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Development and Pilot Evaluation of Sensor-Based Environmental Monitoring and Green Technology Interventions for Pollution Reduction in Indonesian Mining Sites

(Pengembangan dan Evaluasi Pilot Sistem Pemantauan Lingkungan Berbasis Sensor dan Intervensi Teknologi Ramah Lingkungan untuk Pengurangan Pencemaran pada Lokasi Pertambangan di Indonesia)

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Abstract: *This study develops and pilot-tests an integrated package of environmentally friendly operational interventions and a sensor-based environmental monitoring system at two mining locations in Indonesia. The research used a pilot multiple-site case study over three months, combining field observation, document review, and repeated measurement of water, air, and soil quality indicators. The analytical focus was on descriptive before–after comparison and compliance-gap assessment, because the pilot dataset was limited to two sites and did not justify inferential statistics. The results show that PM2.5 declined from 58 to 41 µg/m^3 at Mine Location A (29.3%) and from 65 to 55 µg/m^3 at Mine Location B (15.4%) after intervention. However, several parameters remained above or below the required benchmarks, including turbidity (15–25 NTU versus ≤5 NTU), dissolved oxygen (3.8–4.5 mg/L versus ≥5 mg/L), arsenic (10–12 ppb versus ≤5 ppb), and soil organic matter (2.0–2.5% versus ≥3%). These findings indicate that the monitoring system is effective for early detection and operational feedback, whereas the green technology interventions produced only partial environmental improvement. The study contributes a practical framework for integrating site-level monitoring, threshold-based evaluation, and adaptive environmental management in Indonesia's mining sector. The main implication is that sensor deployment should be scaled together with stronger mine-water treatment, dust suppression, calibration routines, and compliance reporting requirements.*

Keywords: *sensor-based monitoring; PM2.5; mine water quality; environmental compliance; sustainable mining; Indonesia.*

Abstrak: *Penelitian ini mengembangkan dan menguji secara pilot paket intervensi operasional ramah lingkungan yang terintegrasi dengan sistem pemantauan lingkungan berbasis sensor pada dua lokasi pertambangan di Indonesia. Rancangan penelitian menggunakan pilot multiple-site case study selama tiga bulan dengan memadukan observasi lapangan, telaah dokumen, dan pengukuran berulang terhadap indikator kualitas air, udara, dan tanah. Fokus analisis diletakkan pada perbandingan deskriptif sebelum–sesudah dan penilaian kesenjangan kepatuhan, karena dataset pilot hanya mencakup dua lokasi dan tidak memadai untuk statistik inferensial. Hasil penelitian menunjukkan bahwa kadar PM2.5 menurun dari 58 menjadi 41 µg/m^3 pada Lokasi Tambang A (29,3%) dan dari 65 menjadi 55 µg/m^3 pada Lokasi Tambang B (15,4%) setelah intervensi. Namun, beberapa parameter masih belum memenuhi ambang yang dipersyaratkan, yaitu turbiditas (15–25 NTU dibandingkan dengan ≤5 NTU), dissolved oxygen (3,8–4,5 mg/L dibandingkan dengan ≥5 mg/L), arsenik (10–12 ppb dibandingkan dengan ≤5 ppb), dan bahan organik tanah (2,0–2,5% dibandingkan dengan ≥3%). Temuan ini menunjukkan bahwa sistem pemantauan efektif untuk deteksi dini dan umpan balik operasional, sedangkan intervensi teknologi*

ramah lingkungan baru menghasilkan perbaikan lingkungan yang parsial. Kontribusi utama studi ini adalah penyediaan kerangka praktis untuk mengintegrasikan pemantauan tingkat lokasi, evaluasi berbasis ambang baku, dan pengelolaan lingkungan yang adaptif pada sektor pertambangan Indonesia. Implikasi utamanya adalah bahwa perluasan penggunaan sensor harus dibarengi dengan penguatan pengolahan air tambang, pengendalian debu, prosedur kalibrasi, dan kewajiban pelaporan kepatuhan.
Kata kunci: *pemantauan berbasis sensor; PM2.5; kualitas air tambang; kepatuhan lingkungan; pertambangan berkelanjutan; Indonesia.*

Introduction

Indonesia's mining sector remains economically important, but the environmental burden of mining is still substantial. Recent work on Indonesia's critical mineral industries shows that mining and processing can generate significant pressures on air, water, soil, and human health if pollution controls are weak (Wahyono et al., 2024). In addition, geo-hazard studies in mining regions such as Bone Bolango demonstrate that mining-related disturbances can amplify broader socio-environmental risks when environmental monitoring is inadequate (Kimijima & Nagai, 2023).

Green mining technologies are increasingly promoted to reduce energy use, harmful emissions, water contamination, and ecological disturbance. A recent review concluded that cleaner technologies can reduce greenhouse gas emissions and improve waste handling; however, their effectiveness depends on proper integration with operational practices and regulatory oversight (Onifade et al., 2024). Mine-water management remains especially challenging: integrated treatment systems can recover water and salts at high efficiency, yet many technologies still face implementation barriers related to sludge handling, reusability, and economic feasibility (Matebese et al., 2024).

The monitoring side faces a parallel problem. Indonesian studies show that advanced environmental monitoring can improve evidence-based decision-making, real-time hotspot detection, and public accountability; however, current monitoring systems often remain fragmented and too slow for timely intervention (Nugroho et al., 2025). Low-cost particulate sensors also offer practical advantages for expanded coverage, although their performance still requires calibration and contextual interpretation (Kurniawati et al., 2025). Remote sensing studies in Kalimantan have strengthened regional-scale monitoring of coal mining and reclamation (Prasetya & Tsai, 2025a, 2025b); however, these approaches do not replace site-level measurements needed for day-to-day pollution control.

The research gap is therefore clear. Previous studies have largely emphasized reviews, remote sensing, or broad environmental assessments, while empirical pilot evidence that combines site-level green technology interventions with sensor-based monitoring and threshold-based evaluation in Indonesian mining operations remains limited. This gap matters because practical environmental management depends not only on identifying impacts but also on determining which parameters improve after intervention and which parameters remain non-compliant.

Based on that gap, this study addresses three questions: (1) how does the integrated intervention package affect selected environmental indicators at two Indonesian mining sites? (2) Which indicators remain non-compliant after implementation? (3) What operational and policy implications follow from these results? The novelty of this paper lies in the integration of a pilot site-level intervention, a sensor-supported monitoring workflow, and an explicitly compliance-oriented evaluation framework. This design is aligned with Indonesia's evolving regulatory requirements for environmentally responsible mining and environmental protection (Republic of Indonesia, 2020, 2021; Ministry of Environment and Forestry of the Republic of Indonesia, 2022).

Methods

Research Design and Study Sites

This study used a pilot multiple-site case study with mixed evidence sources. Quantitative evidence consisted of site measurements of water, air, and soil quality, while qualitative evidence came from field observations and documentation of the intervention workflow. The pilot was conducted for three months at two active mining locations in Indonesia, anonymized as Mine Location A and Mine Location B for confidentiality. Each site included at least two operationally relevant observation points: a water-related point near mine discharge or river flow, and a processing-related point associated with airborne dust and soil exposure.

The sensors used for air quality measurements, including PM2.5, CO, and SO_2, were calibrated using factory calibration standards. Calibration was conducted at the beginning of the study and at regular intervals during the pilot phase to ensure measurement accuracy.

The study evaluated an integrated package rather than a single patented technology. The intervention package combined: (a) environmentally friendly operational measures for dust reduction near processing areas; (b) strengthened mine-water handling practices, including observation of settling and discharge control; and (c) a sensor-supported monitoring workflow. Air quality monitoring focused on PM2.5, CO, and SO_2. Water and soil quality evaluation focused on pH, turbidity, dissolved oxygen, arsenic, lead, and organic matter. Because not all parameters can be measured continuously using low-cost sensors, the monitoring system combined sensor-based measurement for routine field monitoring with periodic field sampling and documentation for parameters that required point-in-time testing. The resulting data were reviewed in a simple site dashboard for operational feedback.

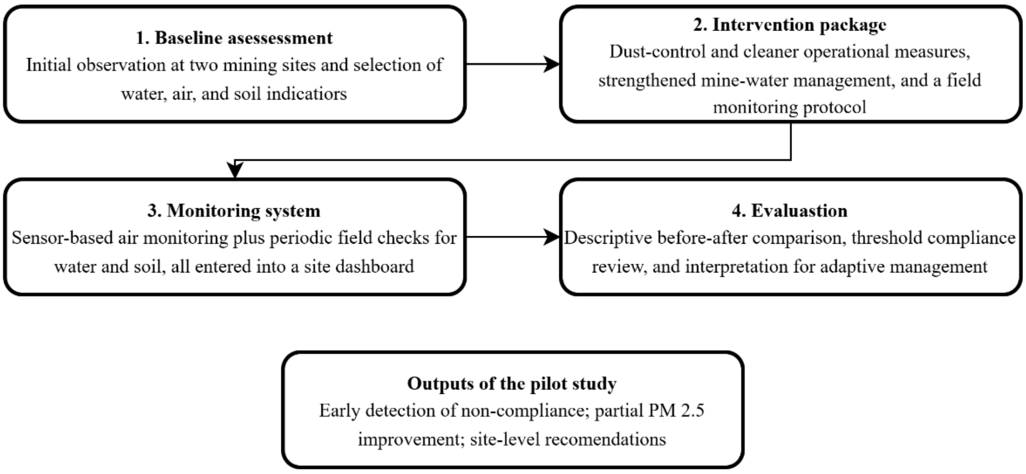

Figure 1. Integrated pilot workflow for green technology interventions and sensor-based environmental monitoring.

Variables, Benchmarks, and Analytical Approach

The monitored variables were grouped into three domains: water quality, air quality, and soil quality. Threshold limits were harmonized from site operational benchmarks and relevant external references, particularly the environmental protection framework in Indonesia, mining wastewater guidance, and air-quality benchmarks for PM2.5 (Republic of Indonesia, 2021; Ministry of Environment and Forestry of the Republic of Indonesia, 2022; World Health Organization, 2021).

The analysis emphasized descriptive rigor. First, endline values were compared with threshold limits to classify each parameter as compliant, non-compliant, or near-threshold. Second, before–after comparison was applied to PM2.5 because baseline and endline values were available at both sites. Percent reduction was used to evaluate practical improvement. Inferential statistics such as paired t-tests, ANOVA, and regression were intentionally not used because the available pilot dataset covered only two sites and a very limited number of before–after observations, which would make significance testing methodologically weak and potentially misleading. This decision was made to preserve analytic validity.

Results

Environmental Quality Status After Intervention

Table 1 summarizes the endline measurements after implementation of the intervention package. The results show a mixed pattern. Several basic parameters were already within the acceptable range, including water pH, soil pH, CO, and SO_2. Lead at Mine Location A was exactly at the threshold limit, while Mine Location B remained slightly below it. The major environmental concerns remained water turbidity, dissolved oxygen, arsenic concentration, PM2.5, and soil organic matter.

From a compliance-gap perspective, the most severe deviations occurred in turbidity and arsenic. Turbidity exceeded the benchmark by 200% at Mine Location A and by 400% at Mine Location B. Arsenic was approximately two to 2.4 times the reference limit. PM2.5 exceeded the benchmark by 28.6% at Mine Location A and 57.1% at Mine Location B. These findings show that the environmental technologies were not equally effective across pollution domains and that water-quality control remained the dominant unresolved issue.

Table 1. Endline Environmental Quality Data and Compliance Interpretation

Domain	Parameter	Mine Location A	Mine Location B	Threshold Limit	Interpretation
Water quality	pH	7.2	6.8	6.5–8.5	Compliant
Water quality	Turbidity (NTU)	15	25	≤ 5	Non-compliant
Water quality	Dissolved oxygen (mg/L)	4.5	3.8	≥ 5	Non-compliant
Water quality	Arsenic (ppb)	10	12	≤ 5	Non-compliant
Air quality	PM2.5 (μg/m^3)	45	55	≤ 35	Non-compliant
Air quality	CO (ppm)	0.3	0.4	≤ 0.5	Compliant
Air quality	SO_2 (ppm)	0.05	0.06	≤ 0.1	Compliant
Soil quality	pH	6.3	6.1	6.0–7.5	Compliant
Soil quality	Lead (ppb)	50	45	≤ 50	At threshold (A)
Soil quality	Organic matter (%)	2.5	2.0	≥ 3	Non-compliant

Illustration of Monitoring Implementation

Table 2 presents examples of how measurements were organized across environmental media. Water and air quality were checked at operationally sensitive points, while soil indicators were recorded on a monthly basis to reflect slower environmental change.

Table 2. Example of Monitoring Implementation During the Pilot Phase

Parameter	Location	Time of Measurement	Measurement Result
Water quality (pH)	Point 1 (river/discharge area)	Morning	7.2
Water quality (turbidity)	Point 1 (river/discharge area)	Morning	8 NTU
Air quality (PM2.5)	Point 1 (near processing area)	Afternoon	45 μg/m^3
Soil quality (pH)	Point 1 (near processing area)	Month 1	6.3
Soil quality (lead)	Point 1 (near processing area)	Month 1	50 ppb

Before–After PM2.5 Comparison

Baseline and endline PM2.5 values were available for both sites, making them the clearest indicator for before–after evaluation. Average PM2.5 decreased from 61.5 to 48.0

μg/m^3, equivalent to an average reduction of 22.0%. Mine Location A recorded a larger improvement than Mine Location B; however, both sites remained above the benchmark of 35 μg/m^3 at the end of the pilot.

Table 3. Descriptive Before–After Comparison of PM2.5

Site	Before (μg/m^3)	After (μg/m^3)	Reduction (%)	Endline Status
Mine Location A	58	41	29.3	Still above benchmark
Mine Location B	65	55	15.4	Still above benchmark

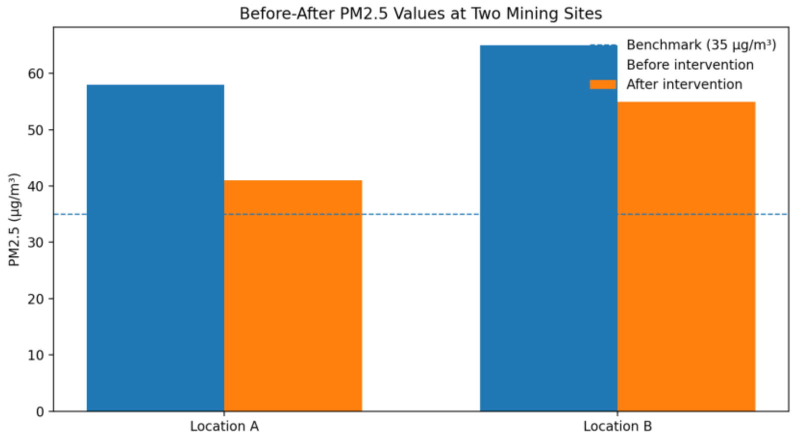

Figure 2. Before–after PM2.5 values at the two mining sites.

Discussion

The pilot results support a restrained but important conclusion: the integrated intervention package helped reduce airborne particulate exposure, yet it did not solve the broader environmental problem. A 29.3% reduction at Mine Location A and a 15.4% reduction at Mine Location B indicate that cleaner operational practices and localized monitoring can improve performance; however, the remaining exceedance above the PM2.5 benchmark shows that these measures were not sufficient on their own. This reinforces a key principle in scientific reporting: improvement is not the same as full compliance.

Water quality remained the weakest dimension. Elevated turbidity and arsenic, together with dissolved oxygen below the reference level, suggest that mine-water management still requires stronger treatment and discharge control. This finding is consistent with the wider literature, which shows that mining wastewater treatment usually requires integrated rather than single-step solutions and that practical challenges such as sludge handling, maintenance, and cost frequently limit field performance (Matebese et al., 2024). It also indicates that monitoring systems are useful only when they are coupled with a credible response mechanism; measurement without corrective action has limited environmental value.

The monitoring architecture itself remains a meaningful contribution. Indonesian literature emphasizes that environmental monitoring systems should provide timely, spatially relevant, and decision-oriented data (Nugroho et al., 2025). The present study translates that general argument into a mining-site pilot by showing how routine measurements can identify which parameters improve quickly and which require structural intervention. At the same time, the pilot reinforces a practical warning from low-cost sensor studies: monitoring instruments require calibration, contextual interpretation, and quality control to avoid false confidence (Kurniawati et al., 2025).

This study has several limitations. The sample covered only two sites over a three-month period; the intervention package was not evaluated against a control site; and baseline–endline data were available only for a subset of variables. The pilot also did not quantify energy savings, cost-effectiveness, or long-term ecological recovery. Therefore, the findings should be interpreted as a preliminary operational evaluation rather than definitive evidence of sectorwide effectiveness. Future research should extend the monitoring period, incorporate control or comparison sites, include cost and energy indicators, and link site-level monitoring to broader reclamation tracking, such as remote-sensing-based compliance evaluation (Prasetya & Tsai, 2025a, 2025b).

Conclusion

This study concludes that the combined use of environmentally friendly operational interventions and a sensor-based monitoring workflow generated partial environmental improvement at the pilot mining sites. The clearest improvement was observed in PM2.5, which declined at both sites after intervention. However, the endline data show that several critical parameters remained non-compliant, particularly turbidity, dissolved oxygen, arsenic, and soil organic matter. Accordingly, the appropriate conclusion is not that the intervention solved the environmental problem, but that it improved monitoring capacity and delivered limited performance gains that still require stronger follow-up action.

Three practical recommendations follow from the pilot. First, mining operators should scale sensor-supported monitoring only alongside mandatory calibration, maintenance, and data-review routines. Second, regulators should require threshold-based reporting for a defined set of priority indicators, particularly PM2.5, turbidity, dissolved oxygen, and heavy metals. Third, incentives and enforcement should focus on improved mine-water treatment, dust suppression, and adaptive response once non-compliance is detected. These measures are more realistic than generic sustainability claims because they link technology adoption directly to measurable environmental performance.

In policy terms, Indonesia's mining governance agenda would benefit from combining site-level monitoring, environmental protection standards, and staged adoption of cleaner technologies. In research terms, the next step is a larger longitudinal study to test whether integrated interventions can move sites not only toward improvement but toward full compliance.

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Conflict of Interest

The authors declare that there are no conflicts of interest related to this publication. No external party influenced the study design, data collection, analysis, manuscript preparation, or the decision to submit this article.

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