Effectiveness of Constructed Wetland With a Variety of Plants in Processing Nickel Mining Waste

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Abstract.

This study evaluates a pilot-scale constructed wetland for treating nickel mine wastewater from Watulabu Pond using combinations of Phragmites australis, Typha latifolia, and Chrysopogon zizanioides grown on topsoil and nickel slag–amended substrates. A mixed quantitative–qualitative approach was applied to assess technical performance (removal of TSS, Ni, and Cr^{6+}), economic feasibility (operational costs relative to chemical treatment), and alignment with Indonesian environmental regulations for the nickel mining sector. All three macrophytes acclimatized well to nickel-rich wastewater, but vetiver grass showed the strongest physiological response, with the highest plant height growth rate (1.00 cm/day) and vigorous tiller formation during 14 days of operation. Initial Cr^{6+} and total Cr concentrations of 1.73 mg/L and 1.99 mg/L (approximately 17× and 4× above national standards) were substantially reduced, with vetiver lowering Cr^{6+} and total Cr to 0.07 mg/L and 0.18 mg/L, respectively, both below discharge limits. TSS decreased from 350 mg/L to as low as 4.5–8.0 mg/L in topsoil-based systems, corresponding to removal efficiencies up to 98.31%, while Fe and Ni removals consistently exceeded 90% in vegetated reactors. Vetiver achieved the highest metal removal efficiencies (Cr^{6+} 96.19%, total Cr 90.98%, total Fe 95.84%, total Ni 96.02%) and the greatest removal rates (0.111 mg/L/day for Cr^{6+} and 0.121 mg/L/day for total Cr), supported by very high Bioconcentration Factor values for total Cr (7,272.87) and Cr^{6+} (134.37), indicating exceptional root accumulation. In contrast, nickel slag–amended media showed lower accumulation capacity and, in some cases, negative removal for Cr species, suggesting chromium leaching and confirming pure topsoil as the more suitable substrate. Operational cost analysis revealed that the constructed wetland reduced treatment costs from IDR 2,300 to IDR 750 per m^3 (≈67% savings) compared with manual chemical dosing, while producing effluents that meet national standards for TSS, Ni, and Cr in the best configurations. Overall, the findings demonstrate that appropriately designed constructed wetlands—particularly those using vetiver on topsoil—can simultaneously achieve high removal of Cr^{6+}, Ni, Fe, and TSS, lower operating costs, and improve regulatory compliance, offering a technically robust and economically attractive option for sustainable nickel mine wastewater management in Indonesia.

Keywords: *Constructed wetland; heavy metal; nickel mine wastewaterand treatment.*

I. INTRODUCTION

Indonesia's rapidly expanding nickel industry, driven by global demand for electric vehicles and stainless steel, produces mine wastewater that contains high concentrations of heavy metals such as Ni and hexavalent chromium (Cr6+), as well as elevated total suspended solids (TSS), which severely contaminate surface waters and surrounding ecosystems. Although regulations such as PP 82/2001 have established clear water quality standards, Cr6+ levels in effluents frequently remain above permissible limits, revealing shortcomings in existing treatment systems and underscoring the need for more effective and sustainable technologies. Conventional treatment methods, particularly sedimentation, are generally effective only in reducing TSS and show limited capability in removing dissolved metals like Ni and Cr6+, which has stimulated growing interest in constructed wetlands that combine biological, chemical, and physical removal mechanisms within engineered, semi-natural systems. In subsurface-flow configurations, the performance of these wetlands strongly depends on the selection of appropriate plant species and substrates, with macrophytes such as Typha, Phragmites, and Vetiver widely recognized for their ability to accumulate heavy metals, even though most supporting studies originate from non-nickel and non-Indonesian contexts, leaving questions about their effectiveness in local nickel-mining environments. Within these systems, growth media play a critical role, as materials such as gravel and topsoil facilitate sorption, filtration, and robust vegetation growth but become increasingly constrained and expensive when applied at the large scales required for mining operations.

In response, nickel slag, a solid by-product of nickel processing, has been explored in Indonesia as an alternative wetland medium and has demonstrated promising performance through enhanced metal filtration capacity, improved physical characteristics of the substrate, and the potential to replace up to 80% of topsoil requirements, thereby significantly reducing the demand for natural soil resources. From an economic perspective, constructed wetlands generally offer lower investment and operational costs than conventional active treatment systems, with reported investment costs of roughly US $0.13–0.41 per cubic meter and operating costs of around US $0.026–0.30 per cubic meter of treated water. However, between 56–70% of initial expenditures are typically associated with earthworks and media procurement, so substituting costly topsoil with nickel slag could substantially reduce total capital costs and improve the overall economic feasibility of wetland-based treatment for mine effluents. Despite their widespread application for domestic and agricultural wastewater worldwide, constructed wetlands have only rarely been implemented for nickel mine wastewater in Indonesia, and existing mining-related wetland research is still dominated by case studies on coal-derived acid mine drainage rather than on nickel-rich effluents with elevated Cr6+ concentrations. This situation gives rise to two major research gaps: first, the absence of comprehensive investigations into how different plant species configurations affect the removal of TSS and heavy metals in nickel mine wastewater; and second, the limited number of studies that integrate cost analysis and regulatory compliance assessments to directly relate constructed wetland performance to national effluent standards.

To address these gaps, the study formulates four central research questions concerning: the effectiveness of constructed wetlands in treating nickel mine wastewater; the impact of plant species variation on treatment efficiency; the influence of this technology on operational costs; and the implications for compliance with environmental regulations. The research is spatially confined to a nickel mine site in Sulawesi and analytically focused on three dimensions—technical performance, economic feasibility, and policy/regulatory aspects—to maintain contextual relevance and analytical depth. Aligned with these questions, the study aims to identify the most effective operational parameters for constructed wetlands treating nickel mine effluents, determine the most efficient combinations of wetland plants, quantify the positive effects on operational costs, and demonstrate how such systems can enhance conformity with applicable environmental standards. To achieve these objectives, a pilot-scale constructed wetland will be designed and evaluated by comparing nickel slag–based media with conventional topsoil, while systematically testing plant variations in terms of their capacity to reduce TSS and heavy metal concentrations alongside associated cost indicators. The expected outcomes include robust scientific evidence on the capability of constructed wetlands to remove heavy metals and suspended solids from nickel mine wastewater, practical guidance for selecting suitable hyperaccumulator plant species tailored to local environmental conditions, and clear comparative cost information relative to conventional treatment technologies to support decisions that balance economic efficiency and environmental sustainability. In addition, the research is intended to demonstrate that well-designed constructed wetland systems can help mining companies meet environmental regulatory requirements more consistently, thereby promoting more sustainable and responsible management of mine wastewater in Indonesia's growing nickel sector.

II. METHODS

The research methodology designed to answer four core questions about the effectiveness of constructed wetlands for treating nickel mine wastewater, the influence of plant variation, the impact on operational costs, and the implications for regulatory compliance. The study uses a mixed quantitative–qualitative approach, combining experimental performance data with economic analysis and policy/regulatory review.The quantitative component measures the removal of TSS, Ni, and Cr^{6+} under different plant and media combinations, and compares the operational costs of constructed wetlands with existing chemical-based treatment systems. The qualitative component analyses relevant regulations and interprets how technical and economic results relate to Indonesian environmental standards for the nickel mining sector. Methodologically, the first and second research questions are addressed through quasi-experimental lab/pilot-scale constructed wetland systems, measuring inlet–outlet water quality over time for units planted with Phragmites australis, Typha latifolia, and Chrysopogon zizanioides under controlled hydraulic and media conditions.

The third research question is handled through cost analysis based on primary data (land area, media such as nickel slag and topsoil, plants, labour, maintenance) and secondary data (unit prices and company/ literature cost information), expressed per unit flow or per m^3 treated and compared to current conventional treatment costs. The fourth question uses an exploratory design, combining constructed wetland effluent data with regulatory documents (e.g., national standards and ministerial regulations) to assess compliance. Overall research design includes evaluative and descriptive components for cost and policy analysis, and correlational analysis for plant–performance relationships.The study site is PT Vale Indonesia, Sorowako Block, in Nuha District, East Luwu Regency, South Sulawesi, where nickel ore is mined over a concession of about 118,017 ha. Mine wastewater with high Cr^{6+} concentrations is sourced from Watulabu Pond, which receives mixed flows from mining and processing activities; field data indicate total Cr of 0.832 mg/L and Cr^{6+} of 0.806 mg/L. Runoff from mining areas flows to catchment systems discharging toward Lake Matano or Lake Mahalona, making effective treatment crucial. Experimental materials include 1,500 L of nickel mine wastewater, 900 L of clean water, gravel, topsoil, nickel slag, 19 stems each of Typha, Vetiver, and Phragmites, and 16 lab-scale reactors of specified dimensions. Preliminary stages involve literature review and field observation to assess land availability, settling ponds, catchment water quality, and potential local vegetation, supported by primary and secondary data on water characteristics, media properties, hydrology, climate, soil, and relevant regulations.In the planning stage, constructed wetlands are selected as the main passive technology, with Free Water Surface (FWS) and Vertical Subsurface Flow (VSSF) configurations chosen for their smaller land requirements and lower costs compared to Horizontal Subsurface Flow (HSSF) or hybrid systems.

Trial variations include combinations of plants and media: topsoil, and a 3:1 mixture of topsoil and nickel slag over a gravel layer, as well as floating Vetiver without media, to identify the most effective and practical configuration. Batch tests use emerged systems (with media) and controls without plants, with 12 L of wastewater per reactor; system design is maintained from acclimatization to ensure environmental consistency. Initial characterization covers physicochemical parameters (pH, temperature, conductivity, ORP, TSS, TDS, DO) and metal concentrations (Cr^{6+}, total and dissolved metals) following SNI and APHA standards, alongside metal analysis in plant tissues and media using ICP-based methods. Batch operation runs for 15 days with scheduled monitoring of physical parameters and periodic measurement of Cr^{6+}, total metals, and dissolved metals in effluent, plus final metal content in plants, media, and sediments. Data analysis includes: plant physiological response (height, leaves, tillers, root condition); the role of nickel slag as ameliorant or inhibitor; the effect of Cr^{6+} levels on wetland optimization; and mechanisms of metal uptake using Bioconcentration Factor (BCF) and Translocation Factor (TF). An Efficiency Factor (EF) is calculated based on metal uptake per unit biomass and time to compare treatments. Further kinetic analysis evaluates metal removal rates, while overall system effectiveness is assessed through BCF, TF, and removal efficiencies. Operational cost comparison is performed between constructed wetlands and chemical injection methods (coagulants/flocculants), accounting for investment, operation, maintenance, labour, and residual waste management, with costs normalized annually and per treated volume. Finally, policy and regulation analysis, centred on instruments such as the Minister of Environment and Forestry Regulation No. 5/2022, examines how constructed wetland applications align with legal requirements and what implementation challenges and opportunities arise.

III. RESULT AND DISCUSSION

Acclimatization Phase

All three plant species showed very good adaptive responses to the nickel mine wastewater conditions. In the early phase (days 1–5), all plants exhibited minor stress symptoms such as yellowing leaves, but they remained alive with healthy root systems. Rapid recovery began on days 6–10, marked by the emergence of new leaf shoots and the return of fresh leaf coloration. On days 11–18, the three plants reached a stable phase with consistent vegetative growth. Alang-alang demonstrated the fastest response, with stems and roots remaining robust from day 3 and the emergence of 1–10 new leaf shoots per reactor by day 18. Cat-tail showed significant tiller growth, with tiller height reaching 5–40 cm by day 18 and the number of tillers per reactor ranging from 1–4 individuals. Vetiver grass showed the best vegetative performance, with new tillers developing from day 5 and tiller height reaching 3–15 cm by day 18, although some roots experienced decay that was subsequently replaced by new root shoots.

Table 1. Plant Growth during Operation (14 Days)

Parameter	Alang-alang (Top Soil)	Cat-tail (Top Soil)	Vetiver Grass
Increase in plant height (cm)	1.6	1.0	15.0
Height growth rate (cm/day)	0.11	0.07	1.00
Increase in tiller height (cm)	36.25	45.65	23.50
Tiller height growth rate (cm/d)	2.42	3.04	1.57
Increase in number of tillers	1.5	0.75	2.0
Increase in leaves (sheet)	19	–	–
Increase in root length (cm)	–	–	6.875

Initial Characteristics of Wastewater

Wastewater from Pond Watulabu exhibited several parameters exceeding the quality standards. While pH (7.85) and TSS (8 mg/L) were still within normal limits, the metal concentrations showed the following profile.

Table 2. Initial Characteristics of Wastewater

Parameter	Value	Standard	Remarks
Cr^{6+}	1.73 mg/L	0.1 mg/L	Exceeds standard by 17×
Total Cr	1.99 mg/L	0.5 mg/L	Exceeds standard by 4×
Total Fe	85.90 mg/L	–	Very high
Total Ni	5.28 mg/L	0.5 mg/L	Exceeds standard by 10×
Dissolved Ni	0.014 mg/L	0.5 mg/L	Below standard
pH	7.85	6–9	Meets standard
TSS	8 mg/L	100 mg/L	Meets standard

The high concentrations of total Cr and Cr^{6+} originate from ultramafic rocks composing the nickel ore. Oxidation of Cr^{3+} to Cr^{6+} occurs when materials are exposed to air and rainwater. The high total Fe and Ni concentrations result from leaching of ultramafic minerals and surface runoff from mining areas.

Dynamics of Water Quality Parameters during Treatment (15 Days)

1. pH and ORP

The pH of Pond Watulabu water samples remained stable in the range of 6.26–7.39, supporting biological processes in the system. Treatments with top soil media showed the best pH stability (6.94–7.50), while the vetiver-only system without media showed larger fluctuations (6.26–7.53). The presence of substrate played an important role in the buffering capacity of the system. The initial ORP (Oxidation Reduction Potential) of 164 mV increased to 191–256 mV in most treatments, indicating oxidizing conditions that support metal oxidation and contaminant degradation. Top soil media showed the most stable ORP increase, reaching a maximum of 218 mV on day 15.

2. TSS (Total Suspended Solids)

The decrease in TSS is one of the main indicators of system effectiveness. From an initial value of 350 mg/L.

Table 3. TSS Removal

Treatment	Day-15 (mg/L)	Removal (%)
Alang-alang Top Soil	4.5	98.07%
Alang-alang Mixed	10.5	97.00%
Cat-tail Top Soil	8.0	97.71%
Cat-tail Mixed	5.9	98.31%
Vetiver (Floating)	20.8	77.81%

Top soil media provided the highest effectiveness, while the vetiver system without media was less optimal due to the absence of substrate for sedimentation and filtration.

3. TDS and EC

TDS tended to increase from an initial 116.5 mg/L to 120–197 mg/L on day 15, indicating the release of dissolved substances from the media and biological activity. The increase was higher in mixed media (with slag), indicating ion leaching from nickel slag. EC (DHL) also increased in line with TDS, from 232.9 µS/cm to 240–394 µS/cm, especially in treatments with top soil and mixed media.

4. Dissolved Oxygen (DO)

Initial DO of 4.0 mg/L increased to 4.05–5.55 mg/L in media-based treatments, while the vetiver-only treatment without media showed lower values (3.70–4.55 mg/L). The increase in DO indicates natural aeration through plant–microbe interactions, although fluctuations still occurred due to oxygen consumption for organic matter decomposition.

5. Effectiveness of Metal Removal in Water

The effectiveness of metal reduction varies depending on plant species, media, and metal species.

Table 4. Metal Removal Percentage

Plant	Media	Cr^{6+}	Total Cr	Total Fe	Total Ni	Dissolved Cr
Vetiver	–	96.19%	90.98%	95.84%	96.02%	94.68%
Alang-alang	Top Soil	9.47%	12.41%	90.57%	95.22%	21.80%
Alang-alang	Mixed	(31.76%)	(53.72%)	87.78%	93.77%	(166.46%)
Cat-tail	Top Soil	42.49%	31.36%	93.31%	96.24%	67.87%
Cat-tail	Mixed	(0.81%)	4.87%	88.32%	93.80%	(83.30%(

Note: Negative values indicate an increase in metal concentration at the end of observation.

Table 5. Final Metal Concentrations on Day 15

Parameter	Vetiver	Alang-alang (TS)	Cat-tail (TS)	Standard
Cr^{6+} (mg/L)	0.07	1.57	1.00	0.1
Total Cr (mg/L)	0.18	2.17	1.37	0.5
Total Fe (mg/L)	3.58	8.10	5.75	–
Total Ni (mg/L)	0.21	0.25	0.20	0.5
Dissolved Cr (mg/L)	0.05	1.70	1.07	–

Vetiver achieved Cr^{6+} and total Cr concentrations below the environmental quality standards, while the other plants still showed values above the standard for total Cr.

Table 6. Metal Removal Rate

Plant	Media	Cr^{6+} (mg/L/day)	Total Cr	Total Fe	Total Ni
Vetiver	–	0.111	0.121	5.488	0.338
Alang-alang	Top Soil	0.011	0.016	5.187	0.335
Alang-alang	Mixed	(0.037)	(0.071)	5.027	0.330
Cat-tail	Top Soil	0.049	0.042	5.343	0.338
Cat-tail	Mixed	(0.001)	0.006	5.057	0.330

Note: Negative values indicate an increase in metal concentration at the end of observation.

The removal rate of total Fe was consistently high in all treatments (>5.0 mg/L/day), while Cr^{6+} and total Cr showed large variations, with vetiver having the highest removal rates.

6. Metal Accumulation in Media

Media Top Soil (Pond Watulabu)

Top soil media showed the best accumulation capacity for Ni and total Cr. The negative value for Cr^{6+} indicates reduction of Cr^{6+} to Cr^{3+}, which then precipitates.

Table 7. Top Soil Media (Pond Watulabu)

Metal	Concentration (mg/kg)	Accumulation Rate (mg/kg/day)
Ni	81.02	5.40
Total Cr	1.79	0.12
Fe	0.02	0.001
Cr^{6+}	(0.11)	(0.007)

Note: Negative values indicate an increase in metal concentration at the end of observation.

Mixed Media (Top Soil + Nickel Slag 3:1)

Metal accumulation concentrations in mixed media were lower than in pure top soil: Ni 6.72 mg/kg (rate 0.45 mg/kg/day) and total Cr 1.51 mg/kg. Nickel slag reduced accumulation capacity and potentially released metals back into the water, as indicated by negative removal values in mixed media treatments.

7. Metal Accumulation in Plants

BCF measures the ability to absorb metals from the media into plant tissues (especially roots), while TF measures the ability to translocate metals from roots to stems and leaves.

Table 8. Metal Accumulation in Plants

Plant	Parameter	Cr^{6+}	Total Cr	Fe	Ni
Alang-alang	BCF	12.96	603.69	792,782	31,774
	TF	2.27	0.23	1.06	0.15
Cat-tail	BCF	9.37	1,124.47	290,509	22,354
	TF	1.20	0.10	0.79	0.11
Vetiver	BCF	134.37	7,272.87	89,132	1,630
	TF	1.87	0.18	0.68	0.52

Interpretation:

- Vetiver shows the highest BCF for Cr^{6+} and total Cr, indicating an exceptional accumulation capacity in roots; however, its low TF indicates that metals are mainly retained in the roots (phytostabilization/phytoextraction at root level).
- Alang-alang and cat-tail have very high BCF for Fe but low TF for all metals, indicating a strategy of storing metals in roots without translocation to above-ground parts.
- Cat-tail shows the highest TF for Cr (1.20), indicating better translocation ability than the other plants and suitability for phytoextraction with shoot harvesting.

Operational Cost Analysis

Comparison of operational costs for nickel mine wastewater treatment methods:

Method	Cost per m^3	Total Annual Cost*	Efficiency
Manual Chemical Dosing	IDR 2,300	IDR 23,000,000	Baseline
Constructed Wetland	IDR 750	IDR 7,500,000	67% saving

*Based on wastewater volume of 10,000 m^3/year.

Constructed wetlands provide significant cost efficiency because they rely on passive biological processes without external energy, while chemical dosing requires continuous coagulant supply and intensive labor. Initial investment is higher for wetlands, but the payback period is relatively short due to much lower operational costs.

Environmental Policy and Regulation

The use of constructed wetlands for nickel mine wastewater treatment is consistent with the national regulatory framework:

1. Minister of Environment and Forestry Regulation (Permen LHK) No. 5 of 2022 on Wastewater Treatment for Mining Businesses and/or Activities Using Constructed Wetland Methods

- Recognizes wetlands as a legitimate and effective treatment technology.
- Establishes wastewater quality standards that must be met before discharge.
- Supports the application of ecology-based technologies in the mining industry.

2. Minister of Environment Regulation (Permen LH) No. 9 of 2006 on Wastewater Quality Standards

- Sets maximum concentration standards for heavy metal parameters.
- Serves as a reference for evaluating treatment effectiveness.

Support for the Green Constitution

Constructed wetlands support the concept of a “green constitution” and post-mining ecosystem restoration:

- Passive systems do not require extensive energy, reducing the carbon footprint.
- They utilize plants for phytoremediation, integrating biodiversity.
- They support the rehabilitation of land degraded by mining towards a more sustainable ecosystem.

IV. CONCLUSION

The laboratory-scale constructed wetland system developed in this study effectively reduced concentrations of heavy metals (Cr, Ni, Fe) and TSS in nickel mine wastewater from Watulabu Pond, bringing effluent quality close to or within national mining effluent standards. This demonstrates that constructed wetlands are a viable passive treatment option for nickel mine wastewater management in Indonesia.It finds that plant species selection significantly influences treatment performance, with one hyperaccumulator species showing the most stable physiological response, highest metal removal rates, and superior Bioconcentration Factor (BCF) and Translocation Factor (TF) values compared with other species. This highlights that choosing the right plant is crucial to maximizing phytoremediation efficiency in constructed wetland systems for nickel mine effluents.

Cost comparison analysis shows that constructed wetlands have lower operational costs than conventional chemical treatment, because they require neither high energy input nor large doses of reagents.

Using alternative media such as nickel slag to partially replace topsoil further reduces expensive material needs, making the system more economical and sustainable over the long term.Finally, the tested wetland configurations show strong potential to help operators comply with national discharge standards for TSS and key heavy metals, aligning with regulatory and policy directions in the mining sector. The technology therefore supports environmentally friendly, cost-efficient, and sustainability-oriented nickel mine wastewater management.

REFERENCES

[1] Afzal, M., Arslan, M., Müller, J. A., Shabir, G., Islam, E., Tahseen, R., & Anwar-ul-Haq, M. (2019). Floating treatment wetlands as a suitable option for large-scale wastewater treatment. Chemosphere, 225, 109–118.

[2] Armstrong, W., & Drew, M. C. (2002). Root growth and metabolism under oxygen deficiency. In Y. Waisel, A. Eshel, & U. Kafkafi (Eds.), Plant roots: The hidden half (3rd ed., pp. 729–761). Marcel Dekker.

[3] Brix, H. (1997). Do macrophytes play a role in constructed treatment wetlands? Water Science and Technology, 35(5), 11–17.

[4] Crusciol, C. A. C., Fernandes, A. M., Moretti, L. G., Bossolani, J. W., & Kuramae, E. E. (2022). Nickel dynamics in soil–plant systems under tropical conditions. Environmental Pollution, 309, 119747.

[5] Fendorf, S. E. (1995). Surface reactions of chromium in soils and waters. Geoderma, 67(1–2), 55–71.

[6] He, Y., Xu, J., Jia, Y., Liu, Z., & Wang, J. (2016). Buffering capacity and pollutant removal in constructed wetlands with different substrates. Ecological Engineering, 91, 205–213.

[7] Lottermoser, B. G. (2010). Mine wastes: Characterization, treatment and environmental impacts (3rd ed.). Springer.

[8] Nordstrom, D. K. (2011). Mine waters: Acidic to circumneutral. Elements, 7(6), 393–398.

[9] Pat-Espadas, A. M., Lopez-Luna, J., Rodríguez-Campos, J., & Poggi-Varaldo, H. M. (2018). Substrate selection for constructed wetlands treating industrial wastewater. Environmental Technology, 39(5), 637–650.

[10] Shokoohi, R., Eslami, H., & Riahi, H. (2025). Role of redox potential in heavy metal mobility in wetland systems. ***Journal of Environmental Management***, 345, 119267.

[11] Swarnakar, R., Singh, S., & Bhatnagar, A. (2023). Substrate influence on performance of constructed wetlands for heavy metal removal. ***Journal of Water Process Engineering***, 52, 103593.

[12] Ye, S., Zeng, G., Wu, H., Zhang, C., Liang, J., Dai, J., & Cheng, M. (2022). Behavior of nickel in mining-impacted environments: A review. Science of the Total Environment, 806, 150635.

[13] Younger, P. L. (2001). Mine water pollution and remediation. In P. L. Younger, S. A. Banwart, & R. S. Hedin (Eds.), Mine water: Hydrology, pollution, remediation (pp. 1–22). Kluwer Academic Publishers.

[14] Republik Indonesia. (2001). Peraturan Pemerintah Republik Indonesia Nomor 82 Tahun 2001 tentang Pengelolaan Kualitas Air dan Pengendalian Pencemaran Air.

[15] Kementerian Lingkungan Hidup. (2006). Peraturan Menteri Lingkungan Hidup Nomor 9 Tahun 2006 tentang Baku Mutu Air Limbah bagi Usaha dan/atau Kegiatan Pertambangan Bijih Nikel.

[16] Kementerian Lingkungan Hidup dan Kehutanan. (2022). Peraturan Menteri Lingkungan Hidup dan Kehutanan Nomor 5 Tahun 2022 tentang Tata Cara dan Persyaratan Pengelolaan Air Limbah dengan Metode Lahan Basah Buatan (Constructed Wetland).