Dust and Greenhouse Gas Mitigation in Mining: An LCA-MILP Approach to Sustainable Open Pit Planning

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ABSTRACT

As global demand for mineral resources continues to grow, the environmental impact of the mining industry has become increasingly significant. Sustainable mining practices require integrating environmental considerations into all phases of planning and operations. This paper addresses the urgent need to minimize the negative environmental impacts of long-term open pit mine planning, focusing on reducing greenhouse gas (GHG) and dust emissions. We propose an integrated framework that combines life cycle assessment (LCA) data with a mixed-integer linear program (MILP) to optimize mine planning processes. This framework, termed LCA-MILP, quantifies the environmental impacts of mining activities and examines various GHG constraints alongside economic scenarios. To validate the effectiveness of the LCA-MILP framework, we conducted a case study on an open-pit iron ore mine in the Middle East. Our findings emphasize the importance of aligning environmental impact reduction with long-term mine planning, fostering a more sustainable and socially responsible mining industry. For example, it was possible to reduce GHG emissions by 11.05% while achieving 93.66% of the original NPV. In another scenario, the framework achieved the same NPV as the baseline with a 2% price adjustment, while reducing environmental impact by 5.39%. These results provide mining managers with insights into the trade-offs and opportunities of incorporating environmental factors into long-term mine planning, supporting a sustainable and economically viable mining industry.

1. Introduction

Achieving sustainable development goals in the mining industry necessitates maintaining a harmonious equilibrium between economic progress and safeguarding the environment and social well-being. The Mining sector contributes substantial economic and societal advantages to nations by supplying essential raw materials to both domestic and global industries, fostering infrastructure growth, and generating employment opportunities and income for local communities [1]. While the mining industry positively influences economies and societies, which are integral components of sustainable development, it also possesses potential adverse effects on the environment, the third key pillar of sustainability. Adverse environmental impacts of mining activities encompass the destruction of natural habitats, alteration of landscapes, and degradation of air and water resources quality [1].

Approximately 10% of the world's energy-related anthropogenic greenhouse gas (GHG) emissions stem from the primary production of minerals and metals [2, 3]. Projections based on current trends suggest that by 2030, the escalation of iron ore open-pit mining activities to meet the global

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demand for raw materials could significantly increase GHG emissions, leading to more pronounced environmental degradation [4]. Conversely, an increasing number of governments are pledging to achieve net-zero emissions by either 2030 or 2050 [5]. To sustain or decrease current levels of emissions in the future, it is necessary to enhance efficiency by adopting new and improved methods within the mining industry. Enhancing environmental performance can help mining companies mitigate economic risk, especially as there is a growing demand from governments and consumers for greater environmental and social responsibility [6, 7].

The life cycle assessment (LCA) method stands out as a highly promising approach for quantifying the environmental performance of mining operations when seeking to measure environmental impacts [8]. It is an unbiased approach that assesses the environmental loads associated with a product or process throughout its lifespan, considering the supplementary impacts of materials or energy consumed in the analyzed process. An essential characteristic of LCA is its capability to assess the indirect effects of a process, such as the environmental impacts linked to the production of the fuel that powers the process [9]. So, integrating LCA with mine planning attempts to assess the environmental impact of mining activities, serving as a managerial tool for informed and sustainable decision-making.

While the LCA method has traditionally found more usage among policymakers and researchers [10, 11], mining companies have increasingly embraced it in recent times. Chaulya [12] employed a distinct method, conducting visits to three iron ore mines to quantify particulate emission rates and formulate equations for various surface activities. Emission rates during mining activities can be influenced by the physical properties of the ore. These properties, combined with other data like spatial location, constitute the foundation for the calculations in the LCA presented in their method. Ferreira and Leite [13] conducted an LCA technique to produce iron ore in Brazil. Their investigation focused on the environmental expenses associated with producing iron ore concentrate, emphasizing the significant role of grinding media contributing to mines overall environmental impacts. Vahidi, Navarro [14] presented the inaugural LCA of in-situ leach mining for rare earth elements (REEs) extracted from ion adsorption clays in southern China. The study offers novel insights into the environmental consequences and energy demands associated with this extraction approach. Islam, Vilaysouk [15] utilized remote sensing (RS) and LCA to evaluate the environmental impacts of a copper-gold-silver mine in Laos, focusing on land use change, Global Warming Potential (GWP), and Gross Energy Requirement (GER).

Mine planning, a crucial department in open-pit mines, necessitates mining companies to explore potential environmental impact mitigation strategies within this specific division [16].Mine planning involves the selection of specific materials to be extracted and determining the sequence and timing of extraction to minimize costs or achieve a particular business objective [17]. Within a sustainable framework, the alleviation of environmental impacts can be achieved by incorporating environmental constraints into modeling and employing digital technologies to implement and ensure compliance with appropriate limits for environmental footprints [1]. In recent years, numerous studies have addressed open-pit mine planning using deterministic and stochastic approaches [18-23]. However, there has been relatively less emphasis on integrating environmental impacts, including GHG emissions, into these studies. Muñoz, Guzmán [24] introduced a technique for calculating carbon emissions and energy usage at the Economic Block Model (BM) level for key mining activities. They present a new approach that involves integrating a carbon tax, linked to emissions, as supplementary costs for each block within the mine BM. Pell, Tijsseling [6] presented a novel approach to incorporate the environmental impacts into the BM of a deposit. The results demonstrate that integrating environmental constraints into mine scheduling can lead to significant reductions in global warming impact with minimal economic costs. Agosti, Utili [25] investigated the simultaneous financial and environmental implications of a carbon levy on mining and processing activities, uniquely incorporating environmental costs into the Ultimate Pit Limit

(UPL) determination alongside Net Present Value (NPV) maximization. Table 1 presents a synthesis of key studies dedicated to integrating ecological considerations into the design and strategic planning of mining operations.

Table 1. An overview of research for incorporating environmental consideration into mining design and planning.

Research	Parameters	Goal
Munoz et al [24]	Energy consumption, greenhouse gas emissions, freshwater consumption, acid mine drainage generation, and direct employment generation.	Ore resource evaluation and mine planning
Xu et al. [26]	Land area estimation, lost value of direct ecological services, lost value of indirect ecological services, prevention and restoration costs, ecological cost associated with damaged forest land, and cost of carbon emission from energy consumption	Ultimate pit optimization
Xu et al [27]	Lost value of direct ecological services, restoration costs, lost value of indirect ecological services, and carbon emission cost of energy consumption	Production scheduling
Pell et al. [6]	Dust, Carbon dioxide, PM2.5, and PM10	Mine scheduling
Xu et al. [28]	Area of land destruction, ecological costs, spiritual civilization benefit, regional economy promoting benefit, medical care benefit, and safety investment benefit	Open pit limit optimization
Rijsdijk and Nehring [29]	Carbon dioxide emission	Cut-off grade and optimal pit limits
Xu et al [30]	Ecological service value loss, reclamation costs, carbon emission cost, and lost value of direct ecological services	Ultimate pit optimization
Agosti et al [25]	Carbon dioxide emission	Ultimate pit limit and profitability

This study suggests the integration of environmental data derived from LCA into long-term mine planning to quantify the environmental impact of mining activities. An integrated framework (LCA-MILP) for implementing this approach in mine planning has been formulated through a case study of an iron deposit situated in the Middle East region. This study centers on investigating the CO_2 and dust emissions from mining activities and assessing the economic ramifications associated with these emissions. The proactive inclusion of environmental considerations in mine planning is facilitated through the integration of mine planning and LCA, achieved by defining diverse constraints and economic scenarios. The developed sustainable integrated framework provides valuable insights for environmentally responsible raw material extraction in open-pit mines.

2. Material and Methods

The environmental impact data computed through LCA can be incorporated into the mine planning procedure, allowing for the exploration of scenarios and the adjustment of constraints after the initial results generation, as depicted in Figure 1. Hence, the objective of this study is to formulate an integrated approach aimed at mitigating the environmental impacts of mining operations throughout the process of long-term mine planning. Our research seeks to create a holistic framework by integrating various tools and methodologies. This framework aims to empower mining companies to make well-informed decisions that strike a balance between production objectives and environmental sustainability.

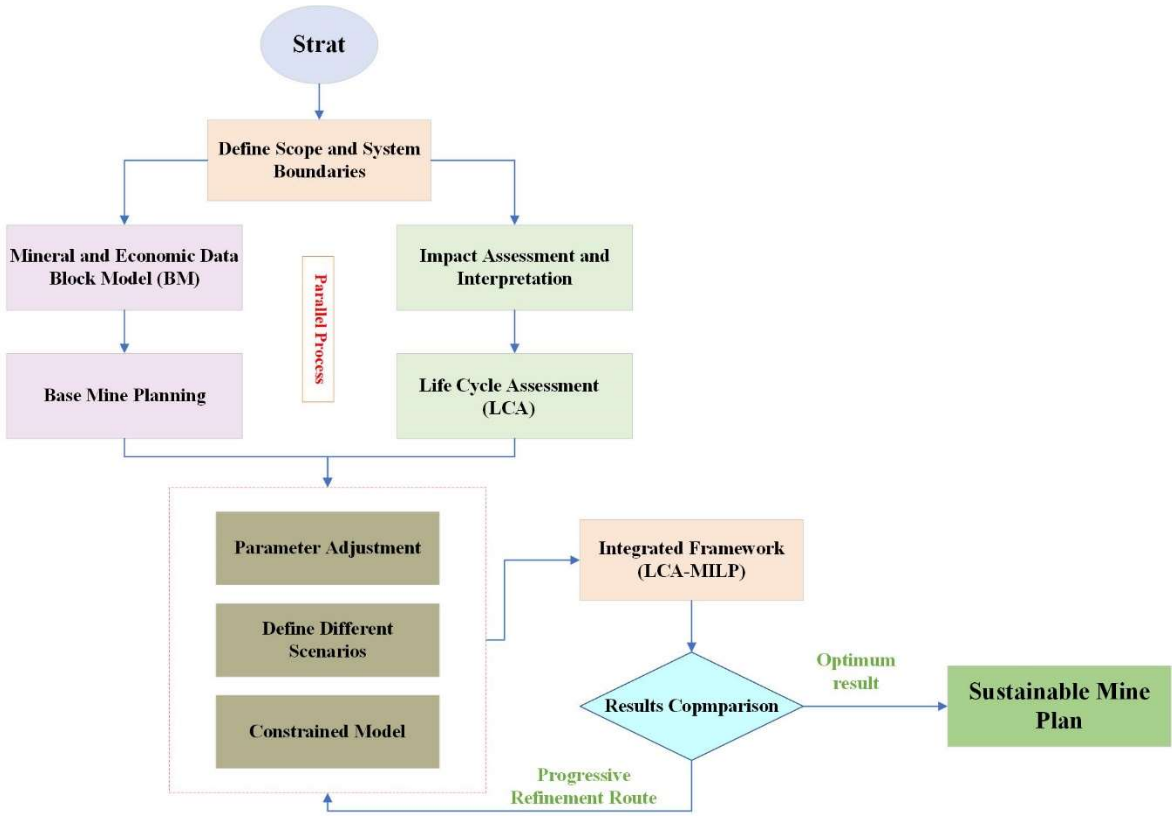

Figure 1. Details of proposed integrated framework (LCA-MILP) in this study.

In summary, the integrated framework for sustainable long-term production planning of open-pit mines commences by defining the scope and system boundaries. The base mine planning phase using a mix integer linear programming (MILP), running in parallel with LCA, establishes an initial production plan devoid of environmental considerations, acting as a reference point for subsequent scenarios. Through parameter adjustment, different scenarios are defined to explore a spectrum of economic and environmental conditions. The culmination of this approach is realized in the integrated framework (LCA-MILP), where LCA information is harmonized with a MILP model to concurrently optimize economic and environmental facets. Results comparison across scenarios facilitates a nuanced evaluation, leading to the formulation of a Sustainable Mine Plan that intricately integrates economic feasibility with environmental responsibility, thereby offering a holistic and forward-thinking strategy for the mining industry.

2.1. Environmental Impacts Measurement

Lately, several studies have emerged in the literature aiming to conduct LCA for open-pit mines [6, 25, 31]. Industries are consistently striving to enhance their environmental sustainability by employing LCA, a methodical approach to assess the environmental impacts of products and processes [1]. The LCA method enables the measurement of impacts and the identification of possibilities for mitigation, either through the exploration of alternative solutions or the improvement of existing products and processes. The objective and focus of LCA part are to evaluate the global warming impact associated with the extraction and transportation of an individual block in the specified case study. The LCA technique from extraction to the gate employed a functional unit of one block of ore or waste. The set of operations, such as drilling, blasting, and loading, remains consistent for each block. The waste block is dumped at the designated waste dump location in the mine, while the ore block undergoes crushing at the crusher, excluding additional processing steps. The LCA system boundary encompasses explosive, electricity, and diesel inputs, along with the corresponding dust and exhaust emissions occurring at the mine site, as depicted in Figure 2.

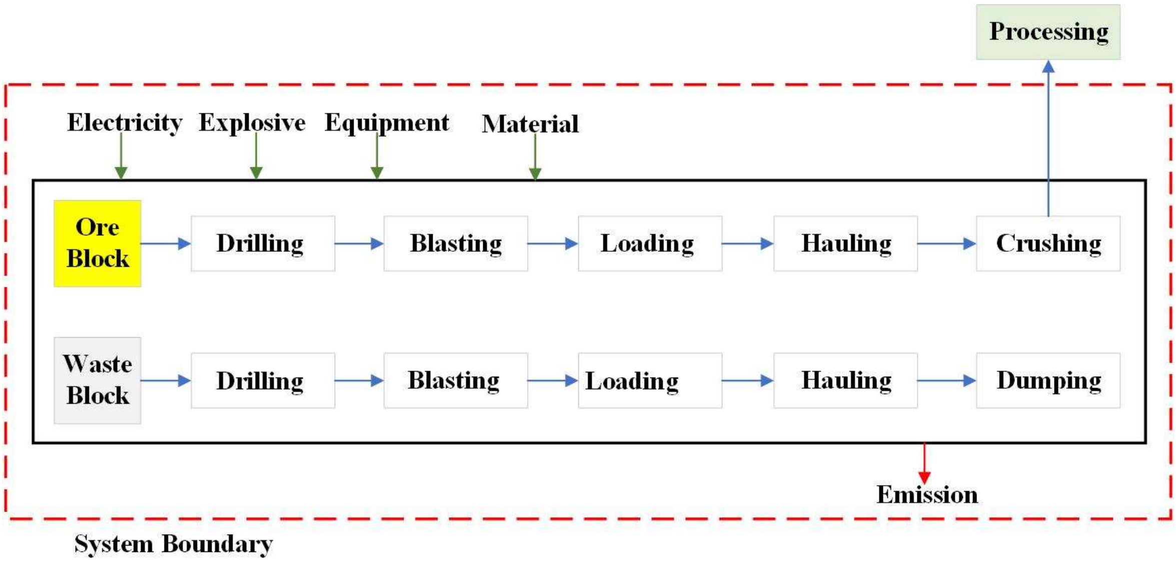

Figure 2. Environmental impact system boundary for each block.

The formulas used for particle emissions follow the methodology outlined by Chaulya [12], while the calculations for emissions related to equipment, diesel, and electricity consumption are based on the approaches by Muñoz, Guzmán [24], NPI [32]. To gain a thorough understanding of the environmental impact quantification, the equation for calculating the GWP of the mining operation can be found in Muñoz, Guzmán [24], NPI [32]. These equations include emission factors and operational parameters that are tailored to this particular study. All variables, excluding the block's physical properties, remained constant. This encompassed the environmental conditions, and the machinery utilized. Unless otherwise specified, diesel equipment is employed, chosen in accordance with the regulations applicable to the region.

Table 2. The inputs and outputs to the process of LCA.

Procedure	Element	Unit	Explanation
Drilling	Diesel	MJ	Input
Blasting	Explosives	kg	Input
Loading	Diesel	MJ	Input
Hauling	Diesel	MJ	Input
Crushing	Electricity	MJ	Input
Entirely	Carbon dioxide	kg	Output
Entirely	Dust	kg	Output

Finally, the findings in this research assess the GWP midpoint indicator using the TRACI 2.2 LCA methodology. TRACI is an application for ecological impact evaluations that can be used for products, processes, buildings, businesses, and communities. It offers characterization elements for Life Cycle effect Assessment (LCIA), industrial ecology, and sustainability measures [33]. Information regarding diesel, explosives, energy consumption, and emissions was sourced from the GaBi® database [34]. The LCA was conducted using GaBi® 6.0 software. Table 2 shows the inputs and outputs incorporated in the LCA method. The provided data comprises the primary factors contributing to the impact of GWP, a correlation supported by earlier LCA studies on mining operations [6, 35].

2.2. Long-Term Mine Planning

To formulate a mine plan, the essential information needed about the deposit includes the grade of the element of interest and the tonnage of each block. The arrangement of grade and tonnage throughout the deposit is also crucial in the process of mine planning. This study acquired information about the ore body from an iron mine situated in Iran. The authors conducted the Kriging Neighborhood method to generate an impartial estimation of the diverse elements present within the deposit on a mining block scale.

An economic and a waste value has been estimated and allocated to every block based on the elemental grades and tonnage of the block. The economic value is estimated by considering the value of the iron in the block and subtracting mining costs, processing costs, and penalties associated with the present contaminants. The economic value of the iron is determined by multiplying the iron grade with the block tonnage using an iron ore price. The waste cost is computed by multiplying the block's tonnage, determined by multiplying specific gravity by the block's dimensions, with the mining cost per tonnage (Equation 1).

$$V_i = b_i \times \left[(R \times P \times g_i) - C_p - C_m \right] \tag{1}$$

A mixed integer linear programming (MILP) model was developed for the purpose of long-term planning of the ore body. The blocks in the block model are scheduled directly on an annual basis, adhering to operational constraints (e.g., annual extraction or plant capacity) as well as desired constraints, such as product grade or maximum annual environmental impact. The ultimate objective of the optimization process is to maximize the overall NPV of the project.

Equations 2 to 8 illustrate the MILP model for long-term planning [20]. In these equations, T, I, and O denote the indices and the number of time periods, the number of blocks, and the number of ore blocks, respectively. M_{el}^t, M_{eu}^t, M_{pl}^t, and M_{pu}^t represent the minimum and maximum extraction capacities, as well as the maximum and minimum processing capacities. g_i, g_u^t, and g_l^t specify the grade of block i, the maximum required grade, and the minimum required grade for processing, respectively. b_i represents the tonnage of block, ε is the discount rate, and V_i denotes the economic value of block i. I_{pi} is a set of blocks that need to be extracted before block i. Finally, x_i^t is decision variable which equals one if block i is extracted in time period t; otherwise, it is zero.

$$Max \quad \sum_{t=1}^{T} \sum_{i=1}^{I} \frac{V_i}{(1+\varepsilon)^t} x_i^t, \qquad x_i^t \epsilon \{0,1\} \tag{2}$$

$$\sum_{r=1}^{t} x_j^r - x_i^t \geq 0, \quad \forall\, t = 1, \dots, T; i \in I; j \in I_{pi} \tag{3}$$

$$M_{el}^t \leq \sum_{i=1}^{I} b_i\, x_i^t \leq M_{eu}^t, \quad \forall\, t = 1, \dots, T \tag{4}$$

$$M_{pl}^t \leq \sum_{i=1}^{O} b_i\, x_i^t \leq M_{pu}^t, \quad \forall\, t = 1, \dots, T \tag{5}$$

$$\sum_{i=1}^{O} b_i\, x_i^t (g_i - g_u^t) \leq 0, \quad \forall\, t = 1, \dots, T \tag{6}$$

$$\sum_{i=1}^{O} b_i\, x_i^t (g_i - g_l^t) \geq 0, \quad \forall\, t = 1, \dots, T \tag{7}$$

$$\sum_{t=1}^{T} x_i^t \leq 1, \quad \forall\, i = 1, \dots, I \tag{8}$$

Where, in the above model, the objective function (Equation (2)) maximizes the NPV. The NPV is determined by adding up the economic value of every block, while taking into consideration the changing economic conditions and extraction costs, by discounting them over time using the discount rate (ε). Equation (3) represents the slope stability constraint. According to this constraint, if block j is a prerequisite for extracting block i, then block j must be extracted before block i. This constraint maintains the integrity of the mining structure and prevents the destabilization of blocks. Equation (4) indicates the maximum and minimum extraction capacities. According to this equation, the total tonnage of waste and ore blocks extracted must adhere to the mining extraction capacity. According to Equation (5), the input feed to the processing plant must fall within the required range for the plant in each time period, constrained by the minimum and maximum processing capacities. Additionally, Equations (6) and (7) establish the grade constraints for the processing plant. Equation (6) ensures that the weighted average grade of the processed ore does not exceed the upper limit, while Equation (7) guarantees that it does not fall below the lower limit. According to Equation (8), each block can be extracted at most once.

In this research, GWP per block and Fe content, contingent on economic values, were computed and assigned to all blocks in the block model. In essence, the integrated framework for sustainable long-term production planning of open-pit mines starts by defining the scope and system boundaries. Initially, we develop a base mine plan using MILP and LCA to establish a production plan without considering environmental factors. Simultaneously, we explore various scenarios by adjusting parameters, leading to the final phase's integrated framework (LCA-MILP). This integrated framework optimizes both economic and environmental factors by merging LCA information with a MILP model. It assesses the economic performance of the operation, determines metal production tonnages, and calculates annual environmental impact. By comparing results across scenarios, we can evaluate the framework comprehensively and formulate a sustainable mine plan that combines economic feasibility and environmental responsibility. In the upcoming sections, we will delve into each aspect of the framework, providing a detailed exploration of its components and implications.

2.3. Parameter Adjustment and Scenarios Definition

The initial pit scheduling was conducted without any environmental constraints, establishing the baseline for the study, and serving as a basis for subsequent assessments. Within the integrated framework, supplementary constraints were introduced, imposing an upper limit on the annual emissions output (Equation (9)). As a limitation, six levels ranging from 5 to 30 percent of the annual baseline output were selected. The chosen constraint levels were carefully selected to explore the trade-off between reducing environmental impact and economic costs. This range was chosen for two reasons. Firstly, it allows for a detailed examination of the impact at different levels, helping us understand when environmental improvements become significant. Secondly, by incorporating a range of constraint levels within our existing operational capacity, we can assess the feasibility of making changes without major alterations to our facilities. This approach provides valuable insights into the practicality and adaptability of the proposed environmental constraints within our current mining infrastructure. Overall, the selected range ensures a thorough analysis of the relationship between environmental sustainability and economic considerations, providing actionable insights for the industry. The levels of reduction of GHG emissions are presented in Table 3.

$$\sum_{i=1}^{I} E_i \, x_i^t \leq Upper\ Limit, \quad \forall\, t = 1, \ldots., T \tag{9}$$

Where E_i represents the emissions associated with block i.

Table 3. The levels of environmental constraints.

Level	Environmental threshold
Base	None
Level 1	5% reduce
Level 2	10% reduce
Level 3	15% reduce
Level 4	20% reduce
Level 5	25% reduce
Level 6	30% reduce

Moreover, the economic value of Fe was modified by augmenting the base Fe price of $120 per ton by 1%, 2%, 3%, 4%, and 5%, respectively. Thus, scenarios were defined by combining environmental constraints and price adjustments. The justification for assigning added value to Fe in evaluations involving global warming thresholds is grounded in the findings of numerous studies, which indicate that integrating environmental constraints into mining operations can enhance the overall value of minerals [1, 6, 36]. By incorporating a heightened economic value for Fe, it becomes feasible to assess the potential additional value a company could theoretically add to a product with reduced carbon emissions. With this clarification for future evaluation, Table 4 outlines the defined scenarios.

The procedure outlined in the mine planning section was adhered to, incorporating the environmental constraints detailed in Table 4 for all scenarios. An augmented economic value for the block was also implemented within the constraints elucidated in Table 4 for scenarios 2–6. This was done to comprehend the elevated block value necessary to align with the baseline under environmentally constrained conditions. Subsequently, the data generated from the integrated framework (LCA-MILP) can be evaluated in terms of both environmental impact and its corresponding influence on the NPV. In this phase of comparing results, it is also feasible to picture relationships between scenarios and adjust constraints for additional assessment.

Table 4. The details of scenarios employed in this study.

Scenario	Symbol	Goal	Price adjustment	Environmental threshold
1	S1	Max NPV	None	Base and All levels
2	S2	Max NPV	1%	Base and All levels
3	S3	Max NPV	2%	Base and All levels
4	S4	Max NPV	3%	Base and All levels
5	S5	Max NPV	4%	Base and All levels
6	S6	Max NPV	5%	Base and All levels

3. Results

In this section, our proposed integrated framework is implemented in various scenarios to showcase its efficacy. The implementation was carried out using Python® programming language [37] and the CPLEX® solver [38]. All experiments were conducted on a Windows 11 workstation equipped with an AMD Ryzen 7 5800H CPU and 16GB of RAM. To validate and test the developed LCA-MILP, we applied it to a case study involving an open-pit iron mine. This iron deposit is located in the Middle East region. The reserve modeling, planning activities, and long-term production planning were grounded in drill-hole prospecting data.

3.1. Mine Planning Without Environmental Issues

As previously stated, the initial mine plan was formulated without environmental constraints, establishing the study's baseline and providing a foundation for subsequent evaluations. Hence, Figure 3 illustrates the financial and environmental aspects of this approach. The mine planning, conducted without environmental constraints, resulted in annual emissions ranging from 80,000 to 95,000 equivalent ton, with a cumulative total of 439,000 equivalent ton. Emissions exhibit an ascending trend from the outset, peaking in period 4, and subsequently experiencing a substantial decrease toward the end. At the same time, CO2 accounted for 55% and dust for 45%, equating to 241,000 equivalent ton and 198,000 equivalent ton, respectively. Figure 3 illustrates the cumulative NPV, showcasing the optimization of the target cut-off grades. By the end of period 5, the baseline achieved an NPV of $1,188 million.

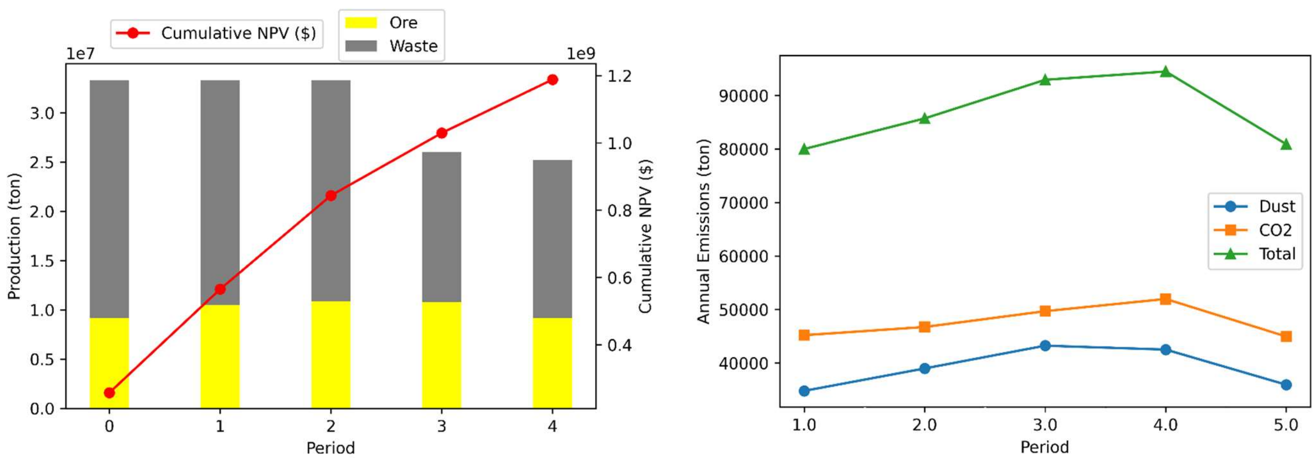

Figure 3. Annual production and cumulative NPV (left) alongside annual emissions (right) in the baseline.

3.2. Environmentally Constrained Mine Planning

Implementing annual environmental constraints in the mine planning framework has an impact on both the annual and cumulative global warming potential emissions as well as NPV. Table 5 presents cumulative emissions and NPV values under various environmental constraints. In these scenarios, the constraint is defined to restrict the global warming impact up to 30% of the average global warming value for all threshold levels. The first level witnessed a 6.24% decrease in emissions, leading to a corresponding NPV reduction of $37.9 million, equivalent to a 3.19% decrease compared to the baseline. At the second level, similar to the first one, there is a slight decline in financial returns with an 11.05% reduction, resulting in an NPV decrease of $75.29 million. This signifies a 3% difference between the two levels. However, as the threshold increases, the differences become more pronounced. For instance, the disparities between levels 4 and 5, as well as levels 5 and 6, were 5.8% and 5.91%, respectively. This results from the more stringent constraint restricting the extraction of blocks with higher impact. The relationship between NPV and environmental impact rate is non-linear, as shown in Table 5. This distinction serves as a crucial factor for planners in crafting strategic plans, allowing them to assess how deviation from desired financial outputs can be minimized alongside emission reductions. This suggests the potential for finding an optimal solution through the exploration of various constraints and economic values.

Table 5. Impact of environmental constraint on financial and environmental outputs.

Detail	Environmental threshold	Emissions		NPV	
		Amount (ton)	Decrease (%)	Amount (M$)	Decrease (%)
Mine Plan	Base	439133	0.00	1188.46	0.00
	Level 1	411728	6.24	1150.56	3.19
	Level 2	390630	11.05	1113.18	6.33
	Level 3	368750	16.03	1062.47	10.60
	Level 4	347000	20.98	1000.45	15.82
	Level 5	326772	25.59	931.54	21.62

This paper seeks to explore the possibilities of reducing environmental emissions and the associated economic consequences without the need for facility modifications. One bottleneck in mining operations lies in meeting the plant's feed requirements. To address this concern, Figure 4 illustrates the influence of each environmental constraint level on the incoming feed to the plant. In the initial and final periods of the first and second levels, the annual ore production remains comparable to the baseline, while there is a more pronounced reduction in the middle periods. For the third level, the reduction exhibits an irregular pattern, and the fourth and fifth levels demonstrate a consistently significant reduction. However, in the sixth level, non-compliance with the minimum plant feed is observed throughout the periods except for the last one, based on the specified threshold. For this reason, the sixth level of environmental constraint is not considered in further analysis.

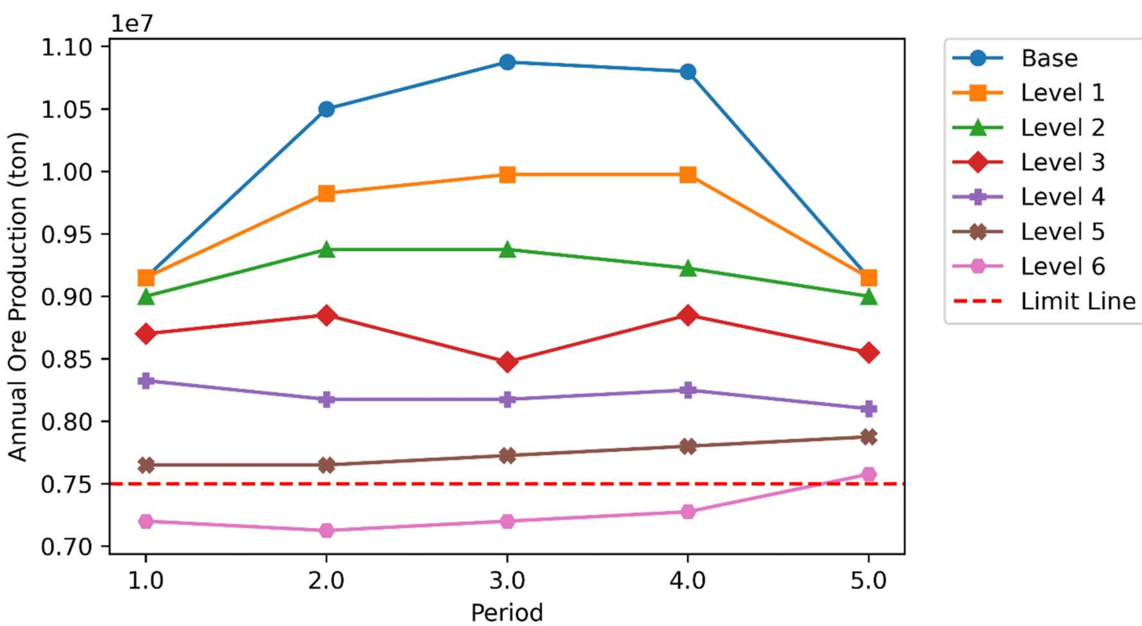

Figure 4. Annual ore production for each level of environmental constraint.

Figure 5 depicts the relative carbon emissions from mining processes for two selected blocks. Transportation emerges as the key contributor to carbon output, with each block's transport emissions calculated separately. An increase in the depth of the pit is projected to amplify carbon emissions from hauling, as longer haul cycles will require more fuel per ton of material transported. Additionally, the process of crushing is responsible for 27% of the total carbon emissions produced by mining activities for ore blocks.

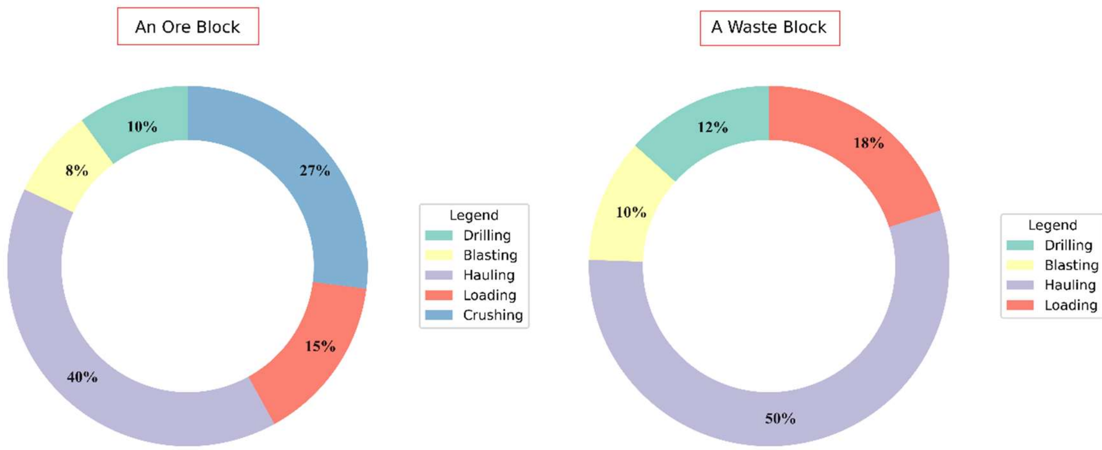

Figure 5. Distribution of carbon dioxide emissions among various mining processes.

3.3. Scenario Results Comparison

Some mining companies voluntarily adhere to environmental standards and carbon dioxide emission limits, offering their raw material products at premium prices due to a reduced global warming footprint. In certain regions, like Canada, carbon taxes have been implemented, creating economic incentives for the reduction of CO2 emissions. Scenarios are defined by introducing environmental thresholds alongside a gradual increase in the economic value of Fe, ranging from 1% to 5%. This approach enables us to assess the necessary value increase to sustain the baseline NPV while simultaneously reducing the GWP impact. Table 6 presents the outcomes for the six scenarios incorporating elevated Fe values and emissions constraints.

As depicted in Table 6, the NPV performance is contrasted between scenarios, comparing the baseline with the outcomes of incorporating environmental constraints. In scenario 1, the outcomes pertain to the condition where the mine plan runs without any price adjustment. This provides insights to managers regarding the costs associated with reducing emissions in operations. For instance, by implementing an environmental constraint, it was feasible to attain 88.95% of the global warming impact while achieving 93.66% of the NPV compared to the baseline. The change highlighted in Table 6 is derived by subtracting the baseline NPV, and the negative value indicates that this condition has a higher NPV. In scenario 3, it is viable to achieve nearly the same NPV as the baseline while attaining a 94.61% reduction in global warming impact through a 2% price adjustment. In scenario 5, introducing a 4% price adjustment resulted in achieving 91.37% reduction in global warming impact. For a better understanding of the impact of applied changes, Figure 6 illustrates the NPV performance in scenarios one and six.

According to Figure 6, it is evident that in the scenario with a 5% adjustment, in addition to the first level of emission constraint, which has a higher NPV compared to the baseline, the second level of constraint also accurately covers both the annual and cumulative NPV of the baseline. Incorporating price adjustments into the modeling process leads to variations in financial outcomes, block sequencing, and emission levels. At lower percentages (1% and 2%), the outcomes suggest that the fundamental optimization is making minimal change to the selection and order of block extraction. However, in scenarios with 4% and 5% adjustments, the heightened economic value of Fe opens new economically viable areas within the deposit, even while adhering to emission thresholds. These alterations can substantially influence the overall cumulative emissions.

Table 6. The outcomes for the six scenarios incorporating elevated Fe values and emissions constraints.

Scenario	Environmental	Price Adjustment	NPV

	threshold		Amount (M$)	Change (%)
Scenario 1	Base	-	1188.46	0.00
	Level 1	-	1150.56	3.19
	Level 2	-	1113.18	6.33
	Level 3	-	1062.47	10.60
	Level 4	-	1000.45	15.82
	Level 5	-	931.54	21.62
Scenario 2	Base	-	1188.46	0.00
	Level 1	1%	1167.58	1.76
	Level 2	1%	1129.58	4.95
	Level 3	1%	1078.11	9.29
	Level 4	1%	1015.20	14.58
	Level 5	1%	945.35	20.46
Scenario 3	Base	-	1188.46	0.00
	Level 1	2%	1184.59	0.33
	Level 2	2%	1145.97	3.58
	Level 3	2%	1093.74	7.97
	Level 4	2%	1029.96	13.34
	Level 5	2%	959.17	19.29
Scenario 4	Base	-	1188.46	0.00
	Level 1	3%	1201.60	-1.11
	Level 2	3%	1163.26	2.12
	Level 3	3%	1110.26	6.58
	Level 4	3%	1045.60	12.02
	Level 5	3%	973.87	18.06
Scenario 5	Base	-	1188.46	0.00
	Level 1	4%	1218.62	-2.54
	Level 2	4%	1179.67	0.74
	Level 3	4%	1125.91	5.26
	Level 4	4%	1060.37	10.78
	Level 5	4%	987.70	16.89
Scenario 6	Base	-	1188.46	0.00
	Level 1	5%	1235.63	-3.97
	Level 2	5%	1195.17	-0.56
	Level 3	5%	1140.65	4.02
	Level 4	5%	1074.22	9.61
	Level 5	5%	1000.61	15.81

4. Discussion

The results of this research have implications for mining managers who are working towards creating strategic mine plans that balance economic goals with environmental responsibility. Our study offers insights to decision makers who want to align mining operations with sustainability objectives by integrating environmental impact assessment into long term planning for open-pit mines. The main purpose of incorporating factors into the mine planning process is to enable mining companies to make decisions that consider both production goals and environmental sustainability. The findings emphasize the role of decision making in achieving a harmonious equilibrium between economic performance and its impact on the environment.

As previously discussed, the introduction of price adjustments results in variations in emitted emissions. Table 7 illustrates the environmental performance and adjustment justifies spending money to decrease emissions across diverse scenarios. The difference within a column between the two scenarios is inconspicuous, while the variance between Scenario 1 and Scenario 6 is approximately 2%. Thus, Figure 7 visually depicts annual emissions in relation to Scenarios 1 and 6. The improvement in costs serves as an additional criterion for managers to evaluate, determining which strategies align with the company's policies in this domain. The presence of negative values indicates a profitable outcome for the scenario. This is attributed to the enhanced value assigned to the block, surpassing the baseline in terms of economic performance in these scenarios.

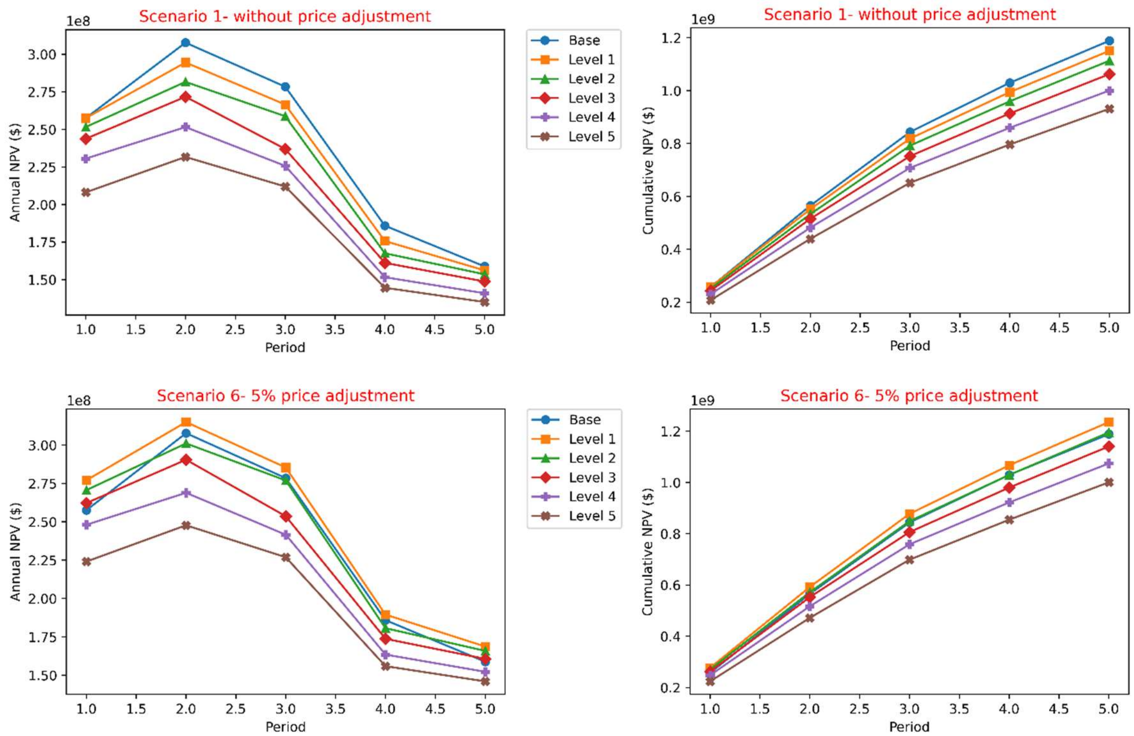

Figure 6. The obtained NPV of scenarios 1 and 6 relative to base.

Table 7. Comparative analysis of environmental impact and cost enhancements across various scenarios.

Scenario	Emission amount with each level					Emission per ton of iron ore	$ Per kg emission saved
	Level 1	Level 2	Level 3	Level 4	Level 5		
Scenario 1	411728	390630	368750	347000	326772	8.44 to 8.56	1.38 to 2.29
Scenario 2	414020	392801	370799	348924	328568	8.49 to 8.61	0.83 to 2.2
Scenario 3	415432	394155	372088	350139	329725	8.52 to 8.64	0.16 to 2.10
Scenario 4	416400	395077	372978	350973	330427	8.55 to 8.67	-0.58 to 1.97
Scenario 5	418227	396820	374616	352515	331950	8.58 to 8.71	-1.44 to 1.87
Scenario 6	419863	398368	376069	353885	333238	8.61 to 8.74	-2.45 to 1.77

The LCA scores for various scenarios suggest that for a ton of iron ore extracted emissions were between 8.44 and 8.74 at the mine. Pell et al [6] computed a value of 8.22 kg per ton of extracted ore, considering scenarios without the inclusion of crushing in the cycle and under various mine conditions. These values fall within the range reported by Norgate and Haque [39], who determined a CO_2 emission of 11.9 per ton of Fe concentrate, and Ferreira and Leite [13], who calculated 13.32 kg CO_2 per ton of Fe concentrate [40, 41].

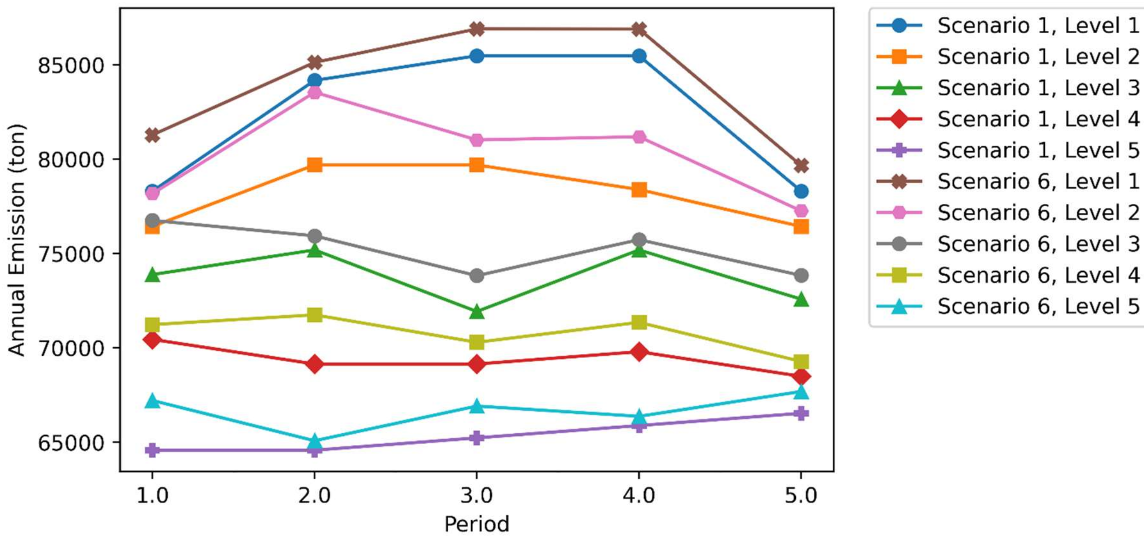

Figure 7. The obtained NPV of scenarios 1 and 6 relative to base.

One important finding is the non-linear relationship between NPV and environmental impact, especially when emission constraints are imposed. Mining managers face the challenge of optimizing NPV while adhering to environmental limitations in their long-term planning. Our study examines various scenarios to understand how different levels of environmental constraints and economic adjustments affect the economic and environmental performance of mining operations. The research shows that sustainable mining practices can be achieved without sacrificing economic viability. By introducing environmental constraints and making incremental adjustments to the economic value of iron ore, we discovered a range of feasible scenarios. This insight is invaluable for managers who want to develop mine plans that not only meet financial targets but also contribute to environmental stewardship. The study highlights the importance of assigning a higher economic value to iron ore (Fe) in successfully implementing environmentally constrained mine plans. Under certain scenarios, the additional value attributed to Fe can lead to profitable outcomes that surpass the baseline economic performance. This finding gives managers a strategic lever to explore economically viable options while minimizing the ecological footprint.

The analysis of ore production within environmental constraints highlights operational challenges, particularly in meeting plant feed requirements. This understanding prompts mining managers to not only consider the economic feasibility of extraction, but also the practicalities of maintaining consistent production levels under varying environmental limitations. The study's comparative environmental analysis provides insights into the cost benefits associated with different scenarios. The presence of negative values in certain scenarios indicates profitable outcomes, emphasizing that environmentally responsible practices can align with economic success. This information serves as a valuable criterion for managers to evaluate strategies that adhere to the company's sustainability policies. By drawing on real-world case studies and emerging trends, our research contributes to the evolving landscape of sustainable mining practices. The defined scenarios, along with economic adjustments, offer mining managers a practical roadmap to navigate the complexities of integrating environmental considerations into mine planning.

The results of this research provide mining managers with a strategic framework to effectively address the changing demands for sustainable and socially responsible mining. By demonstrating the viability of mine plans that prioritize environmental constraints, the study contributes to a transformative shift in the industry, where economic success and ecological responsibility are intertwined objectives. These findings empower mining managers to actively shape the future of mining operations, promoting a more sustainable and socially responsible mining industry. While our study establishes a strong foundation, future research should explore the integration of social impacts, regulatory considerations, and community engagement into mine planning strategies. Additionally, investigating the applicability of the proposed methodology in different mining contexts and commodities could further enhance its practical usefulness

5. Conclusion

This study highlights the importance of considering environmental impacts in long-term mine planning to promote sustainability in the mining industry. The results show that by strategically implementing environmental constraints, it is possible to reduce global warming potential emissions by 25.59% without compromising the lower limit of processing plant. Additionally, NPV shows a decreasing trend of up to 21.62%. The integrated framework (LCA-MILP) developed in this study, which incorporates environmental impact factors as constraints in mine planning, is a valuable tool for mining managers. It helps them navigate the complex trade-offs between economic objectives and environmental responsibility. The findings of this study provide practical insights on how mining operations can minimize their ecological footprint while optimizing economic performance.

Additionally, by exploring scenarios that consider both environmental limitations and adjustments in the economic value of the extracted resource, a more comprehensive understanding of potential strategies can be gained. This knowledge can be utilized by mining managers to develop sustainable and economically feasible mine plans, taking into consideration factors such as emission reduction targets and economic implications. By quantifying the outcomes, this research provides tangible strategies that can be used by stakeholders in the mining industry to make well-informed decisions. The study aims to promote a shift towards responsible and sustainable resource extraction, aligning with global efforts to address environmental challenges. Given the increasing scrutiny faced by the mining sector, the insights from this research contribute to the ongoing conversation about balancing economic objectives with environmental stewardship to create a resilient and socially responsible mining industry.

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