efforts is safety. Thus, the relevant actors must take steps to immediately safeguard the health and safety of employees within this sector.

4.2. What techniques are mostly used to minimize air, water, and soil pollution during mining operations?

The first research question focused on identifying and examining the techniques and ongoing operational interventions employed in minimising air, water and soil pollution during mining operations. Emphasis was placed on understanding the technological, procedural and regulatory measures implemented across different mining contexts.

4.2.1. Procedural Interventions

The prevalence of silicosis is largely attributed to the inhalation of fine silica dust produced during extensive mining and quarrying activities (Sishodiya, 2022). Farjana et al. (2019) studied key metrics for environmental sustainability, including efficient resource use, limiting land disruption, reducing pollution, and properly decommissioning and rehabilitating or reclaiming depleted mining sites. An alternative approach to sustainable mining broadens the focus beyond the immediate operational footprint, emphasising the responsible management of the mineral resource throughout its entire life cycle, from extraction to use and end-of-life stages. Blinova et al. (2022) add that integrating ESG factors across the mining ecosystem can prime key actors within this industry to reduce their carbon output. This sentiment is shared by Antwi et al. (2022), who argue that employing green supply chain practices across mining operations can play a crucial role in mitigating pollution impacts.

This life cycle perspective aims to decrease the quantity of material extracted and protect reserves for future generations. Minerals mined from the earth ore are finite and non-renewable. However, the development of technologies such as the solvent extraction method for recovering previously uneconomical metals in mining waste and recycling methods for metals makes the finite resource infinitely renewable and hence sustainable (Rajaram, Dutta and Parameswaran, 2005). The United States (U.S.), Russia, China, and Australia rank among the world's largest mineral producers (Tang and Werner, 2023).

4.2.2. Regulatory Interventions

According to the United States Geological Survey (USGS) data from the year 2000, the U.S. significantly contributed to global mineral output, producing 59% of copper, 57% of silver, 39% of zinc, and 34% of both gold and lead. Regulatory frameworks across various jurisdictions ensure mining practices align with environmental standards, aiming to protect ecosystems and manage environmental impacts to promote industry sustainability (Rajaram, Dutta and Parameswaran, 2005). In the United States, federal laws like the Clean Air Act (CAA), National Environmental Policy Act (NEPA), and Clean Water Act (CWA) regulate mining practices related to emissions, land use, and water quality to promote sustainability (AGI, 2014). Canada's Minerals and Metals Policy similarly encourages sustainable practices in its mining sector (Canada, 2011).

In the European Union, the European Commission and other regional bodies enforce frameworks that promote corporate sustainability, guiding the sector toward environmentally responsible and competitive practices across jurisdictions. These regulatory frameworks govern environmental quality alongside social responsibility, community engagement, safety, resource efficiency, and economic viability (Laurence, 2011).

4.2.3. Technological Interventions

Technological advancement plays a critical role in driving efficiency within the mining industry. By employing these tools, mining companies can effectively realise their sustainability goals and carry out their operations in a more environmentally conscious manner (Aznar-Sánchez et al., 2019). Technology and sustainability are invariably linked; hence, mining companies that integrate cutting-edge innovations to minimise their environmental impact tend to optimise resource utilisation and improve operational safety (Cacciuttolo et al., 2023). Although several sustainable mining technologies are available to firms, a few have gained widespread prominence in recent years.

For a start, automation and artificial intelligence (AI) driven mining employs the use of autonomous drilling, AI-powered mineral exploration and robotic ore sorting to reduce energy

consumption during mining expeditions, all while reducing the waste produced by the extraction process (Ali and Frimpong, 2020). This produces a more efficient resource utilisation process and minimises the environmental impact of mines. By harnessing the power of machine learning models and AI-powered analytics, mining companies can predict ore quality, improve mineral recovery rates and optimise drilling patterns, making energy-extensive processes energy efficient (Bende and Bara, 2024). Additionally, Wan and Ni (2020) found sustainable water management systems such as strip filling can improve the resource burden of many mining operations, while improving functional efficiency.

Closed-water circulation systems are yet another intervention that can help mines recycle water and reduce the amount of water used and discharged during mining operations. This is done by lowering freshwater consumption while minimising the risk of water pollution (Kinnunen et al., 2020). The underlying technology utilises advanced filtration, chemical treatment and sedimentation technologies to enable mines to purify and reuse process water, reducing the dependency on external water sources and ensuring compliance with ecological regulations (Le et al., 2020). Since water scarcity is fast becoming a looming threat for several regions around the world, this technology will be invaluable in assisting mining companies to operate with a lower environmental footprint and sustain efficient mineral processing (Banks et al., 2017). This also limits the release of contaminated wastewater into waterbodies located close to the mines, protecting aquatic ecosystems in the process.

4.3. How effective are these tools in reducing environmental impacts?

The second research question explored the efficacy of existing pollution control techniques in successfully mitigating the environmental impacts of mining activities. Attention was placed on evaluating the practical outcomes of practitioners and scholars who have implemented these interventions across diverse operational settings.

4.3.1. Effectiveness of Environmental Management Tools and Interventions

As the prospect of global environmental implosion continues to loom across several key economies, it has become immensely imperative to assess the effectiveness of environmental management tools and interventions. Anglo American's Closed-Loop System at Mogalakwena Platinum Mine in Limpopo uses a fibre-optic sensing system to monitor real-time water flow. This intervention has resulted in a 66% reduction in operational water requirements for the mine, a true testament of the efficacy of closed water circulation systems in recycling operational water needs to enhance resource efficiency (Muir, 2019). Similarly, a study at the Alkane Energy Markham site showed that abandoned coal mines can be used as low-enthalpy water reserves/energy reservoirs. These employed systems achieved a Coefficient of performance (COP) of 2.7 – 3.97; variations are due to several factors like water depth and flow rates. The COP is determined by analysing the ratio between the useful thermal energy output and the electrical energy input required to operate a given system. However, higher flow rates reduced system efficiency (Al-Habaibeh et al., 2017). In any case, Kinnunen et al. (2020) found that technologies such as the closed-loop water management system can significantly reduce operational waste generation and optimise resource utilisation in mining outfits. Waste recycling plays an imperative role in circular economy dynamics by substantially reducing the environmental impacts attributed to these carbon-intensive endeavours.

Automation and AI have also played critical roles in improving the precision and environmental sustainability of mining operations around the world. According to a study conducted by O'Brien et al. (2023), AI increased mineral reserve prediction accuracy by 58% in copper mining, reducing yield variability. Additionally, Jain (2024) found that machine learning reduced equipment downtimes in mines by analysing real-time sensor data and employing predictive maintenance protocols. These interventions are essential in driving operational efficiency and minimising operational waste. This, in turn, drastically reduces the environmental footprint of mining activities by optimising the resource extraction process.

Environmental policy interventions have also yielded some positive results. For example, in the post-Clean Water Act era, waste discharge into the Potomac River in the US has dropped from 240 million gallons a day to negligible levels. This has gone a long way to boost recovery and

eliminate toxic algae blooms in the natural water resource (Damianos, 2023). The use of regulatory intervention, thus, has the potential to serve as a powerful tool for catalysing environmental restoration endeavours, providing the mechanisms for driving mandatory industry compliance with environmental standards and encouraging the adoption of cleaner technologies in high-carbon-emitting sectors like mining.

4.4. What challenges hinder the implementation of sustainable mining practices, and what potential solutions can address these challenges?

The third research question examined the key obstacles that impede the ubiquitous adoption of sustainable mining technologies and processes within the sector. This research question will provide much-needed insight into the stumbling blocks that are actively working against the acceptance of these interventions among the primary actors and players in mining.

4.4.1. Challenges and Barriers to Sustainable Mining

One of the primary limiting factors that is actively preventing the realisation of global sustainability goals is the significant regulatory and governance gaps that exist among key economies. The prevalence of weak and sometimes contradictory regulations, especially in developing nations, has created enforcement gaps which have placed economic interests at odds with environmental ones. For example, in Ghana, although mining has wreaked havoc on many of the country's natural ecosystems, the government is still reluctant to penalise non-compliance with sustainable practices, particularly in regions that are heavily dependent on mining revenue (Amoah & Eweje, 2021).

Moreover, there are significant economic and investment barriers that are frustrating sustainability efforts within the global mining industry. Specifically, the high initial costs required to fully integrate novel technologies into legacy frameworks. Transitioning to renewable energy supplies, closed-loop water systems, and electric operational equipment requires a considerable amount of upfront investment, which is a key deterrent for many policymakers in mining firms. Thus,

management tends to prioritise immediate returns over long-term sustainability due to pressure from shareholders and volatile commodity markets (Wu et al., 2016). Amegboleza and Ülkü (2025) further that logistical complexities continue to make it increasingly difficult for mining companies to fully implement novel sustainable energy technologies into their legacy operations and infrastructure. This is further compounded by issues relating to regulatory compliance pressures and health and safety regulations within the sector (Berberoglu et al. 2024).

There are also several technological limitations that are of critical concern in the adoption of these technologies. Emerging sustainable technologies are still in their nascence and are characterised as immature innovations by some authors like Magnusson and Berggren (2017). This poses a challenge to widespread adoption due to limitations in scalability and adaptability in diverse geological conditions. Additionally, integration challenges further disrupt these endeavours. Retrofitting legacy infrastructure with eco-friendly systems can disrupt operations and limit the efficiency of ongoing mining operations (Veriforce, 2023).

4.5. Which case studies from Finnish mines demonstrate successful pollution reduction strategies?

The fourth research question investigated real-world examples or illustrations of sustainable mining practices in Finnish firms, highlighting the organisations that have successfully implemented pollution reduction strategies in facilitating key operational functions. This section details the methods and technologies that have contributed to the effectiveness of these firms, while offering insights that could inform best practices in sustainable mining globally.

4.5.1. Environmental Sustainability in Finnish Mining

Like many of the world's most advanced economies, Finland places considerable emphasis on environmental sustainability within its domestic mining industry (Poelzer et al., 2021b). This commitment is reflected in stringent regulations, sustainable mining initiatives and ongoing

investments in eco-friendly technologies. However, challenges still exist within the industry which plague the industry's sustainability efforts.

Finland is no stranger to mining scandals of its own. A notable example is the Talvivaara Mine Environmental Disaster of 2012. During that year, the Talvivaara nickel mine in Sotkamo experienced a severe leak from its gypsum waste pond, which released a substantial amount of toxic metals, including uranium, zinc and nickel, into the surrounding area (YLE, 2014). This incident caused widespread environmental contamination, as well as legal actions against company executives. Ultimately, Talvivaara Mining Company was unable to recover from the fallout of the disaster and eventually filed for bankruptcy (Sairinen et al., 2017). In 2014, a similar disaster occurred. Due to equipment failure, the Norilsk Nickel Refinery in Harjavalta accidentally discharged an estimated 66 tonnes of nickel into the Kokemäenjoki (Helsinki Times, 2014). This caused the nickel concentration in the river to be 400 times higher than the normal levels, making this disaster the biggest known nickel leak in Finnish history.

To ensure that disasters never repeat themselves, the Finnish government has implemented stricter mining regulations, enhanced environmental monitoring and increased oversight of mining operations throughout the country.

Several mines in Finland have taken steps to limit their environmental impact. For example, the Pyhäsalmi Mine (Pyhäjärvi), which produces copper and zinc, has implemented advanced ventilation systems in its underground operations. These systems have significantly reduced occupational diseases related to particles and dust (United Nations Sustainable Development, 2018). The mine also focuses on investing in closure-related research and development, creating real-life solutions and reference materials to ensure environmentally sustainable mine closure. Yet, the mine's core focus is on reducing metal and wastewater emissions throughout its value chain. This commitment has made it one of the safest and most environmentally friendly mining firms in all of Finland (United Nations Sustainable Development, 2018).

5. Conclusion

This study focused on assessing sustainable mining practices with a primary focus on pollution control, waste management and energy efficiency across the global mining sector, using Finland as a key illustrative context. Through a systematic literature review and thematic analysis, four main research questions were used to guide the inquiry, each exploring a distinct aspect of sustainability within the context of mining operations, from the tools and techniques used to ameliorate the negative implications of mining to the real-world applications of these best practices.

The findings indicated that pollution control and waste management in mining have seen notable advancements through the use of sophisticated technologies such as closed-loop water systems and predictive AI models. However, while innovations in sustainable technologies, procedures and functions have proven effective in addressing sustainability concerns within the sector, their implementation and advancement have been constrained by regulatory, economic and technical barriers, especially in jurisdictions with complex legal frameworks.

Moreover, the analysis of Finnish case studies revealed a dual narrative for the most part. On one hand, Finland demonstrates superior leadership in eco-conscious mining through the implementation of stringent environmental regulations, company-driven ESG frameworks and state oversight. On the other hand, legacy issues, like those highlighted by the Talvivaara disaster, continue to underscore the prevalence of operational risks among key stakeholders and the emerging need for more robust implementation mechanisms across the entire sector. Across the global and local contexts, the study reaffirms the centrality of sustainability to contemporary mining operations and the importance of aligning strategic interventions with climate goals and ecological safeguards.

6. Recommendations

Based on the insights generated through this study, the researcher recommends that regulatory agencies should create and enforce robust environmental regulations, given the success of policies such as the Clean Water Act. Thus, existing policies such as the EU Mining Waste Directive and Finland's Environmental Protection Act should be supported by frameworks that detail cogent compliance monitoring schemes and punitive measures for violations. Additionally, it is imperative for mining companies to invest in emerging technologies that enhance their resource utilisation and pollution mitigation processes. Investments in technologies such as real-time environmental monitoring, low-impact extractive methods, and AI-based predictive maintenance can equip these firms to minimise their carbon output and enhance their sustainability performance. While such strategic endeavours can be quite expensive, engaging in public-private partnerships can provide much-needed financial relief in adopting these innovations

Furthermore, it is worth noting that emerging sustainable mining processes and technologies require novel skillsets. Thus, mining firms must take deliberate steps to address any evident skill gaps they might have within their operations. By harnessing the power of international knowledge exchange, mining companies, especially those in emerging economies, can gain expertise on best sustainability practices to supercharge their operations and enhance their pollution mitigation mechanisms. Moreover, mining firms must endeavour to strengthen engagement with both internal and external stakeholders. Being inclusive and prioritising employee safety are surefire ways of ensuring that sustainable business practices are kept at the heart of operations.

Future studies should focus on adopting a mixed-methods methodology to evaluate the long-term effectiveness of pollution controls from a global perspective. Additionally, researchers should investigate the socio-economic trade-offs that are involved in enforcing sustainable mining protocols in both advanced and resource-endowed developing nations.

References

Al-Habaibeh, A., Athresh, A.P. and Parket, K., 2017. *Performance analysis of using mine water from an abandoned coal mine for heating buildings using an open loop based single shaft GSHP system*. [online] Innovative and Sustainable Built Environment Technologies Research Group (iSBET). Available at: http://www.irep.ntu.ac.uk/id/eprint/21 [Accessed 13 Jun. 2025].

Ali, D. and Frimpong, S., 2020. Artificial intelligence, machine learning and process automation: existing knowledge frontier and way forward for mining sector. *Artificial Intelligence Review*, 53(8), pp.6025–6042. https://doi.org/10.1007/s10462-020-09841-6

Ali, O., 2024. *The economic impact of mining: From local communities to global markets*. [online] AZoMining. Available at: https://www.azomining.com/Article.aspx?ArticleID=1802 [Accessed 26 Apr. 2025].

Altiti, A.H., Alrawashdeh, R.O. and Alnawafleh, H.M., 2021. Open pit mining. *IntechOpen eBooks*. https://doi.org/10.5772/intechopen.92208

Amegboleza, A.A. and Ülkü, M.A., 2025. Sustainable energy transition for the mining industry: A bibliometric analysis of trends and emerging research pathways. *Sustainability*, 17(5), p.2292. https://doi.org/10.3390/su17052292

Amoah, P. and Eweje, G., 2021. Barriers to environmental sustainability practices of multinational mining companies in Ghana: An institutional complexity perspective. *Corporate Governance*, 22(2), pp.364–384. https://doi.org/10.1108/cg-06-2021-0229

Antwi, B.O., Agyapong, D. and Owusu, D., 2022. Green supply chain practices and sustainable performance of mining firms: Evidence from a developing country. *Cleaner Logistics and Supply Chain*, 4, p.100046. https://doi.org/10.1016/j.clscn.2022.100046

Asr, E.T., Khorshid-Doust, R., Kazemi, H., Mansouri, M. and Côté, R.P., 2019. A review of studies on sustainable development in mining life cycle. *Journal of Cleaner Production*, 229, pp.213–231. https://doi.org/10.1016/j.jclepro.2019.05.029

Aznar-Sánchez, J.A., Velasco-Muñoz, J.F., Belmonte-Ureña, L.J. and Manzano-Agugliaro, F., 2019. Innovation and technology for sustainable mining activity: A worldwide research assessment. *Journal of Cleaner Production*, 221, pp.38–54. https://doi.org/10.1016/j.jclepro.2019.02.243

Banks, D., Athresh, A., Al-Habaibeh, A. and Burnside, N., 2017. Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. *Sustainable Water Resources Management*, 5(1), pp.29–50. https://doi.org/10.1007/s40899-017-0094-7

Ben-Awuah, E., Richter, O., Elkington, T. and Pourrahimian, Y., 2016. Strategic mining options optimization: Open pit mining, underground mining or both. *International Journal of Mining Science and Technology*, 26(6), pp.1065–1071. https://doi.org/10.1016/j.ijmst.2016.09.015

Bende, N. and Bara, A.B., 2024. A study on the role of automation and AI in operational efficiency and sustainable mining. *International Journal of Scientific Research in Engineering and Management*, 8(10), pp.1–5. https://doi.org/10.55041/ijsrem37963

Berberoglu, Y., Mangla, S.K. and Kazancoglu, Y., 2024. Towards sustainable mining in an emerging economy: Assessment of sustainability challenges. *Resources Policy*, 97, p.105288. https://doi.org/10.1016/j.resourpol.2024.105288

Blair, G., Coppock, A. and Humphreys, M., 2019. Declaring and diagnosing research designs. *American Political Science Review*, 113(3), pp.838–859. https://doi.org/10.1017/s0003055419000194

Blinova, E., Ponomarenko, T. and Knysh, V., 2022. Analyzing the concept of corporate sustainability in the context of sustainable business development in the mining sector with elements of circular economy. *Sustainability*, 14(13), p.8163. https://doi.org/10.3390/su14138163

Boliden Kevitsa, 2025. Updated Mineral Resources and Mineral Reserves for Kevitsa as well as grade guidance for 2025. [online] Available at: https://investors.boliden.com/en/press/updated-mineral-resources-and-mineral-reserves-kevitsa-well-grade-guidance-2025-2292057 [Accessed 12 Feb. 2025].

Cacciuttolo, C., Muñoz, J.P., Domínguez, J. and Rivas, R., 2023. Low-cost sensor technologies for monitoring sustainability and safety issues in mining activities: Advances, gaps, and future directions in the digitalization for smart mining. *Sensors*, 23(15), p.6846. https://doi.org/10.3390/s23156846

Chay, A., Jeong, S. and Magramo, K., 2023. At least 32 dead after landslide at Myanmar Jade Mine. [online] CNN. Available at: https://edition.cnn.com/2023/08/16/asia/myanmar-jade-mine-landslide-deaths-intl-hnk/index.html [Accessed 12 Feb. 2025].

Child, M., Kemfert, C., Bogdanov, D. and Breyer, C., 2020. The role of energy prosumers in the transition of the Finnish energy system towards 100% renewable energy by 2050. *Futures*, 124, p.102644. https://doi.org/10.1016/j.futures.2020.102644

Cooper, J., 2016. Life Cycle Assessment (LCA): A Guide to Best Practice, by Walter Klöpffer and Birgit Grahl. Weinheim, Germany: Wiley-VCH, 2014, 440 pp., ISBN 978-3-527-32986-1, hardcover, 89 Euros. *Journal of Industrial Ecology*, 20(4), pp.938–939. https://doi.org/10.1111/jiec.12424

Damianos, 2023. *Five Clean Water Act success stories*. [online] Peril & Promise. Available at: https://www.pbs.org/wnet/peril-and-promise/2023/02/five-clean-water-act-success-stories/ [Accessed 13 Jun. 2025].

Daugaard, D., 2019. Emerging new themes in environmental, social and governance investing: a systematic literature review. *Accounting and Finance*, 60(2), pp.1501–1530. https://doi.org/10.1111/acfi.12479

De Luca, A.I., Iofrida, N., Strano, A. and Falcone, G., 2017. Evaluation of sustainable innovations in olive growing systems: A Life Cycle Sustainability Assessment case study in southern Italy. *Journal of Cleaner Production*, 171, pp.1187–1202. https://doi.org/10.1016/j.jclepro.2017.10.119

Degen, F., 2023. Lithium-ion battery cell production in Europe: Scenarios for reducing energy consumption and greenhouse gas emissions until 2030. *Journal of Industrial Ecology*, 27(3), pp.964–976. https://doi.org/10.1111/jiec.13386

Dikgwatlhe, P. and Mulenga, F., 2022. Perceptions of local communities regarding the impacts of mining on employment and economic activities in South Africa. *Resources Policy*, 80, p.103138. https://doi.org/10.1016/j.resourpol.2022.103138

Egbert, J. and Sanden, S., 2019. Research paradigms. In: *Routledge eBooks*. pp.30–44. https://doi.org/10.4324/9780429452963-4

Eilu, P., Molnár, F. and Peltonen, P., 2020. A thematic issue on current developments of economic geology research in Finland. *Mineralium Deposita*, 55(8), pp.1511–1514. https://doi.org/10.1007/s00126-020-01016-1

Ellram, L.M. and Tate, W.L., 2016. The use of secondary data in purchasing and supply management (P/SM) research. *Journal of Purchasing and Supply Management*, 22(4), pp.250–254. https://doi.org/10.1016/j.pursup.2016.08.005

Ericsson, M. and Löf, O., 2020. Extractive dependency in lower-income countries: Evolving trends during the transition to a low carbon future. *Working Paper Series*. https://doi.org/10.35188/unu-wider/2020/877-1

Escamilla, C., 2024. *The importance of mining in modern society*. [online] School of Mining & Mineral Resources. Available at: https://mining.arizona.edu/news/importance-mining-modern-society [Accessed 26 Apr. 2025].

European Commission, 2023. *2040 climate target*. [online] Climate Action. Available at: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en [Accessed 21 Apr. 2025].

European Investment Bank, 2024. *Finland: EU and Sibanye-Stillwater, through its Keliber lithium project, join forces in €150 million deal to improve EU access to and resilience in battery materials*. [online] Available at: https://www.eib.org/en/press/all/2024-313-eu-and-sibanye-stillwater-through-its-keliber-lithium-project-in-finland-join-forces-in-eur150-million-deal-to-improve-eu-access-to-and-resilience-in-battery-materials [Accessed 13 Jun. 2025].

European Union, 2025. *Biodiversity strategy for 2030*. [online] Available at: https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en [Accessed 12 Feb. 2025].

Finkbeiner, M., Schau, E.M., Lehmann, A. and Traverso, M., 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment*, 11(2), pp.80–85. https://doi.org/10.1065/lca2006.02.002

Food and Agriculture Organisation, 2020. *FAOLEX: Finland - Mining Act (No. 621/2011)*. [online] Available at: https://www.fao.org/faolex/results/details/en/c/LEX-FAOC124340/ [Accessed 12 Feb. 2025].

Food and Agriculture Organisation, 2025. *FAOLEX - Environmental Protection Act (No. 527 of 2014)*. [online] Available at: https://www.fao.org/faolex/results/details/en/c/LEX-FAOC174194/ [Accessed 12 Feb. 2025].

Gaia Foundation, 2020. *Rewilding Finland after mining*. [online] Available at: https://gaiafoundation.org/rewilding-finland-after-mining/ [Accessed 4 May 2025].

Ghorbani, Y., Nwaila, G.T., Zhang, S.E., Bourdeau, J.E., Cánovas, M., Arzua, J. and Nikadat, N., 2022. Moving towards deep underground mineral resources: Drivers, challenges and potential solutions. *Resources Policy*, 80, p.103222. https://doi.org/10.1016/j.resourpol.2022.103222

Government of Canada, 2025. *Minerals and the economy*. [online] Natural Resources Canada. Available at: https://natural-resources.canada.ca/minerals-mining/mining-data-statistics-analysis/minerals-economy [Accessed 13 Jun. 2025].

Gräser, M., 2024. Industrial versus artisanal mining: The effects on local employment in Liberia. *Journal of Rural Studies*, 111, p.103389. https://doi.org/10.1016/j.jrurstud.2024.103389

Green Deal, 2024. *Finnish Environment Institute (SYKE)*. [online] GreenDeal-NET. Available at: https://www.greendealnet.eu/finnish-environment-institute [Accessed 12 Feb. 2025].

Hallingberg, B., Turley, R., Griffin, T., Macmillan, A. and Mills, N., 2018. Exploratory studies to decide whether and how to proceed with full-scale evaluations of public health interventions: a systematic review of guidance. *Pilot and Feasibility Studies*, 4(1). https://doi.org/10.1186/s40814-018-0290-8

Helsinki Times, 2014. *Norilsk Nickel plant leaks 66 tonnes of nickel into environment*. [online] Available at: https://www.minesandcommunities.org/article.php?a=12712 [Accessed 12 Feb. 2025].

Hietala, S., Järvenranta, K., Hakala, K. and Virtanen, Y., 2021. Environmental life cycle assessment of Finnish beef – cradle-to-farm gate analysis of dairy and beef breed beef production. *Agricultural Systems*, 194, p.103250. https://doi.org/10.1016/j.agsy.2021.103250

Hresc, J., Riley, E. and Harris, P., 2018. Mining project's economic impact on local communities, as a social determinant of health: A documentary analysis of environmental impact statements. *Environmental Impact Assessment Review*, 72, pp.64–70. https://doi.org/10.1016/j.eiar.2018.05.009

Hunkeler, D., 2016a. Life Cycle Assessment (LCA): a guide to best practice. *The International Journal of Life Cycle Assessment*, 21(7), pp.1063–1066. https://doi.org/10.1007/s11367-016-1083-z

Hunkeler, D., 2016b. Life Cycle Assessment (LCA): a guide to best practice. *The International Journal of Life Cycle Assessment*, 21(7), pp.1063–1066. https://doi.org/10.1007/s11367-016-1083-z

IEA, 2024. *EU directive on the management of waste from extractive industries – Policies*. [online] Available at: https://www.iea.org/policies/25196-eu-directive-on-the-management-of-waste-from-extractive-industries [Accessed 12 Feb. 2025].

Ilgın, H.E., Kaya, D., Turan, G. and Karakuş, C., 2024. Life cycle assessment of an office building in Finland using a custom assessment tool. *Buildings*, 14(7), p.1944. https://doi.org/10.3390/buildings14071944

Le, T., Schreithofer, N. and Dahl, O., 2020. Dissolution test protocol for estimating water quality changes in minerals processing plants operating with closed water circulation. *Minerals*, 10(8), p.653. https://doi.org/10.3390/min10080653

Li, T.-T., Wang, L., Yang, R., Zhang, H. and Wang, Y., 2021. ESG: Research progress and future prospects. *Sustainability*, 13(21), p.11663. https://doi.org/10.3390/su132111663

Liu, Q., Fang, G., Liu, H., Tian, S. and Jiang, R., 2022. Metallic mineral exploration by using ambient noise tomography in Ashele copper mine, Xinjiang, China. *Geophysics*, 87(3), pp.B221–B231. https://doi.org/10.1190/geo2020-0923.1

Llatas, C., Soust-Verdaguer, B. and Passer, A., 2020. Implementing Life Cycle Sustainability Assessment during design stages in Building Information Modelling: From systematic literature

review to a methodological approach. *Building and Environment*, 182, p.107164. https://doi.org/10.1016/j.buildenv.2020.107164

Magnusson, T. and Berggren, C., 2017. Competing innovation systems and the need for redeployment in sustainability transitions. *Technological Forecasting and Social Change*, 126, pp.217–230. https://doi.org/10.1016/j.techfore.2017.08.014

Mining Visuals, 2024. *Mining companies by number of employees*. [online] MiningVisuals. Available at: https://www.miningvisuals.com/post/mining-companies-by-number-of-employees [Accessed 27 Apr. 2025].

Mitra, S., 2018. Depletion, technology, and productivity growth in the metallic minerals industry. *Mineral Economics*, 32(1), pp.19–37. https://doi.org/10.1007/s13563-018-0165-8

Monteiro, N.B.R., Da Silva, E.A. and Neto, J.M.M., 2019. Sustainable development goals in mining. *Journal of Cleaner Production*, 228, pp.509–520. https://doi.org/10.1016/j.jclepro.2019.04.332

Muir, T., 2019. *Closing the loop*. [online] Mining Decisions. Available at: https://www.miningdecisions.com/sustainability/closing-the-loop/ [Accessed 28 Apr. 2025].

Myllyviita, T., Leskinen, P., Seppälä, J. and Huhtala, A., 2019a. Assessing biodiversity impacts in life cycle assessment framework: Comparing approaches based on species richness and ecosystem indicators in the case of Finnish boreal forests. *Journal of Cleaner Production*, 236, p.117641. https://doi.org/10.1016/j.jclepro.2019.117641

Myllyviita, T., Leskinen, P., Seppälä, J. and Huhtala, A., 2019b. Assessing biodiversity impacts in life cycle assessment framework: Comparing approaches based on species richness and ecosystem indicators in the case of Finnish boreal forests. *Journal of Cleaner Production*, 236, p.117641. https://doi.org/10.1016/j.jclepro.2019.117641

Nanchalal, K.R., 2024. *Mining Industry Outlook 2024*. [online] Infosys. Available at: https://www.infosys.com/iki/research/mining-industry-outlook2024.html [Accessed 26 Apr. 2025].

Niu, Y., Li, Y., Ding, Y., He, Y. and Yang, L., 2021. Prolonging life cycles of construction materials and combating climate change by cascading: The case of reusing timber in Finland. *Resources, Conservation and Recycling*, 170, p.105555. https://doi.org/10.1016/j.resconrec.2021.105555

Nourelfath, M., Lababidi, H.M. and Aldowaisan, T., 2022. Socio-economic impacts of strategic oil and gas megaprojects: A case study in Kuwait. *International Journal of Production Economics*, 246, p.108416. https://doi.org/10.1016/j.ijpe.2022.108416

O'Brien, M., Yusufali, F. and Lind, G., 2023. *How AI is revolutionising the mining industry*. [online] IMARC. Available at: https://imarcglobal.com/news/articles/how-ai-is-revolutionising-the-mining-industry [Accessed 28 Apr. 2025].

Pati, D. and Lorusso, L.N., 2017. How to write a systematic review of the literature. *HERD: Health Environments Research & Design Journal*, 11(1), pp.15–30. https://doi.org/10.1177/1937586717747384

Patra, A.K., Gautam, S. and Kumar, P., 2016. Emissions and human health impact of particulate matter from surface mining operation—A review. *Environmental Technology & Innovation*, 5, pp.233–249. https://doi.org/10.1016/j.eti.2016.04.002

Petley, D. and Petley, D., 2024. *An update on the 13 February 2024 landslide at Çöpler Mine in Turkey*. [online] The Landslide Blog. Available at: https://eos.org/thelandslideblog/copler-mine-update [Accessed 13 Jun. 2025].

Ren, Q. and West, J., 2022. Cleaner waters and urbanization. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4305399

RFA Burmese, 2025. *Dozens missing in mudslide at Myanmar Jade Mine*. [online] Available at: https://www.rfa.org/english/myanmar/2025/01/13/kachin-jade-mudslide-mining-disaster/ [Accessed 12 Feb. 2025].

Rinne, R., Ilgın, H.E. and Karjalainen, M., 2022. Comparative study on life-cycle assessment and carbon footprint of hybrid, concrete and timber apartment buildings in Finland. *International Journal of Environmental Research and Public Health*, 19(2), p.774. https://doi.org/10.3390/ijerph19020774

Sairinen, R., Tiainen, H. and Mononen, T., 2017. Talvivaara mine and water pollution: An analysis of mining conflict in Finland. *The Extractive Industries and Society*, 4(3), pp.640–651. https://doi.org/10.1016/j.exis.2017.05.001

Sanyé-Mengual, E. and Sala, S., 2022. Life Cycle Assessment support to environmental ambitions of EU policies and the Sustainable Development Goals. *Integrated Environmental Assessment and Management*, 18(5), pp.1221–1232. https://doi.org/10.1002/ieam.4586

Segura-Salazar, J., Lima, F.M. and Tavares, L.M., 2019. Life Cycle Assessment in the minerals industry: Current practice, harmonization efforts, and potential improvement through the integration with process simulation. *Journal of Cleaner Production*, 232, pp.174–192. https://doi.org/10.1016/j.jclepro.2019.05.318

Shannon-Baker, P., 2015. Making paradigms meaningful in mixed methods research. *Journal of Mixed Methods Research*, 10(4), pp.319–334. https://doi.org/10.1177/1558689815575861

Shestakov, A.V. and Zuenko, A.A., 2024. Two methods of local search in open-pit mining planning. *Transactions of the Kola Science Centre of RAS Series Engineering Sciences*, 14(7/2023), pp.92–101. https://doi.org/10.37614/2949-1215.2023.14.7.010

Simsek, Z., Fox, B. and Heavey, C., 2021. Systematicity in organizational research literature reviews: A framework and assessment. *Organizational Research Methods*, 26(2), pp.292–321. https://doi.org/10.1177/10944281211008652

Smith, J. and Noble, H., 2014. Bias in research. *Evidence-Based Nursing*, 17(4), pp.100–101. https://doi.org/10.1136/eb-2014-101946

State Treasury Republic of Finland, 2024. *Central government debt management – Biodiversity in Finland*. [online] Available at: https://www.treasuryfinland.fi/investor-relations/sustainability-and-finnish-government-bonds/biodiversity-in-finland/ [Accessed 12 Feb. 2025].

Teixeira, R.F.M., Maia de Souza, D., Curran, M.A. and Antón, A., 2015. Towards consensus on land use impacts on biodiversity in LCA: UNEP/SETAC Life Cycle Initiative preliminary recommendations based on expert contributions. *Journal of Cleaner Production*, 112, pp.4283–4287. https://doi.org/10.1016/j.jclepro.2015.07.118

Terrafame, 2025. *Our product journey*. [online] Available at: https://www.terrafame.com/offering/our-product-journey.html [Accessed 12 Feb. 2025].

Tillman, A.-M., Ekvall, T., Baumann, H. and Rydberg, T., 1994. Choice of system boundaries in life cycle assessment. *Journal of Cleaner Production*, 2(1), pp.21–29. https://doi.org/10.1016/0959-6526(94)90021-3

Tost, M., Hitch, M., Chandurkar, V., Moser, P. and Feiel, S., 2018. The state of environmental sustainability considerations in mining. *Journal of Cleaner Production*, 182, pp.969–977. https://doi.org/10.1016/j.jclepro.2018.02.051

United Nations Sustainable Development, 2018. *Mining*. [online] United Nations. Available at: https://sustainabledevelopment.un.org/content/documents/dsd/dsd_aofw_ni/ni_pdfs/NationalReports/finland/Mining.pdf [Accessed 4 May 2025].

Valdivia, S., Ugaya, C.M.L., Hildenbrand, J., Traverso, M., Mazijn, B., Sonnemann, G. and Finkbeiner, M., 2021. Principles for the application of life cycle sustainability assessment. *The International Journal of Life Cycle Assessment*, 26(9), pp.1900–1905. https://doi.org/10.1007/s11367-021-01958-2

Veriforce, 2023. *Sustainable mining practices: 5 strategies to consider*. [online] Available at: https://veriforce.com/blog/sustainable-mining-practices-5-strategies-to-consider [Accessed 13 Jun. 2025].

Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Laurent, A. and Fantke, P., 2017. LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. *Journal of Cleaner Production*, 161, pp.957–967. https://doi.org/10.1016/j.jclepro.2017.05.206

Von Der Goltz, J. and Barnwal, P., 2018. Mines: The local wealth and health effects of mineral mining in developing countries. *Journal of Development Economics*, 139, pp.1–16. https://doi.org/10.1016/j.jdeveco.2018.05.005

Wan, R. and Ni, M., 2020. Sustainable development of energy, water, and environmental systems. *Environmental Science and Pollution Research*, 27(12), pp.12839–12841. https://doi.org/10.1007/s11356-020-08279-1

Williams, G. and Nikijuluw, R., 2020. The economic and social benefit of coal mining: the case of regional Queensland. *Australian Journal of Agricultural and Resource Economics*, 64(4), pp.1113–1132. https://doi.org/10.1111/1467-8489.12401

Witchalls, S., 2024. *The environmental problems caused by mining*. [online] Earth.Org. Available at: https://earth.org/environmental-problems-caused-by-mining/ [Accessed 13 Jun. 2025].

Wu, L., Subramanian, N., Abdulrahman, M.D., Liu, C. and Pawar, K.S., 2016. Short-term versus long-term benefits: Balanced sustainability framework and research propositions. *Sustainable Production and Consumption*, 11, pp.18–30. https://doi.org/10.1016/j.spc.2016.09.003

YLE, 2014. *Talvivaara leak report blames mining company, officials and media*. [online] News, 3 February. Available at: https://yle.fi/a/3-7066583 [Accessed 12 Feb. 2025].

Zhang, J., Zhang, J., Wu, C., Zhang, Y., Guo, M., Li, H. and Wang, R., 2023. Comprehensive quantitative evaluation of the future mining: A comparison of socio-economic benefits and eco-environmental impacts. *Ore Geology Reviews*, 162, p.105727. https://doi.org/10.1016/j.oregeorev.2023