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The Effects of Emission-Reduction Baselines on Comparative Mine Performance: Implications for Health and Environmental Sustainability

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Abstract

Robust assessment of emission-reduction performance in mining depends on the baseline against which reduction is defined. However, limited attention has been given to how alternative baselines alter estimated reductions and comparative performance. This study evaluates this baseline effect using PM_{10} emissions from three limestone mines in Thailand through an Inventory Scenario (I_S), benchmarked against each mine's emission inventory, and a Compliance Scenario (C_S), benchmarked against the regulatory ambient PM_{10} limit. The analysis examines reduction asymmetry, performance classification shifts, and ranking variability, identifying a baseline-contingent performance divergence. I_S yielded estimated reductions of 160, 723, and 2760 t yr^{-1} for M1–M3, compared to 280.13, 279.61, and 245.01 t yr^{-1} under C_S. The resulting asymmetry was −120.13, 443.39, and 2514.99 t yr^{-1}, with rankings reversing from M3 > M2 > M1 under I_S to M1 > M2 > M3 under C_S. The findings further reveal an equity–efficiency paradox, whereby inventory reduction and compliance attainment identify different dimensions of performance, and a marginal-effect paradox, in which the significance of further abatement depends on a mine's proximity to the regulatory boundary. These findings establish baseline selection as a substantive component of emission-reduction performance assessment with implications for benchmarking, ESG reporting, incentivization, and regulatory decision-making.

Keywords: particulate emission; emission management; emission scenario; compliance; mining; ESG; EIA; environmental sustainability; pollution

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1. Introduction

Despite the significant economic contribution of mining to global development, the sector remains a major contributor to atmospheric pollution, generating fugitive dust and particulate matter, including PM_{10} and $PM_{2.5}$, through drilling, blasting, crushing, material handling, and transportation [1,2]. Exposure to these pollutants is associated with respiratory, cardiovascular, and other adverse health outcomes [3,4], with particulate concentrations frequently elevated in and around mining areas relative to background locations [2,5,6]. These environmental, health, and socioeconomic burdens have made emission reduction an essential component of sustainable mining [7,8], subjecting mining

operations to environmental management requirements and regulatory standards intended to control and abate associated emissions [9–14].

Within the emission-abatement paradigm in mining, two assessment perspectives are particularly relevant. The first is an inventory-based perspective, in which emission reduction is evaluated relative to the emissions generated by a mine's operational activities [15,16]. This perspective considers the difference between estimated emissions under uncontrolled and controlled operating conditions, thereby emphasizing the extent to which point-source emission control strategies reduce the mine's emission-generating potential. The second is a compliance-based perspective, in which environmental performance is evaluated against a regulatory standard or permissible ambient air-quality threshold [9,10,17]. Rather than quantifying point-source reductions, this perspective assesses the extent to which monitored ambient conditions fall below the applicable regulatory limit. These perspectives therefore represent different reference points for evaluating emission-reduction performance: the operational emission inventory and the regulatory compliance threshold, respectively.

It is essential to note that both reference points do not account for historical emission baselines, industry-average benchmarks, or projected business-as-usual emission scenarios. The inventory-based reference in this study represents estimated emissions from each mine's unique activities, while the compliance-based reference represents the applicable regulatory ambient PM_{10} limit. Thus, their selection reflects two complementary dimensions of mining environmental performance: the effectiveness of emission controls at source and the attainment of acceptable ambient air quality. Although operational inventory emissions contribute to ambient particulate pollution, the two assessment perspectives are not computationally dependent because ambient concentrations are also influenced by atmospheric dispersion, meteorological conditions, background pollution, and other environmental factors [2,9,10,17]. Consequently, they provide distinct but environmentally connected assessments of the same underlying pollution problem.

Moreover, the choice between these reference points can substantially influence the interpretation of emission-reduction performance. For instance, a mine with a large emission inventory may achieve a substantial reduction relative to its operational emissions while exhibiting a comparatively smaller margin below the regulatory ambient threshold. On the contrary, a mine with a smaller emission inventory may achieve a lower absolute reduction but maintain a greater margin below the regulatory limit. Consequently, baseline selection can produce baseline-contingent performance divergence, whereby the magnitude of estimated reduction and the relative ranking of mining operations depend on the reference point adopted. This divergence further exposes a broader equity–efficiency paradox: inventory-based assessment primarily recognizes reduction efficiency in relation to an operation's emission-generating potential, whereas compliance-based assessment evaluates environmental performance against a common regulatory boundary, emphasizing the attainment of an acceptable environmental condition. Thus, prioritizing source-level reduction efficiency or common-threshold compliance may produce different conclusions about which mining operation performs better.

This tension also raises questions about how additional emission reductions should be recognized as a mine approaches the regulatory threshold. In particular, the environmental and regulatory significance of further abatement may differ depending on the magnitude of a mine's operational emissions and its proximity to the compliance boundary. However, how different emission-reduction baselines or reference points affect estimated emission levels and the comparative ranking of mining performance remains insufficiently explored.

Despite extensive research on particulate emission inventories, emission factors, regulatory compliance, and the health consequences of mining emissions [2,4,7,9,10,18–20],

limited attention has been given to how these alternative emission-reduction reference points influence the assessment outcomes and comparative environmental performance across mining operations. Principally, it remains uncertain whether the use of operational inventory and regulatory compliance references produces substantially different reduction estimates, changes performance classifications, or reverses comparative mine rankings. This gap is important because the reference point adopted can influence environmental benchmarking, regulatory evaluation, mitigation priorities, and the incentives used to recognize emission-reduction performance [18,20]. Without considering these contrasts, assessments based on a single reference point may provide an incomplete, conflicting or potentially misleading representation of comparative environmental performance.

To address this gap, this study adopts a scenario-based approach to compare two alternative perspectives for assessing PM_{10} emission-reduction performance across small-, medium-, and large-scale limestone mines in Thailand: an Inventory Scenario (I_S) and a Compliance Scenario (C_S). The I_S estimates source-level PM_{10} reductions using mine-specific operational activities and activity-based emission factors, while the C_S evaluates ambient PM_{10} conditions against the applicable regulatory threshold using reported monitoring data. Precisely, the study examines: (1) the magnitude and direction of emission-reduction asymmetry between the I_S and C_S; (2) the extent to which the alternative assessment baselines alter mine performance classification; and (3) the extent to which they produce variability or reversals in comparative mine rankings.

In doing so, the study contributes to literature on emission accounting and environmental performance assessment by conceptualizing baseline-contingent performance divergence and demonstrating the equity–efficiency paradox that can arise from alternative assessment criteria. It shows that the reference point adopted influences not only the magnitude of estimated PM_{10} emission reductions but also their comparative interpretation and the management signals they generate. These findings have implications for environmental risk management, public health protection, pollution-control decision-making, and ESG reporting, particularly on how emission reductions are defined, recognized, compared, and used to inform mitigation priorities.

2. Materials and Methods

Figure 1 illustrates the conceptual approach for assessing PM_{10} emission reduction under the Inventory Reduction Scenario (I_S) and Compliance Scenario (C_S), including the associated emission sources, ambient conditions, regulatory threshold, and sensitivity analysis.

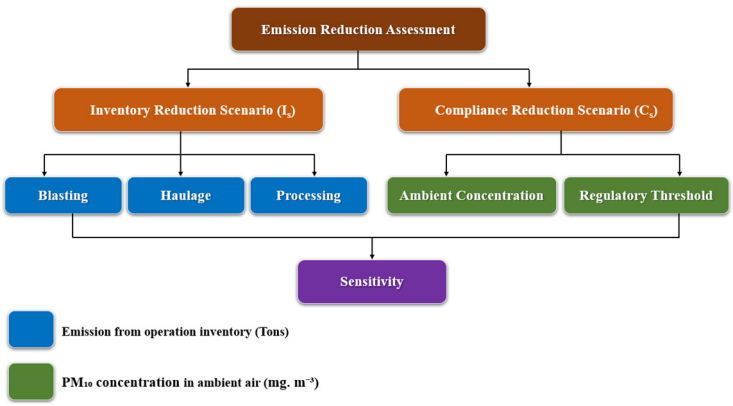

Figure 1. Conceptual approach for the alternate scenario used in the assessment of PM_{10} emission reduction.

2.1. Data Sources, Extraction and Quality Considerations

Datasets for the Inventory Scenario (I_S) and ambient PM_{10} monitoring data for the Compliance Scenario (C_S) were extracted from the respective mine EIA reports from the open source archive (https://eia.onep.go.th/site/eia, accessed on 5 September 2026). The study covered three open-pit limestone quarries/mines (M1, M2, and M3), with annual production capacities of 2.1, 6.9, and 7.3 million tonnes, respectively. I_S data included annual production, blasting frequency, haul-road characteristics, vehicle/haulage trips, operating days, and mineral-processing throughput. These variables were used with US EPA AP-42 emission factors to estimate source-specific PM_{10} emissions. For the C_S, reported ambient PM_{10} concentrations were evaluated against the applicable regulatory standard. Data reliability was supported by documented mine information and established technical guidance. Emission factors and control efficiencies were selected based on US EPA AP-42, the WRAP Fugitive Dust Handbook, and documented mine-specific dust-control practices [21–25]. Sensitivity analysis further examined the influence of variations in key operational parameters and atmospheric mixing height on the resulting estimates (Section 4.4).

2.2. Inventory Reduction Scenario (I_S)

The Inventory Reduction Scenario (I_S) represents the operational perspective of PM_{10} reduction, in which emission performance is assessed against the quantity of particulate matter generated by the mine's production activities [16]. The inventory was estimated by mapping the principal particulate emission generating processes within each mining operation and quantifying their annual PM_{10} contributions under the documented operating and control conditions. Three representative limestone mines were selected and designated M1, M2, and M3, representing small-, medium-, and large-scale operations, respectively.

The production system was divided into three principal emission processes: blasting, haulage, and mineral processing, with the latter comprising crushing, screening, and material-transfer activities. This process-based structure follows the source categories addressed in the U.S. EPA AP-42 Compilation of Air Pollutant Emission Factors, which provides source-specific factors for particulate emissions from mining and mineral-processing activities [21–25]. Operational data were obtained from the Environmental Impact Assessment (EIA) reports of the selected mines, including annual production, blasting activities, and other parameters previously mentioned in section 2.1.. These activity data were combined with the corresponding AP-42 emission factors and reported control efficiencies to estimate the annual PM_{10} contribution of each emission source.

2.2.1. Blasting Emissions

Blasting is a routine activity in mining operations used to fragment rock and facilitate subsequent excavation and material handling. The detonation of explosives generates intense mechanical forces that fracture and eject rock, producing fine particles that can become airborne. Blasting, therefore, represents a short-duration but significant source of fugitive PM_{10} emissions and is an important source to consider in mine-scale air-quality assessments. For blasting, annual PM_{10} emissions were estimated from the quantity of material subjected to blasting using the EPA AP-42 scaling approach:

$$EF_{PM10} = 0.52 \times EF_{TSP} \quad (1)$$

where 0.52 factor represents the PM_{10}-to-TSP mass ratio adopted by the US EPA based on particle-size distribution data from material-handling emission tests [22]. Therefore, annual PM_{10} emissions from blasting (E_b) are given as:

$$E_b = B_f \times EF \times (1 - CE) \quad (2)$$

where B_f is the blast frequency per year and CE is control efficiency. Note: the resulting emissions are initially obtained in kg yr^{-1} because the emission factor is expressed in kg $blast^{-1}$ and blast frequency in blasts yr^{-1}. The result is divided by 1000 to convert kilograms to tonnes, thereby expressing annual PM_{10} emissions in t yr^{-1}. Control efficiency (CE) represents the overall fractional reduction in PM_{10} emissions achieved through the implementation of dust-control measures relative to an uncontrolled or baseline condition [22]. CE values were assigned based on established empirical effectiveness ranges for the respective control practices, considering their type, intensity and documented implementation. The assignments were supported by mine-specific EIA reports and cross-validated against US EPA AP-42 guidance and the WRAP Fugitive Dust Handbook [22,23]. Table S1 presents the basis for control-efficiency assignment. Formally, CE represents the relative difference between uncontrolled ($E_{uncontrolled}$) and controlled ($E_{controlled}$) emission rates or concentrations, expressed as:

$$CE(\%) = \left(1 - \frac{E_{controlled}}{E_{uncontrolled}}\right) \times 100 \quad (3)$$

2.2.2. Haulage Emissions

Mineral haulage involves the transportation of extracted ore and waste rock between mining areas, processing facilities, and stockpiles, typically along unpaved haul roads. The movement of heavy vehicles over these surfaces causes mechanical disturbance and tire–road abrasion, resuspending fine particles accumulated on the road surface. Thus, haul-road traffic can represent a substantial source of fugitive PM_{10} emissions in mining operations and is therefore an important component of mine-scale air-quality assessment. PM_{10} emissions from haul-road transportation were estimated using the AP-42 formulation for industrial unpaved roads. The source-specific emission factor was determined as a function of road-surface silt content and mean vehicle weight:

$$EF = 423 \times \left(\frac{S}{12}\right)^{0.9} \times \left(\frac{W}{3}\right)^{0.45} \quad (4)$$

where EF is PM_{10} emission factor (g VKT^{-1}), s is surface material silt content (%), and W is mean vehicle weight (tons). The AP-42 unpaved-road methodology uses these variables to estimate particulate emissions generated by vehicle movement over unpaved surfaces. Annual PM_{10} emissions from haul transport (E_t) were calculated by multiplying the daily emission rate (E_R) by the number of operational days (N), converting grams to tonnes (dividing by 10^6), and adjusting for control efficiency $(1 - CE)$, Equation (5).

$$E_t = \left(\frac{E_R \times N}{10^6}\right) \times (1 - CE) \quad (5)$$

where E_t is expressed in tons per year (t yr^{-1}). This approach accounts for the influence of haul-road surface characteristics, vehicle loading, operational activity, and dust-control systems on PM_{10} emissions.

2.2.3. Mineral-Processing Emissions

Mineral processing involves a series of material-handling operations, including crushing, screening, and transfer, that mechanically reduce and convey extracted rock. These activities can disturb and resuspend fine particles, resulting in the release of fugitive PM_{10}, particularly where material is repeatedly crushed, screened, or transferred between processing units. Mineral processing also constitutes an important source of PM_{10} emissions in mining operations. Mineral processing was treated as a collection of individual

emission nodes rather than as a single source. PM_{10} emissions from crushing, screening, and material transfer were therefore estimated as:

$$E_P = \sum_{k=1}^{m} \left(Q_k \times EF_k \times (1 - CE) \right) \quad (6)$$

where E_P is annual PM_{10} emissions from mineral processing (t yr^{-1}), Q_k is the annual material throughput of processing unit k(t yr^{-1}), EF_k is the corresponding AP-42 PM_{10} emission factor, CE is the control efficiency, and m represents the number of processing sources. AP-42 Section 11.19.2 provides source-specific emission factors for crushed-stone processing activities, including crushing, screening, and material transfer.

2.2.4. Aggregate PM_{10} Inventory

The total annual PM_{10} inventory under the Inventory Scenario (E_{IS}) was obtained by summing the controlled emissions from blasting, haulage, and mineral processing, expressed:

$$E_{IS} = E_B + E_H + E_P \quad (7)$$

where E_{IS} is the total annual PM_{10} emission inventory under the Inventory Scenario (Is). The subsequent emission inventory represents the operational reference baseline for the Is. The overall effectiveness of the applied control measures was subsequently expressed as the percentage reduction relative to the corresponding uncontrolled baseline inventory (E_0):

$$R_{IS}(\%) = \frac{E_0 - E_{IS}}{E_0} \times 100 \quad (8)$$

where R_{IS} is the overall PM_{10} reduction (%) and E_0 and E_{IS} represent the annual uncontrolled and controlled PM_{10} inventories, respectively. Because control efficiencies were incorporated at the individual source level, no additional control adjustment was applied at the inventory level.

2.3. Compliance Reduction Scenario (Cs)

Compliance performance was considered as an alternative assessment scenario because maintaining emissions within applicable regulatory limits is a fundamental requirement for the continued operation of mining activities. Compliance with prescribed environmental standards is typically linked to the maintenance of operating permits and licenses, as well as regulatory oversight and stakeholder acceptance. Hence, evaluating compliance performance provides a practically relevant scenario for assessing whether mining operations can maintain ambient PM_{10} concentrations below applicable regulatory thresholds under measured environmental conditions [26,27]. In this study, ambient PM_{10} concentrations were therefore compared with the regulatory threshold (0.12 mg/m^3) stipulated by the Thailand's Pollution Control Department, to determine the concentration differential attributable to environmental compliance of respective mining operation. This approach provides a common performance reference across the selected mining operations [9,10,17]. The compliance concentration margin was converted to a mass-equivalent PM_{10} reduction by considering the effective volume of the atmosphere represented by the monitoring area and atmospheric mixing height of 1500 m based on the reference value established by Thailand's Pollution Control Department [28]. The daily concentration differential relative to the applicable regulatory standard was multiplied by the horizontal monitoring area (H_a) and atmospheric mixing height (H_m), thereby expressing the ambient compliance margin as an equivalent PM_{10} mass within the affected atmospheric volume. This mass-equivalent reduction was estimated for each operational day and

aggregated over the assessment period to obtain the annual compliance-related PM_{10} reduction, consistent with the 24 h averaging period used for the applicable PM_{10} standard [29]. The approach assumes that the measured concentration differential is representative of the defined atmospheric control volume, with the resulting mass converted from milligrams to tonnes using the appropriate unit conversion factor. where ΔC_d is the daily concentration differential (mg. m^{-3}), C_s is the applicable regulatory PM_{10} standard (mg. m^{-3}), and $C_{m,d}$ is the measured ambient PM_{10} concentration on day d. The daily concentration differential was calculated as the margin between the regulatory standard and the measured concentration:

A positive ΔC_d indicates that the measured concentration is below the regulatory threshold and therefore represents the concentration margin associated with compliance performance. To express this margin in mass-equivalent terms, ΔC_d was multiplied by the effective atmospheric control volume, defined as the product of the horizontal monitoring area (H_a) and atmospheric mixing height (H_m):

$$M_d = \Delta C_d \times H_a \times H_m \times 10^{-9} \quad (9)$$

where M_d is the daily PM_{10} mass equivalent (t day^{-1}), H_a is the horizontal area represented by the mining-concession monitoring zone (m^2), and H_m is the atmospheric mixing height (m). The product $H_a \times H_m$ represents the effective atmospheric volume over which the concentration differential is assumed to apply. Because ΔC_d is expressed in mg m^{-3}, the resulting mass is in mg and is converted directly to tonnes using the factor 10^{-9}. This formulation therefore provides a mass-equivalent representation of the ambient PM_{10} concentration margin relative to the regulatory standard. The annual PM_{10} mass-equivalent reduction under the Compliance Scenario (C_s) was estimated by aggregating the daily values over the operational period:

$$R_{CS} = \sum_{d=1}^{N} M_d \quad (10)$$

where R_{CS} is the annual PM_{10} mass-equivalent reduction (t yr^{-1}), M_d is the daily PM_{10} mass equivalent (t day^{-1}), and N is the number of operational days during the assessment period. This approach converts the observed ambient concentration margin relative to the regulatory standard into a mass-equivalent metric, enabling the compliance performance scenario to be expressed on a basis comparable with the inventory scenario. The corresponding daily percentage compliance margin was calculated as:

$$R_{CS,d}(\%) = \frac{C_s - C_{m,d}}{C_s} \times 100 \quad (11)$$

where $R_{CS,d}$ is the percentage PM_{10} compliance margin on day d, C_s is the regulatory PM_{10} concentration standard (mg. m^{-3}), and $C_{m,d}$ is the measured ambient PM_{10} concentration (mg. m^{-3}). Positive values indicate concentrations below the applicable regulatory threshold, whereas negative values indicate exceedances.

3. Results

For consistency with the different assessment components, different annual operating periods were used to estimate PM_{10} reductions. The compliance assessment uses 365 days yr^{-1} because the regulatory PM_{10} threshold applies throughout the year, while 208 days yr^{-1} for blasting and 299 days yr^{-1} for haulage represent their respective scheduled operating days and were used to annualize activity-based emissions. Definitions of the parameters used in the emission estimation equations are provided in Appendix A Table A1. for clarity and reference. Under inventory reduction scenario, the results indicate that blast-related PM_{10} emissions vary primarily with blast area and the effectiveness of the

applied emission controls. The emission factor (EF) was derived from the blast area (A) and adjusted to represent the PM_{10} fraction (kg blast^{-1}). Annual emissions were then estimated from the resulting emission factor, blast frequency, and control efficiency (CE), allowing the uncontrolled and controlled emission levels to be quantified for each mine. Among the mines, M3 had the largest blast area (7728 m^2) and the highest PM_{10} emissions proportion, estimated at 16.2 t yr^{-1} which reduced to 8.08 t yr^{-1} after applying a 0.50 CE. M1 (3950 m^2) generated 5.9 t yr^{-1} which reduced to 4.43 t yr^{-1} at CE = 0.25, while M2 (1360 m^2) emitted 1.2 t yr^{-1}, reduced to 0.60 t yr^{-1} at CE = 0.50 (Tables S1 and S2 in Supplementary Materials). Emissions from haulage activities (g VKT^{-1}) were estimated under uncontrolled and controlled scenarios using operational data; daily production (D_p), haul length (H_l), trip frequency (T_f), payload (P_c), and emission factors (EF) (Table S3, in Supplementary Materials). The daily production (D_p) and trip frequency (T_f) were derived from the annual production and vehicle payload capacity (P_c) of the mines, respectively. Accordingly, M3 has the largest daily production, with a payload of 36.5 t, which requires approximately 669 haul trips per day, while M2 and M1 required 632 and 83 trips per day, respectively. Daily PM_{10} emissions were estimated as the product of the emission factor (EF), trip frequency (T_f), and haul road length (H_l). When scaled to 299 operational days (N), the resultant annual PM_{10} emissions were 3560.34 t for M3, 1173.17 t for M2, and 247.09 t for M1. Applying control efficiencies (CE = 0.75 for M3; 0.55 for M1 and M2) reduced emission to 890.09 t, 527.93 t, and 111.19 t, respectively (Figure 2). Emissions from mineral processing were estimated for key activities; screening, crushing, and conveyor transfer, under uncontrolled and controlled scenarios. Process-specific emission factors from the U.S. EPA AP-42 (Section 11.19.2) and annual production data were used, with control efficiencies applied according to mine reports. Annual uncontrolled emissions were 24.82, 85, and 89.93 t year^{-1} for M1, M2, and M3, respectively. Under controlled scenario, emissions reduced to 2.35, 7.87, and 8.32 t year^{-1}, respectively. (Table S4 in Supplementary Materials). Emission inventory for the three mines was compiled by aggregating contributions from blasting, haulage, and mineral processing. M1, M2, and M3 emitted 278, 1259, and 3666 t yr^{-1}, respectively. Implementation of control scenarios reduced emissions to 117.97, 536.39, and 906.49 t yr^{-1}, this corresponds to emission reductions of 159.8 (57.6%), 723.0 (57.4%), and 2759.9 t yr^{-1} (75.3%). The emission trend follows the difference in scale of respective annual production, indicating a strong positive correlation between production scale and PM_{10} output.

Under the compliance reduction scenario (C_S), M1 and M2 achieved comparable PM_{10} reductions, with concentration differentials of 0.1023 and 0.1021 mg/m^3, corresponding to 85.28% and 85.12% reductions relative to the 0.12 mg m^{-3} regulatory threshold. M3 recorded a lower differential of 0.0895 mg/m^3, equivalent to a 74.58% reduction (Table S5 in Supplementary Materials). Based on the defined atmospheric control volume with mixing height of 1500 m and 365-day assessment period, these concentration differentials correspond to annual PM_{10} reductions of 280.13 t for M1, 279.61 t for M2, and 245.01 t for M3, indicating comparatively stronger compliance performance for M1 and M2 than M3.

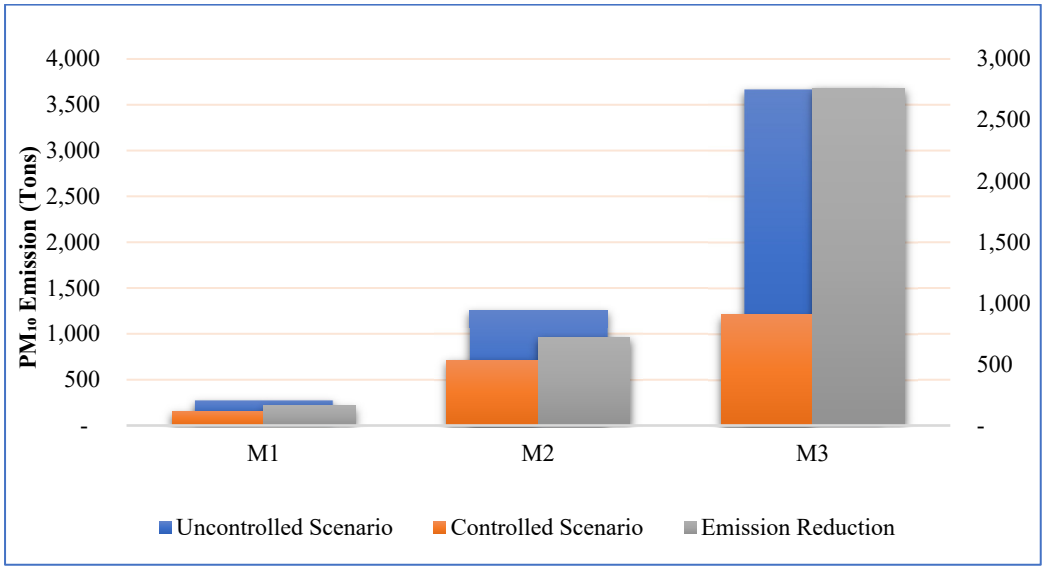

Figure 2. Emission reduction performance of mines under uncontrolled and controlled scenarios.

4. Discussion

4.1. Structural Mechanisms Mediating Emission-Reduction Performance Assessment

The divergence between the Inventory Scenario (I_S) and Compliance Scenario (C_S) indicates that emission-reduction performance is shaped not only by the magnitude of reduction achieved, but also by how that abatement is defined, interpreted, and recognized. The findings reveal three related mechanisms through which baseline selection influences performance assessment. This includes baseline-contingent performance divergence, the equity–efficiency paradox, and the marginal effect paradox. Together, these mechanisms explain how alternate reference baselines can produce different performance conclusions and different implications for decision-making.

4.1.1. Baseline-Contingent Performance Divergence

The two assessment scenarios produced markedly different estimates of PM_{10} reduction, demonstrating that the measured magnitude of emission reduction is contingent on the reference baseline used for assessment. Under the Inventory Scenario (I_S), reductions increased with mine scale, from 160 t yr^{-1} for M1 to 723 t yr^{-1} for M2 and 2760 t yr^{-1} for M3. In contrast, the Compliance Scenario (C_S) produced estimated reductions of 280.13, 279.61, and 245.01 t yr^{-1}, respectively. The resulting asymmetries were −120.13 t yr^{-1} for M1, 443.39 t yr^{-1} for M2, and 2514.99 t yr^{-1} for M3, indicating that C_S produced a higher estimate for M1, whereas I_S produced substantially higher estimates for M2 and M3 (Figure 3). The divergence was therefore not uniform across the mines but increased substantially with mine scale and the magnitude of the underlying emission inventory. More importantly, the difference between the two baselines altered the relative interpretation of mine performance. Based on absolute reduction, I_S ranked the mines M3 > M2 > M1, whereas C_S produced a reversal of M1 > M2 > M3. M3 therefore shifted from the highest reduction under I_S to the lowest under C_S, while M1 shifted from the lowest to the highest; meanwhile M2 remained intermediate under both scenario (Figure 4). This demonstrates that the baseline does not merely influence the numerical magnitude of estimated reduction; it can also determine which mine is interpreted as the optimal or sub-optimal performer.

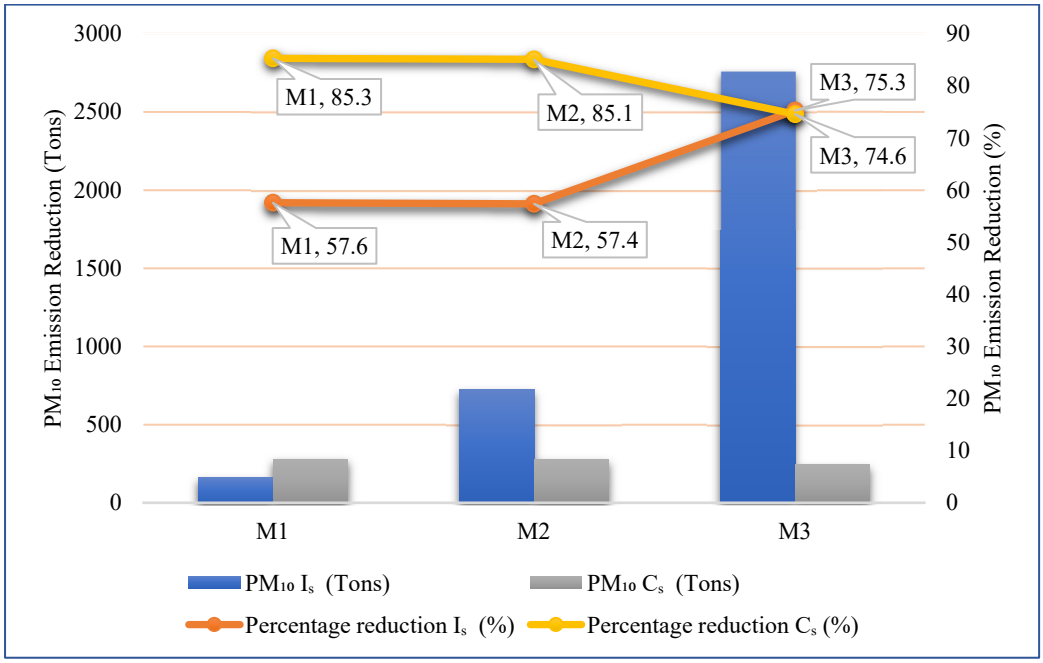

Figure 3. Comparison of PM_{10} emission reductions in absolute (Tons) and percentage by scenario.

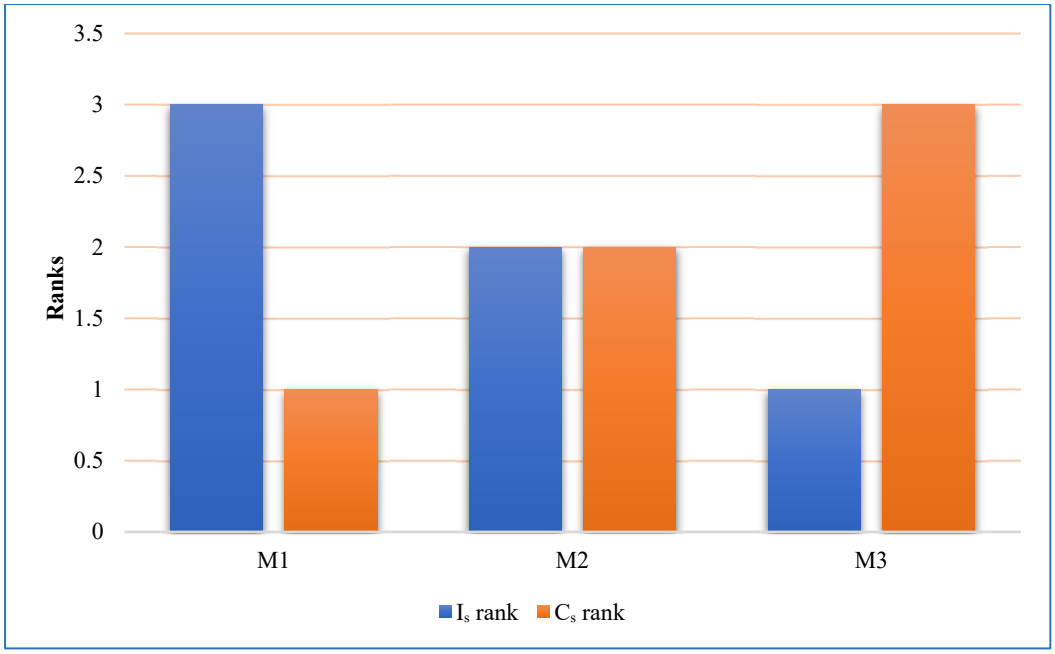

Figure 4. Comparative emission-reduction rankings under the Inventory and Compliance scenarios.

As previously highlighted in Section 1, these differences arise because the two scenarios define reduction against fundamentally different reference baselines. The Inventory Scenario I_S measures avoided emissions relative to each mine's own operational emission burden and is therefore strongly influenced by production scale and the quantity of PM_{10} generated. This explains why M3, which has the largest emission inventory, records the largest reduction under I_S (2760 t yr^{-1}). In contrast, the Compliance Scenario (C_S) uses the regulatory concentration limit as a common reference and therefore reflects the ambient concentration margin below the allowable threshold. Thus, its estimates are consequently less dependent on the absolute quantity of emissions generated and more reflective of ambient environmental performance [9]. The observed pattern is supported by the longitudinal ambient PM_{10} data. From 2021 to 2024, M1 and M2 consistently recorded

lower ambient concentrations than M3. M1 ranged from 0.0177–0.0322 mg m^{-3} and M2 from 0.0179–0.0385 mg m^{-3}, compared to 0.0305–0.0989 mg m^{-3} for M3 (Figure 5; Table S6 in Supplementary Materials). Although all three mines remained below the 0.12 mg m^{-3} regulatory threshold, M3 generally operated closer to the threshold. Consequently, M1 and M2 maintained a more optimal concentration margins below the standard, contributing to their relatively higher C_S estimates despite their substantially smaller operational emission inventories. Thus, the apparently stronger C_S performance of M1 and M2 reflects greater ambient PM_{10} margins below the regulatory threshold and therefore a more competent performance under the compliance criterion.

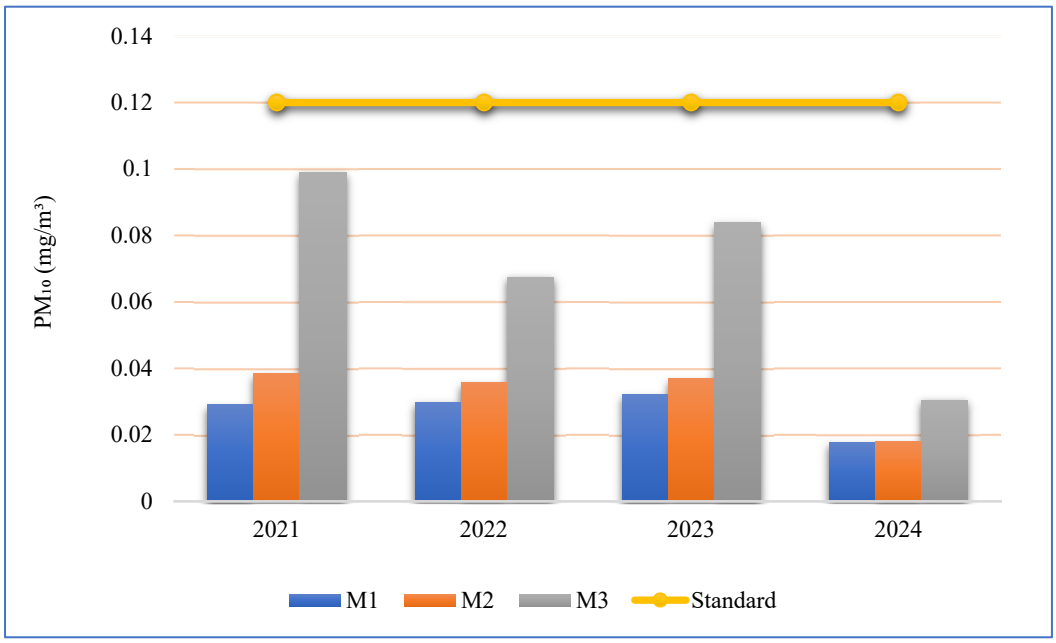

Figure 5. Four-year baseline levels of PM_{10} emission, showing M1 and M2 consistently maintaining lower ambient concentrations below standard limit compared to M3.

Collectively, these results establish a form of baseline-contingent performance divergence, whereby emission performance is not solely an attribute of the emission-reduction intervention itself but is partly determined by the reference baseline against which that reduction is evaluated. The complete reversal in mine rankings demonstrates that choice of baseline can change the inferred comparative performance even when the underlying mines and their interventions remain unchanged. This creates a potential for baseline-dependent interpretation in environmental benchmarking, regulatory assessment, ESG reporting, and operational decision-making, where the assessment yardstick may influence conclusions about which mines are performing better [30,31].

Nonetheless, this divergence is not simply a measurement discrepancy since the two baselines capture different dimensions of emission-abatement performance. The inventory baseline emphasizes the efficiency of reducing emissions from the mine's operational emission burden, whereas the compliance baseline stresses on attainment of ambient air-quality conditions within the common applicable regulatory standard [9,10,15,16,32–34]. This distinction introduces a broader tension between efficient and equitable emission abatement, which forms the basis of the equity–efficiency paradox discussed in the following section.

4.1.2. Equity–Efficiency Paradox

As highlighted in Section 4.1.1., the two scenarios incentivize distinct outcomes: I_S captures the effectiveness of abatement efforts, whereas the latter rewards performance

against an equitable baseline. The contrasting outcomes for M3 and M1 illustrate this tension. M3 achieved the largest I_S reduction but the lowest C_S estimate, reflecting substantial reduction from its large operational inventory but a comparatively lower ambient margin below the regulatory threshold. On the contrary, M1 recorded the smallest I_S reduction but the highest C_S estimate, consistent with its higher ambient PM_{10} margin. Hence, higher reduction efficiency from inventory does not necessarily correspond to equivalent compliance attainment, and vice versa.

This contrast gives rise to an equity–efficiency paradox in which both scenarios recognize different performers as superior. In this context, efficiency reflects the extent of operational abatement achieved, whereas the equity-oriented dimension reflects whether the performance satisfies a common threshold across operations. Thus, mine may therefore perform strongly in one dimension while appearing comparatively weaker in the other. The practical implication is that a single baseline can obscure which dimension of environmental performance is being recognized. An inventory-based assessment may reward substantial abatement effort without fully capturing environmental attainment, while a compliance-based assessment may recognize attainment without differentiating the magnitude of additional reduction achieved. This distinction is particularly relevant for environmental benchmarking and regulatory evaluation, where reducing emissions and achieving an acceptable environmental condition represent related but distinct objectives [9,30,32,34].

The paradox therefore extends beyond the question of which baseline produces the larger reduction estimate. It concerns what environmental performance assessments are designed to incentivize and recognize. If emphasis is placed exclusively on reduction efficiency, substantial residual emissions may remain relevant despite large reductions from a high operational baseline. Equally, if emphasis is placed exclusively on compliance, additional reductions beyond the regulatory threshold may receive limited differentiation despite representing genuine improvements in operational emission performance. This tension raises the question of whether environmental assessment should recognize both outcomes, providing the basis for considering the marginal effects of additional emission reduction in the following section.

4.1.3. Marginal-Effect Paradox

The equity–efficiency paradox raises a further question: if both scenarios represent distinct dimensions of performance, can an assessment framework recognize both simultaneously? A plausible approach is to combine the two baselines hierarchically, first assessing reduction from the operational inventory and then evaluating the residual emissions against the regulatory threshold as a secondary condition. Conceptually, this creates a sequence of inventory baseline; reduction achieved; residual emissions; regulatory threshold. This approach further yields two complementary questions: how much did the mine reduce from its operation inventory, and how close are its residual emissions to the acceptable compliance boundary?

However, combining the two dimensions does not eliminate the underlying tension; it shifts it to the marginal value of additional reduction. The significance of an additional unit of abatement depends on both the mine's operational baseline and its position relative to the regulatory threshold. For M1, C_S exceeded I_S by 120.13 t yr^{-1}, representing approximately 75% more reduction than indicated by the inventory baseline. This suggests that additional reduction carries greater significance when performance is assessed against the regulatory boundary. On the contrary, M3 recorded an I_S reduction 2514.99 t yr^{-1} greater than its C_S estimate, meaning that the inventory-based estimate was more than ten times the compliance estimate. Thus, additional reductions contribute substantially to M3's I_S but comparatively insignificant to its compliance performance.

This creates a marginal-effect paradox whereby the Inventory Scenario can continue to recognize large reductions, while the Compliance Scenario may accord insignificant additional recognition once the regulatory threshold is approached. In essence, reductions needed to reach the compliance threshold may be more important under the Compliance Scenario even when they represent relatively lower inventory reductions. Thus, the significance of an additional unit of reduction depends on which scenario is used and the proximity of mine's emission performance to the regulatory threshold. A hierarchical framework could therefore recognize both dimensions, with the regulatory threshold serving as the compliance benchmark instead of the sole measure of performance. Yet this does not make the assessment neutral. Once performance is evaluated by both reduction achieved and margin from the regulatory threshold, the question shifts from which baseline should determine performance to how additional reductions should be valued across operations with different emission burdens and reduction potentials. In this sense, the equity–efficiency tension is not eliminated but repositioned—from baseline accounting to the recognition and valuation of surplus emission abatement.

These three mechanisms illustrate that baseline choice influences what is measured, incentivized, and valued in emission-reduction assessment. Thus, emission performance assessment may therefore benefit from considering reduction efficiency, compliance attainment, and the marginal value of further abatement instead of relying exclusively on a single baseline.

4.2. Implications for Environmental Risk Management and Public Health Protection

The findings have important implications for environmental risk management and public health protection because PM_{10} emission performance is not only an accounting issue but also a basis for decisions concerning pollution control, regulatory oversight, and environmental protection. Exposure to particulate matter is associated with respiratory and cardiovascular morbidity and mortality, and the health significance of particulate exposure remains significant even at concentrations below some regulatory thresholds [35,36]. Mining and quarrying activities are also recognized sources of particulate emissions, with exposure depending on emission magnitude, particle characteristics, dispersion, and the proximity and vulnerability of exposed populations [7,19,20]. Consequently, the way emission-reduction performance is defined can influence how environmental conditions are interpreted and, in turn, how mitigation priorities are established in terms of monitoring, inspection, and allocation of pollution-control resources [37]. Risk-based environmental management commonly uses information on pollutant magnitude, environmental conditions, exposed populations, and potential consequences to identify priorities for further investigation or intervention. For example, the U.S. Environmental Protection Agency applies risk-based approaches to prioritize sites according to their potential threats to human health and the environment, while screening and ranking tools are used to identify sites that may require further investigation or management [38,39]. Applied to mining emission assessment, this suggests that mines performance should not be prioritized solely according to the quantity of emission reduction achieved or solely according to their margin from a regulatory threshold. Rather, all components should be considered collectively when determining the need for further monitoring or mitigation.

The public-health significance of this approach arises from the distinction between emission reduction and exposure reduction. A large reduction in emissions does not necessarily imply a proportionally large reduction in population exposure, just as regulatory compliance does not necessarily imply the absence of health concern. Actual health risk depends on the concentration to which people are exposed, the duration and frequency of exposure, pollutant characteristics, dispersion conditions, exposure pathways, and the vulnerability of exposed populations [35,40]. Therefore, the study findings should not be

interpreted as evidence that one mine necessarily poses a greater health risk than another. Instead, they demonstrate that different performance metrics can identify different environmental priorities, creating the need to connect emission-performance assessment with ambient monitoring and, where warranted, more detailed exposure and health-risk assessment.

4.3. Implications and Recommendations for Environmental Reporting and ESG Performance

Likewise, this paradigm has implications for environmental reporting, ESG performance assessment, and regulatory decision-making. Regulators and policymakers should require mining operations to clearly identify the baseline used when reporting emission reductions and, where feasible, report both inventory-based reduction and compliance-margin indicators. In this regard, the regulatory standard should be treated as a minimum acceptable environmental condition representing the equity dimension, rather than the sole measure of environmental performance. Hence, broadly, compliance margins can indicate the remaining environmental buffer relative to prescribed thresholds, while inventory-based indicators capture the extent of operational abatement achieved. Furthermore, in the case of comparative evaluation among mines of different scales, inventory reductions should be normalized by production output or another appropriate measure of operational scale to reflect abatement performance relative to operational intensity and enable more meaningful comparison across mines.

From an ESG reporting perspective, emission-reduction claims should therefore be accompanied by a clearly defined baseline, the absolute reduction achieved, the relevant compliance margin, and sufficient contextual information to distinguish operational improvement from regulatory attainment. Such transparency is consistent with established sustainability and emissions-reporting frameworks, which emphasize disclosure of the base year or baseline, the rationale for its selection, the methods used to calculate reductions, and appropriate intensity measures to facilitate meaningful comparison [13,41–43].

Collectively, these findings support a more integrated assessment sequence in which operational emission burden, reduction achieved, residual ambient concentration, compliance margin, and potential exposure to receptors are considered as complementary indicators. Such an approach would preserve the operational efficiency information captured by the Inventory Scenario while retaining the environmental protection perspective provided by the Compliance Scenario. The significance of this approach is not that it removes the equity–efficiency or marginal-effect tensions identified in this study, but that it makes those tensions explicit for environmental decision-makers. Thus, this can support more transparent prioritization of mitigation measures, more balanced interpretation of mine performance, and more precautionary protection of populations potentially exposed to mining-related particulate pollution. Ultimately, the findings suggest that the choice of baseline should be treated as a substantive component of environmental risk assessment rather than merely a technical parameter of emission accounting.

4.4. Sensitivity Analysis

The sensitivity analysis demonstrates that the two assessment scenarios respond to different sources of uncertainty, which is consistent with their fundamentally different assessment configurations. For the Inventory Scenario (I_S), mineral haulage/transport was the dominant emission source, accounting for approximately 96.7% of total PM_{10} emissions. A 20% reduction in haulage emissions produced a 19.3% decrease in total inventory emissions, while ±20% variation in trip frequency and haul length produced an average ±12.1% change. Payload capacity showed an inverse relationship with emissions, while haul velocity also influenced emission intensity, producing relative changes of +6.0%, 0%, and −44.8% for M1, M3, and M2, respectively (Figures 6 and 7; Table S7 in Supplementary

Materials). These results indicate that I_S estimates are principally governed by operational characteristics and therefore reflect the mine's production and emission generation capacity [44–50].

For the Compliance Scenario (C_S), atmospheric mixing height was the dominant sensitivity parameter as it determines the atmospheric volume used to translate concentration differences into estimated mass reductions. Varying mixing height between 800 to 2000 m ranges based on the established pollutant dispersion ranges within the study areas, altered estimated annual reductions from 130.67–149.40 to 326.68–373.51 t yr^{-1}, compared to 245.01–280.13 t yr^{-1} at the baseline height of 1500 m (Table S8 in Supplementary Materials). Thus, C_S estimates are primarily influenced by atmospheric conditions and the conversion of ambient concentration margins into mass-based reduction estimates [51].

Analytically, these sensitivities do not challenge the distinction between I_S and C_S. Rather, they reinforce that the two scenarios measure different aspects of performance: I_S are mainly influenced by the mine's emission-producing activities, whereas C_S is mainly influenced by ambient conditions and atmospheric factors that affect compliance. Consequently, uncertainty in the absolute magnitude of either estimate does not explain the observed divergence between the scenarios; the divergence is structurally embedded in their different reference conditions. From a management perspective, the sensitivity results also indicate that improving I_S performance depends primarily on controlling dominant operational sources of emission, particularly haulage emissions, whereas C_S performance can be enhanced by maintaining ambient PM_{10} concentrations well below the regulatory threshold. This supports the broader interpretation that emission-reduction assessment should distinguish between operational reduction efficiency and compliance attainment, recognizing that each provides a different perspective on environmental performance.

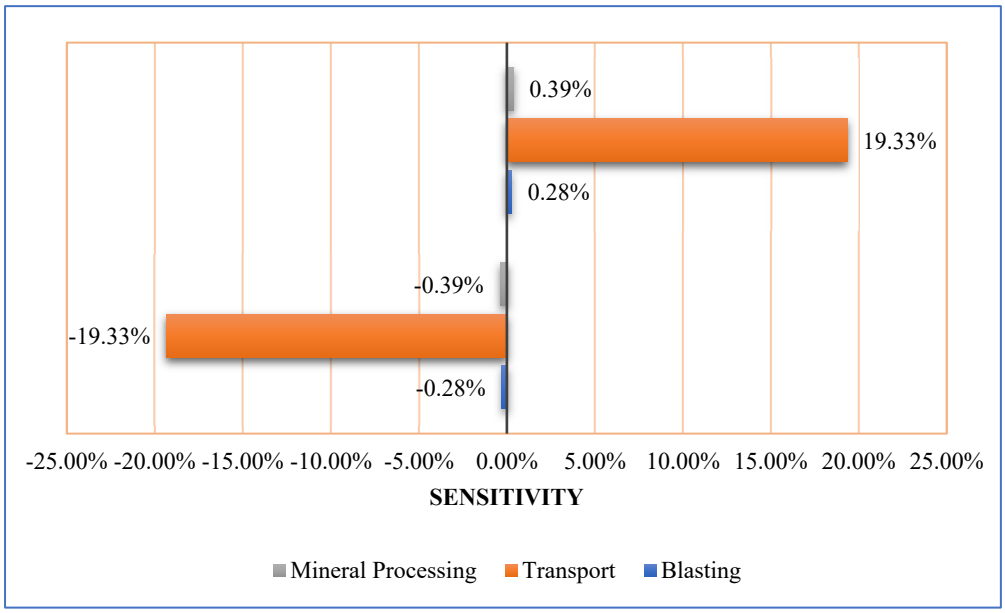

Figure 6. Sensitivity of activities to overall PM_{10} emissions across mines, showing transportation as the most sensitive activity.

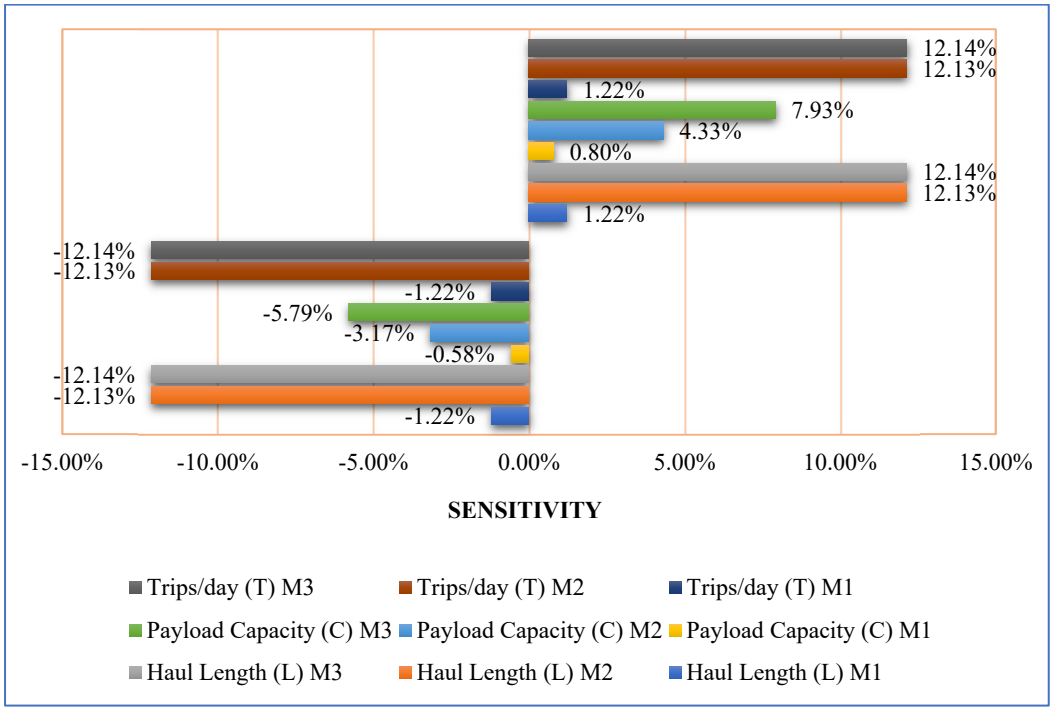

Figure 7. Sensitivity analysis of transport parameters shows T_f and H_l as directly proportional to PM_{10} emissions, while P_c is inversely proportional.

5. Conclusions

This study examined how alternative assessment baselines influence the estimation and interpretation of PM_{10} emission-reduction performance using three limestone mines in Thailand. By comparing an Inventory Scenario (I_S), which evaluates reduction relative to each mine's operational emission burden, with a Compliance Scenario (C_S), which evaluates performance relative to a regulatory ambient PM_{10} threshold, the study demonstrates that emission-reduction performance is fundamentally baseline-dependent. The reduction asymmetry varied substantially among the mines, from −120.13 t yr^{-1} for M1 to 443.39 t yr^{-1} for M2 and 2514.99 t yr^{-1} for M3, while comparative rankings reversed from M3 > M2 > M1 under I_S to M1 > M2 > M3 under C_S. These findings establish baseline-contingent performance divergence and demonstrate an equity–efficiency paradox, whereby inventory-based assessment recognizes the magnitude of operational abatement, whereas compliance-based assessment reflects performance relative to a common environmental boundary. Thus, baseline selection can influence not only the estimated magnitude of reduction but also how comparative environmental performance is interpreted and incentivized. The findings have implications for environmental risk management and ESG reporting, particularly in how mining-related PM_{10} performance is assessed and interpreted. Different performance metrics can produce different management signals; therefore, operational emission burden, reduction achieved, ambient concentrations, and compliance margins should be considered as complementary indicators. Although these assessments can help inform environmental monitoring and mitigation priorities relevant to public health protection, they do not directly establish population exposure or associated health outcomes. Similarly, environmental and ESG reporting should clearly identify the baseline used, report absolute reductions alongside relevant compliance margins, and provide sufficient context to distinguish operational improvement from regulatory attainment. Such transparency is consistent with established sustainability and emissions-reporting frameworks such as GRI, IFRS, etc.

Nevertheless, these findings are interpreted within the study's empirical and methodological scope. The analysis covers three limestone mines in Thailand and PM_{10} only, limiting possible generalization to other mining contexts and pollutants. In addition, both scenarios rely on modelled emissions, and established dispersion estimates and are therefore subject to assumptions within the underlying inventory and dispersion models, notwithstanding the sensitivity analysis. Future research should examine whether the identified baseline-contingent performance divergence and equity–efficiency paradox persist across a broader range of mines, pollutants, and operational contexts. Further investigation could also explore dynamic emission-reduction baselines and longitudinal mine performance to capture changes in operational conditions, emission-control practices, and environmental performance over time. Such extensions could provide a more robust understanding of how baseline selection influences emission-reduction assessment, comparative mine performance, and environmental decision-making across different mining contexts. From the perspective of resource efficiency, future research could also examine how renewable energy integration, fuel substitution, equipment electrification, and energy-efficiency improvements contribute to reducing the broader environmental footprint of mining operations. Finally, the study demonstrates that baseline selection is not merely an accounting choice but a substantive consideration in how environmental performance, risk, and sustainability are evaluated and incentivized.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/mining6040113/s1, Table S1: Basis for control-efficiency assignment; Table S2: PM_{10} emission from Blasting under uncontrolled and controlled scenarios; Table S3: PM_{10} emissions from transportation under uncontrolled and controlled scenarios; Table S4: PM_{10} emissions from mineral processing under uncontrolled and controlled scenarios; Table S5: Emission reduction across mines under compliance scenario; Table S6: Longitudinal ambient PM_{10} data, from 2021 to 2024; Table S7: Speed sensitivity analysis for the three mine sites.; Table S8: Mixing height sensitivity analysis.

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Appendix A

Table A1. Definitions of the parameters used in the emission estimation equations.

Parameter	Definition	Unit	Implication in the Assessment
A	Blast area affected by each blasting event	m^2	Larger blast areas generally increase the amount of PM_{10} generated per blast.

EF	Emission factor representing PM_{10} released per unit of blast activity or vehicle travel	kg blast^{-1}/g VKT^{-1}	Determines the quantity of PM_{10} associated with each emission-generating activity.
PM_{10} fraction	Proportion of total particulate emissions attributable to PM_{10}	%	Converts total particulate emissions into the PM_{10} component assessed in this study.
CE	Control efficiency representing the proportion of emissions removed or prevented by the applied control measure	%	Higher CE produces greater reduction in estimated emissions.
D_p	Daily production transported by the mine	t day^{-1}	Higher production increases the material that must be transported and therefore potential haul emissions.
H_l	Haul-road travel distance associated with each trip	km trip^{-1}	Longer haul distances increase vehicle travel and associated PM_{10} emissions.
T_f	Number of haul trips undertaken per day	trips day^{-1}	More trips increase total vehicle activity and PM_{10} emissions.
P_c	Payload carried by each haul vehicle	t trip^{-1}	Determines the number of trips required to move the daily production volume.
VKT	Vehicle kilometers travelled	km	Represents the total distance travelled by haul vehicles and is used with the haul emission factor.
N	Number of operating days used to annualize daily haul emissions	days yr^{-1}	Converts daily emissions into annual PM_{10} emissions.

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