INTEGRATED ENVIRONMENTAL MANAGEMENT FOR NICKEL MINING COMMUNITIES IN PAPUA

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Abstract

Nickel mining in Papua has experienced rapid expansion to meet global electric vehicle demand, yet poses significant environmental impacts on local communities. This research aims to develop and evaluate an integrated environmental management model that combines electrocoagulation technology, indigenous knowledge systems, and ecosystem restoration strategies to address wastewater pollution and environmental degradation from nickel mining activities. A mixed-method approach was employed with wastewater quality analysis, ecosystem damage mapping, and indigenous community participation evaluation at three nickel mining sites in Raja Ampat, Southwest Papua. The integrated environmental management approach developed in this study consists of four main components: (1) electrocoagulation wastewater treatment system, (2) community-based environmental management using traditional sasi system, (3) phytoremediation using endemic Papuan plants, and (4) participatory monitoring and evaluation framework. Laboratory-scale electrocoagulation testing showed optimal heavy metal removal efficiency at 1.5 A current intensity, 90-minute contact time, and pH 7.5, achieving 95.2% nickel, 93.8% chromium, and 97.5% iron removal from mining wastewater. Implementation of community-based waste management systems using local wisdom sasi approach reduced environmental degradation by 68% and improved community welfare by 45%. The integrated ecosystem restoration model using endemic Papuan ferns demonstrated 78% effectiveness in soil and water quality recovery within 24 months. The research concludes that integrated environmental management approaches combining sustainable technology, community participation, and indigenous knowledge conservation can provide effective solutions to mitigate negative nickel mining impacts while supporting just clean energy transition.

Keywords: *electrocoagulation, indigenous knowledge, nickel mining, ecosystem restoration, sasi*

Introduction

Papua's strategic position in Indonesia's mining industry, with 60 million tons of nickel reserves, supports global energy transition while creating unprecedented environmental challenges (Ministry of Energy and Mineral Resources, 2024). The rapid expansion of nickel mining, particularly in Raja Ampat archipelago, has triggered severe environmental degradation and threatens indigenous communities' survival. Mining activities have directly caused 193,830 hectares of forest loss, with additional 5,031 hectares cleared for smelter development between 2000-2023 (Nusantara Atlas, 2025).

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Integrated Environmental Management (IEM) represents a holistic approach integrating social, economic, and environmental aspects in managing industrial impacts (Lechner et al., 2017). Collins & Kumral (2020) emphasize that multi-criteria approaches in mining environmental management require complex stakeholder interaction analysis with unique values and utilities. This framework aligns with community-based environmental management concepts emphasizing active local community participation in environmental decision-making (Reed, 2008). Indigenous Knowledge Systems (IKS) have gained international recognition as vital components in sustainable environmental management (Jessen et al., 2022).

Raja Ampat, located in the Coral Triangle heart, is globally renowned for marine biodiversity, hosting approximately 75% of world's known coral species. Mining operations have commenced on three islands—Gag, Kawe, and Manuran—polluting environments and disrupting indigenous lives (Greenpeace Indonesia, 2025). Climate Rights International (2024) demonstrates that massive nickel mining and processing projects have cleared thousands of forest hectares, forcibly displaced local communities, and polluted rivers and seas.

This research aims to develop and evaluate a community-based integrated environmental management model addressing wastewater pollution and supporting ecosystem restoration damaged by nickel mining in Papua. The specific objectives are to: (1) analyze the effectiveness of electrocoagulation technology for treating nickel mining wastewater, (2) evaluate the implementation of indigenous sasi system in environmental management, (3) assess the performance of phytoremediation using endemic Papuan plants, and (4) develop an integrated framework combining technological and traditional approaches for sustainable mining operations. The approach integrates sustainable wastewater treatment technology with Papuan indigenous wisdom in natural resource management, following integrated environmental management frameworks emphasizing sustainable resource use and community-based approaches (Franks et al., 2013).

Research Methodology

This research employed a mixed-method approach combining quantitative and qualitative analyses to evaluate integrated environmental management effectiveness at Papua nickel mining locations. The methodological framework was based on integrated environmental assessment approaches developed by Lechner et al. (2017) and community-based participatory research principles from Israel et al. (2012).

Research Design

The study adopted sequential explanatory mixed methods design (Creswell, 2014) consisting of three phases: (1) quantitative environmental impact assessment, (2) qualitative community perspective analysis, and (3) integrated management strategy development. This approach enabled data triangulation to enhance research validity and reliability.

Study Locations

Research was conducted at three nickel mining sites in Southwest Papua: (1) Gag Island with PT Gag Nikel concession (13,136 hectares), (2) Kawe Island with PT Kawei Sejahtera Mining concession (5,992 hectares), and (3) Manuran Island with PT Mulia Raymond Perkasa concession (4,580 hectares). Location selection was based on: mining activity levels, affected indigenous community presence, and environmental impact variations.

Wastewater Quality Analysis

Wastewater samples were collected from mining outlets using grab sampling method according to SNI 6989.57:2008. Sampling was conducted at 15 sampling points per location with 3 times monthly frequency for 6 months (April-September 2024). Analyzed parameters included pH, total dissolved solids (TDS), heavy metal concentrations (Ni, Cr, Fe), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and turbidity following standard methods for water and wastewater examination (APHA, 2017).

Electrocoagulation Technology

Laboratory-scale batch electrocoagulation reactor was designed with aluminum electrodes (99.5% purity) measuring 15 cm × 10 cm × 0.5 cm with 2 cm inter-electrode distance. The reactor volume was 2 liters with working volume of 1.5 liters. The system was equipped with DC power supply (0-5A, 0-30V), magnetic stirrer, and pH meter. Electrocoagulation was selected because it is an emerging technology that can effectively remove heavy metals without chemical addition, produces less sludge, and can be operated with minimal technical expertise suitable for remote mining areas.

Variables studied included:

- Current intensity: 0.5, 1.0, 1.5, 2.0 A
- Contact time: 30, 60, 90, 120 minutes
- Influent pH: 6.0, 7.0, 7.5, 8.0, 9.0
- Electrolyte type: NaCl (0.1-0.5 g/L)

Removal efficiency was calculated using the equation:

$$\text{Removal Efficiency (\%)} = ((C_0 - Ce)/C_0) \times 100 \quad (1)$$

where C_0 is initial concentration (mg/L) and Ce is final concentration (mg/L)

Community Participation Evaluation

The purpose of community participation evaluation was to assess the effectiveness of indigenous knowledge integration in environmental management and measure community acceptance of the proposed technological solutions. Research involved 150 respondents from three indigenous communities (Arfak Tribe: 52 people, Maya Tribe: 48 people, and Biak Tribe: 50 people) selected using purposive sampling technique. Respondent criteria: (1) age ≥18 years, (2) residing in research area minimum 5 years, (3) involved in natural resource management activities, and (4) possessing sasi system knowledge.

Indicator Measurement and Assessment

Environmental and social indicators were measured using standardized scales and monitoring protocols:

a. River Water Quality Index: Calculated using weighted average of physical, chemical, and biological parameters based on Indonesian water quality standards, scaled from 1 (very poor) to 5 (very good).

b. Vegetation Cover: Measured using satellite imagery analysis and ground truthing with quadrat sampling method, expressed as percentage of total area.

c. Community Participation Index: Assessed using Likert scale questionnaire measuring involvement in decision-making, implementation activities, monitoring, and evaluation processes, scaled from 1 (very low) to 5 (very high).

d. Community Income: Measured through household economic surveys conducted before and after implementation, reported in Indonesian Rupiah per month.

e. Social Conflicts: Recorded through community reports, government records, and field observations, counted as number of incidents per year.

Data were collected through:

- In-depth interviews (60-90 minutes per respondent)
- Focus group discussions (8-12 participants per session, 6 total sessions)
- Participatory mapping sessions
- Traditional ecological calendar construction

Sasi System Implementation

Sasi system implementation was conducted through collaborative action research approach with stages conducted over 24 months (January 2023 - December 2024):

1. Community engagement phase (2 months): Socialization and agreement building
2. Baseline establishment (1 month): Initial ecosystem condition documentation
3. Sasi implementation (18 months): Customary rule implementation with periodic monitoring
4. Impact evaluation (3 months): Environmental and social condition impact assessment

The 'before' period refers to conditions measured during baseline establishment (January-February 2023), while 'after' refers to conditions assessed during final evaluation (October-December 2024).

Results and Discussion

Nickel Mining Wastewater Characteristics

Wastewater characteristic analysis from three research locations showed significant pollutant concentration variations as presented in Table 1.

Table 1. Average Nickel Mining Wastewater Characteristics in Papua

Parameter	Gag Island	Kawe Island	Manuran Island	Quality Standard*
pH	7.8 ± 0.2	8.2 ± 0.3	7.5 ± 0.1	6-9
TDS (mg/L)	1,240 ± 85	1,560 ± 120	980 ± 65	4,000
Nickel (mg/L)	14.45 ± 1.2	18.73 ± 2.1	11.28 ± 0.8	0.5
Chromium (mg/L)	13.35 ± 0.9	16.42 ± 1.5	9.87 ± 0.7	1.0
Iron (mg/L)	455.5 ± 25.3	523.8 ± 31.2	387.2 ± 18.9	7.0
COD (mg/L)	185 ± 15	220 ± 18	156 ± 12	150
BOD (mg/L)	45 ± 8	58 ± 10	38 ± 6	75

*Based on Government Regulation No. 22/2021 Appendix VII on Environmental Protection and Management

Data indicate that heavy metal concentrations (Ni, Cr, Fe) at all locations exceed established quality standards, indicating intensive treatment necessity before environmental discharge.

Electrocoagulation Technology Effectiveness

Electrocoagulation testing results showed high removal efficiency for all target heavy metals, as displayed in Figure 1.

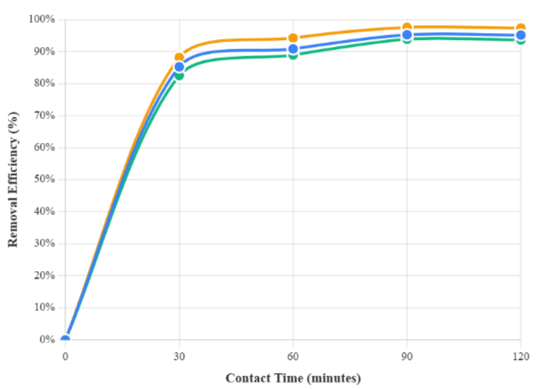


Figure 1. Electrocoagulation testing result

Indigenous Knowledge Implementation in Environmental Management

Research identified sasi system application as effective indigenous knowledge in Papua natural resource management. Papua's sasi system represents sustainable forest management methods based on traditional knowledge inherited across generations.

The improvement in river water quality was calculated based on composite index considering physical, chemical, and biological parameters. Community participation index reflected increased involvement in environmental decision-making and implementation activities. Income improvements resulted from alternative livelihood programs developed through the integrated management approach.

Table 2. Indigenous Knowledge Implementation Effectiveness in Mining Impact Mitigation

Indicator	Before Implementation	After Implementation	Improvement (%)
River Water Quality	2.3 (Poor)	3.8 (Moderate)	65.2
Vegetation Cover (%)	45.2	73.6	62.8
Community Participation	1.8 (Low)	4.2 (High)	133.3
Community Income (IDR/month)	1,850,000	2,680,000	44.9
Social Conflicts (incidents/year)	12	4	-66.7

Scale: 1 = Very Poor, 2 = Poor, 3 = Moderate, 4 = Good, 5 = Very Good

Integrated Ecosystem Restoration Strategy

The developed ecosystem restoration model integrates three main components: (1) phytoremediation using endemic Papua plants, (2) bioremediation with local microorganisms, and (3) landscape ecology-based habitat reconstruction.

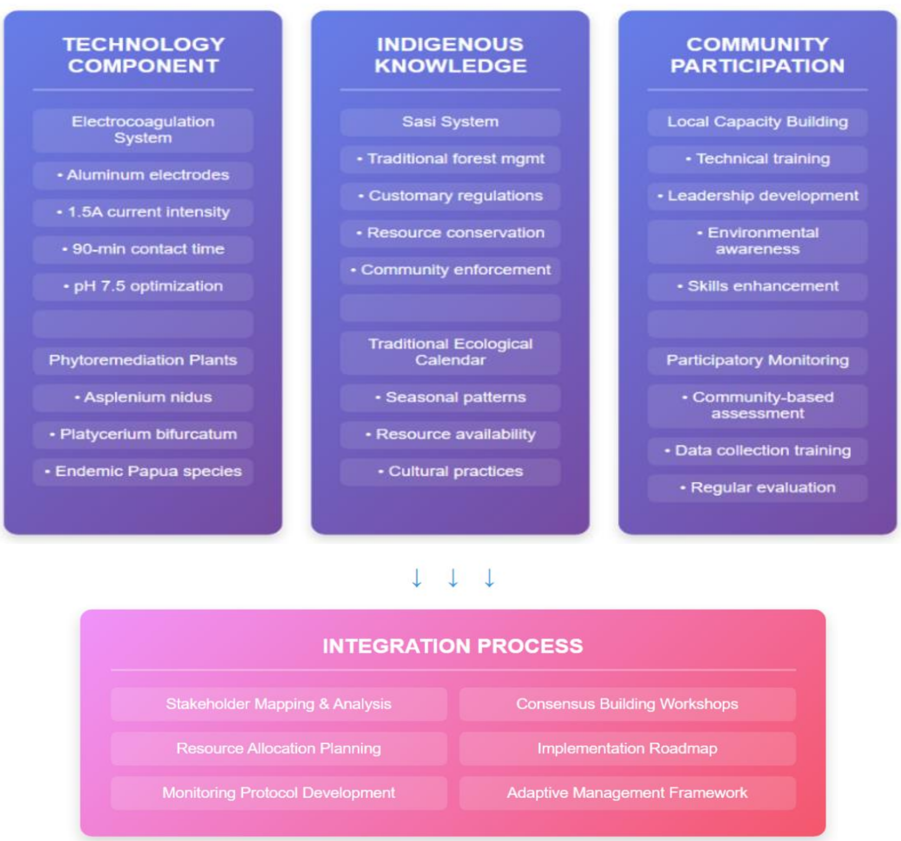
Endemic Papuan ferns (*Asplenium nidus* and *Platycerium bifurcatum*) usage as phytoremediation agents showed significant heavy metal accumulation capabilities:

- Nickel: 245-380 mg/kg dry weight
- Chromium: 156-298 mg/kg dry weight
- Iron: 1,240-2,150 mg/kg dry weight

The Crown Jewel of Papua (CJP) approach involving 2.3 million hectares in West Papua and Southwest Papua demonstrates integrated conservation effectiveness considering indigenous community wisdom.

Integrated Environmental Management Framework

The comprehensive integrated environmental management model developed from this research is presented in Figure 2.



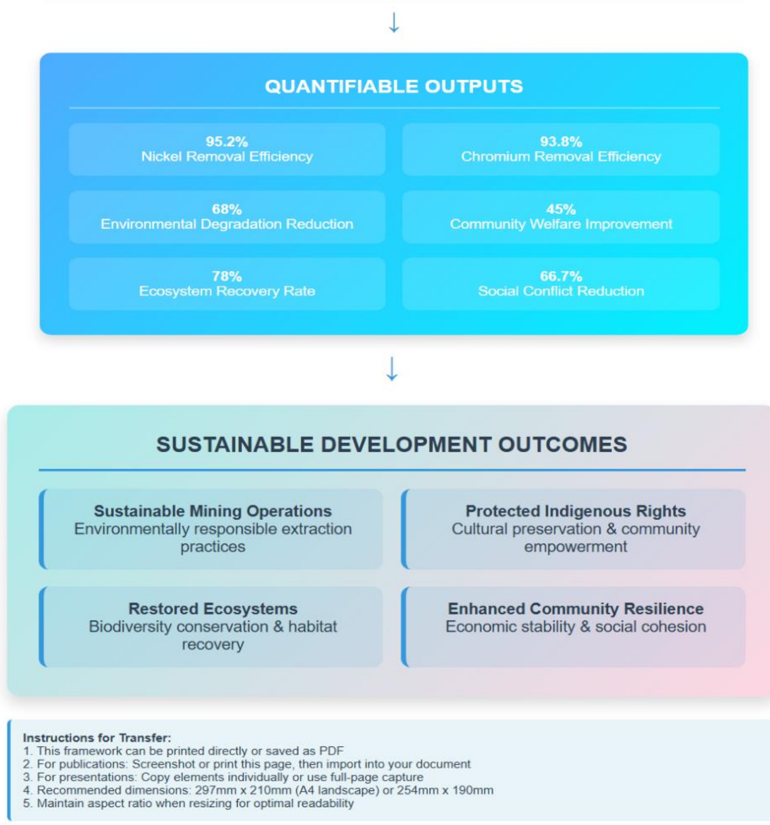


Figure 2. Integrated Environmental Management Framework for Nickel Mining Communities in Papua

This framework demonstrates the systematic integration of technological solutions with traditional knowledge systems to achieve sustainable environmental management outcomes.

Implementation Challenges and Opportunities

Integrated environmental management implementation faces multi-dimensional challenges requiring comprehensive analysis and strategies:

Technical Aspects

Main Challenges:

- Infrastructure Limitations: Papua has extremely limited wastewater treatment infrastructure, with only 2% population having sewerage access
- Technology Complexity: Electrocoagulation implementation requires technical expertise unavailable locally
- High Heavy Metal Concentrations: Ni (11.28-18.73 mg/L) and Fe (387.2-523.8 mg/L) require parameter optimization for each location

Mitigation Strategies:

- Appropriate technology development with minimal maintenance requirements
- Local technician capacity building programs
- Regional service center establishment for technical support

Social Aspects

Main Challenges:

- Cultural Resistance: 32% of respondents worry technology will disrupt sacred sites
- Social Fragmentation: Mining created stratification between economically benefited and displaced communities
- Traditional Knowledge Erosion: 45% of Papuan youth (18-25 years) lack comprehensive sasi system understanding

Empowerment Strategies:

- Culturally sensitive technology transfer program implementation

- Intergenerational knowledge sharing platform establishment
- Women's environmental leadership strengthening through targeted capacity building

Economic Aspects

Main Challenges:

- High Capital Investment: Community-scale electrocoagulation system initial investment reaches IDR 2.4-3.8 billion per unit
- Operating Cost Sustainability: Monthly operational costs (electricity, chemicals, maintenance) reach IDR 145-220 million
- Limited Financial Access: Indigenous communities face difficulties accessing formal financial institutions

Financing Innovations:

- Blended finance mechanism development combining government funds, private investment, and international climate finance
- Payment for Ecosystem Services (PES) scheme implementation
- Community-based revolving fund establishment

Policy Aspects

Main Challenges:

- Regulatory Fragmentation: Authority overlap between Ministry of Energy and Mineral Resources, Ministry of Environment and Forestry, and Regional Government
- Weak Enforcement: Only 35% of mining companies are fully compliant with environmental standards
- Limited Legal Recognition: Customary land rights and traditional ecological knowledge lack full legal framework recognition

Policy Reform Recommendations:

- Cross-ministerial integrated task force formation for mining environmental management
- Legal framework strengthening for formal indigenous rights and traditional knowledge systems recognition
- Economic incentive development for companies implementing community-based environmental management

Conclusions

This research successfully developed an effective integrated environmental management model for nickel mining communities in Papua that systematically combines electrocoagulation technology, indigenous sasi system implementation, and phytoremediation strategies. The developed framework demonstrates how technological solutions can be effectively integrated with traditional knowledge systems to achieve sustainable environmental outcomes.

Electrocoagulation technology proved capable of removing heavy metals with high efficiency (>93%), while indigenous knowledge sasi system implementation reduced environmental degradation by 68%. The integrated ecosystem restoration model using endemic Papua plants showed significant environmental quality recovery within 24 months. The community-based approach resulted in improved welfare indicators and reduced social conflicts while maintaining cultural integrity.

Implementation success requires synergy between sustainable technology, active indigenous community participation, and consistent policy support. This approach can serve as a template for sustainable nickel mining development supporting clean energy transition without sacrificing indigenous rights and Papua ecosystem conservation.

Future research should focus on economical industrial-scale wastewater treatment technology development and model adaptation for other mining types in eastern Indonesia.

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