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Concept of sustainability in using nickel slag as a soil improver for mining land reclamation

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Abstract: Nickel slag presents strong potential as a soil improver for post-mining land reclamation, offering benefits across technical, economic, and social dimensions. This study evaluates the effectiveness of nickel slag in improving soil quality and supporting vegetation growth on nutrient-deficient overburden soils. Experimental results indicate that the incorporation of nickel slag enhances the availability of essential nutrients, particularly phosphorus (P), magnesium (Mg), and calcium (Ca), and improved soil pH. These changes facilitate the growth of pioneer species (*Melaleuca cajuputi*) and cover crops (*Centrosema pubescens*), which are critical for early-stage revegetation.

Melaleuca cajuputi exhibited consistent height and leaf development across treatments, with optimal performance observed in media containing up to 40% nickel slag, even in the absence of topsoil. Meanwhile, *Centrosema pubescens* showed superior leaf production in a mixture of 80% nickel slag and 20% compost. From an economic perspective, the use of nickel slag reduced reclamation costs by up to 32%, primarily through decreased reliance on organic fertilisers, yielding an estimated cost efficiency of IDR 52,500,000 per hectare.

Socially, the innovation has received positive endorsement from experts and is considered environmentally safe. Furthermore, its application supports community empowerment through training and outreach programs. Overall, the utilisation of nickel slag aligns with the three pillars of sustainable development – environmental integrity, economic viability, and social inclusion – and offers a locally sourced, cost-effective strategy for systematic and responsible land reclamation.

Keywords: cost efficiency, land reclamation, nickel slag, social acceptance, soil improver, sustainability

INTRODUCTION

Sustainable development requires prudent and efficient management of natural resources and industrial waste. One of the key challenges faced by the mining industry is the high volume of solid waste generated, including nickel slag. Smelting and refining industries in Indonesia produce approximately 21,800,000 Mg of slag annually, with the steel and nickel sectors contributing the largest share – around 14,173,000 Mg between 2019 and 2024 (Bethary and Intari, 2022). The rapid accumulation of nickel slag over time has created serious challenges for managing waste management in nickel processing industries (Kumar, Holuszko and Espinosa, 2017; Gabasiane, Bhero and Danha, 2019; Petlovanyi *et al.*, 2019; Behera, Farzana and Sahajwalla, 2020).

Nickel slag is a solid residue from the nickel smelting process that has not yet been optimally utilised (Rosalina, Tjahyandari and Darmawan, 2018). It is classified as non-hazardous waste (Non-B3) under Government Regulation No. 22 of 2021 concerning Environmental Protection and Management, Annex XIV (Peraturan, 2021). Toxicity characteristic leaching

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procedure (TCLP) tests have confirmed that nickel slag complies with Indonesian government standards (Behera, Farzana and Sahajwalla, 2020). The leaching levels of heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), and zinc (Zn) remain below the thresholds set by the UK Environmental Agency (Saha and Sarker, 2017). Therefore, nickel slag is considered environmentally safe, consistent with research findings that its utilisation can reduce and mitigate potential environmental risks associated with industrial waste (Hosseini *et al.*, 2016; Zhang *et al.*, 2017; Popov *et al.*, 2021). Although nickel slag has started to be used as a construction material, its adoption remains relatively limited. As a result, significant volumes of slag are still stored in stockpiles.

Several previous studies have indicated the positive potential of nickel slag, particularly for improving the physical and chemical properties of soil. Nickel slag contains minerals such as magnesium, silica, and calcium, which offer promising applications as soil improver. Ground nickel slag contains three major elements: Si, Fe, and Mg (Samnur *et al.*, 2016; Benhelal *et al.*, 2018; Prasetyo *et al.*, 2019; Wibowo *et al.*, 2020), that can serve as nutrient sources to enhance plant productivity. Samnur *et al.* (2016) reported that nickel slag contains 32.86% Si, highlighting its potential as a silicon source. Ferronickel slag (electric furnace slag) contains higher levels of Si and Mg but lower concentrations of Ca, Fe, P, and Mn compared to converter furnance slag. This makes it more effective as a silicon fertiliser for soils with low magnesium content, particularly in revegetated areas (Widiatmaka, Suwarno and Kusmaryandi, 2010).

A major challenge in post-mining land reclamation is the poor soil fertility, which makes soil amelioration necessary (Mansur, 2013). When used as a soil improver, nickel slag offers a viable solution for improving degraded soils in reclamation activities. This approach also supports circular economy principles, in which waste is repurposed into valuable products. Therefore, research on the potential of nickel slag as a soil improver is highly relevant to advancing sustainable development goals, particularly in industrial waste management and the restoration of degraded land. Sustainable development is a critical principle that industry stakeholders must adopt to ensure the long-term viability of their operations (Lotfi, Yousefi and Jafari, 2018; Chen *et al.*, 2020). It encompasses efficient resource utilisation and waste minimisation. Within the circular economy framework, waste is viewed as a resource that can be recycled or repurposed. The use of nickel slag as a soil improver exemplifies this approach, offering dual benefits: reducing industrial waste burdens and improving land quality.

The application of nickel slag in mine land reclamation reflects the implementation of sustainable development principles across three key pillars: economic, environmental, and social. Economically, using nickel slag as a soil improver can reduce reclamation costs by repurposing locally available industrial waste, while also decreasing reliance on expensive commercial ameliorants. Environmentally, it helps reduce solid waste accumulation from smelting industries and enhances the quality of degraded soils without significantly increasing heavy metal concentrations, as demonstrated. Socially, this initiative contributes to local community empowerment through job creation in reclamation and revegetation activities. Moreover, technology transfer through community training in reclamation techniques and nickel slag utilisation can enhance local capacity. Thus, nickel slag-based reclamation not only provides technical and ecological solutions but also delivers strategic contributions across multiple sectors, in line with the Sustainable Development Goals (SDGs 8, 12, 13, and 15) (Arif, 2021).

Based on the above, this study aims to develop a sustainable concept for utilising nickel slag as a soil improver in post-mining land reclamation, with consideration of social, economic, and environmental aspects.

MATERIALS AND METHODS

RESEARCH TIME AND LOCATION

This research was conducted from July 2022 to December 2022 in the greenhouse of the Silviculture Laboratory, Faculty of Forestry and Environment, IPB University, Indonesia.

RESEARCH MATERIAL

The materials used in this study included overburden soil, nickel slag, manure, and topsoil sourced from a nickel mining industry located on Obi Island, North Maluku, Indonesia.

PLANT SPECIES

The plant species used consisted of trees: P_t1 = cajuput (*Melaleuca leucadendron*), P_t2 = red jabon (*Anthocephalus macrophyllus*), P_t3 = jeungjing (*Falcataria moluccana*), P_t4 = nutmeg (*Myristica fragrans*) and cover crops: $P_{cc}1$ = centro beans (*Centrocema pubescens*), $P_{cc}2$ = citronella (*Cymbopogon nardus*), and $P_{cc}3$ = bede grass (*Brachiaria decumbens*).

GREENHOUSE-SCALE EXPERIMENT

- **Preparation of planting media**

1. Overburden soil, manure, and topsoil were sieved and screened, except for the nickel slag.
2. The weight of each material was measured according to the composition percentages.
3. All materials were thoroughly mixed.
4. The mixed media were placed into polybags until full.
5. The media in the polybags were watered.

The composition of planting media types for tree species and cover crop is described as follows, as presented in Table 1 and Table 2.

- **Measurement of planting media parameters**

Nutrient content analysis was conducted at the Laboratory of Soil Science and Land Resources, Faculty of Agriculture, IPB University. The observed parameters included: soil texture (three soil fractions) using the pipette method, exchangeable Ca, Mg, K, and Na (NH_4OAc 1 N, pH 7), cation exchange capacity (*CEC*) (NH_4OAc 1 N, pH 7), organic carbon (Walkley & Black method) (Neswati *et al.*, 2020), soil pH in water (1:5 ratio), total nitrogen (Kjeldahl method), total phosphorus (HCl 25%), available phosphorus (Bray I method), available Fe, Cu, Zn, and Mn (DTPA extraction) (Ngkoimani and Chaerul, 2017), exchangeable Al (KCl 1 N method) (Syahputra *et al.*, 2015). Some of the nutrient analysis data at 0 weeks after planting – namely

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Table 1. Treatments and composition of planting media for tree species

Treatment	Description
M_t0	50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil (w/w)
M_t1	50% overburden soil + 40% nickel slag + 10% manure + 0% topsoil (w/w)
M_t2	50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil (w/w)
M_t3	50% overburden soil + 20% nickel slag + 30% manure + 0% topsoil (w/w)
M_t4	50% overburden soil + 20% nickel slag + 20% manure + 10% topsoil (w/w)
M_t5	50% overburden soil + 20% nickel slag + 15% manure + 15% topsoil (w/w)

Source: own elaboration.

Table 2. Treatments and composition of planting media for cover crops

Treatment	Description
$M_{cc}0$	50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil (w/w)
$M_{cc}1$	50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil (w/w)
$M_{cc}2$	0% overburden soil + 30% nickel slag + 20% manure + 50% topsoil (w/w)
$M_{cc}3$	0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil (w/w)
$M_{cc}4$	0% overburden soil + 70% nickel slag + 30% manure + 0% topsoil (w/w)
$M_{cc}5$	0% overburden soil + 60% nickel slag + 40% manure + 0% topsoil (w/w)

Source: own elaboration.

treatments M_t0, M_t1, and M_t5 for tree planting media, and $M_{cc}0$, $M_{cc}1$, and $M_{cc}3$ for cover crop media – were previously published by the authors (Handayani S *et al.*, 2025). In this study, the data are reused as part of a follow-up analysis to assess nutrient concentrations across all planting media compositions, within a sustainability framework for using nickel slag as a soil improver in post-mining land reclamation.

- **Seedling transplanting procedure**

1. The seedlings were selected based on uniform average height and age.
2. Seedlings ready for transplanting were watered to prevent wilting.
3. A planting hole was made in the centre of each polybag filled with planting media using a wooden stick.
4. Seedling roots were gently lifted while removing any remaining media attached to the roots.
5. Seedlings were placed into the planting hole and the hole was covered.
6. Transplanted seedlings were watered twice daily, in the morning and afternoon.

- **Experimental design**

This study employed a split plot design combined with a completely randomised design (CRD), consisting of six treatments, four tree species, and three cover crop species, with ten replications. A total of 240 tree seedlings and 180 cover crop plants were observed.

- **Measurements**

The observed plant growth parameters included height increment, stem diameter, and leaf count, measured weekly for 20 weeks (trees) and 17 weeks (cover crops). Plant height was measured from the base of the stem (1 cm above the soil surface) to the tip of the apical shoot. Stem diameter was measured using a caliper. Leaves counts included only leaves that remained attached to the plant stem (Wasis *et al.*, 2011; Munthe, Pane and Panggabean, 2018).

- **Data analysis**

Growth parameter data collected during the study were analysed using analysis of variance (ANOVA) with SAS software version 9.4. Mean comparisons were conducted using Duncan's multiple range test (DMRT) at significance levels of α = 5% and 1% to determine the significance of treatment effects and interactions between the two factors (Tuheteru *et al.*, 2015).

SOCIAL ACCEPTANCE

Social acceptance was assessed through structured interviews and questionnaires distributed to representatives from academia (lecturers and researchers), government officials (relevant ministries and agencies), and industry practitioners (mining companies). The data were analysed descriptively. Respondents included representatives from Institut Teknologi Bandung, the Ministry of Energy and Mineral Resources (Ind.: Kementerian Energi dan Sumber Daya Mineral), the Ministry of Environment and Forestry (Ind.: Kementerian Lingkungan Hidup dan Kehutanan), the Coordinating Ministry for Maritime Affairs and Investment (Ind.: Kementerian Koordinator Bidang Kemaritiman dan Investasi), the Ministry of Economic Affairs and Trade (Ind.: Kementerian Perekonomian dan Perdagangan), Harita Nickel, the Environmental Agency of North Maluku Province (Ind.: Dinas Lingkungan Hidup Provinsi Maluku Utara), and the Environmental Agency of South Halmahera Regency (Ind.: Dinas Lingkungan Hidup Kabupaten Halmahera Selatan).

ECONOMIC VALUE

Economic value was assessed by comparing the cost savings from reduced use of manure due to the incorporation of nickel slag in the unit cost of reclamation. The analysis was conducted descriptively.

RESULTS AND DISCUSSION

NUTRIENT CONTENT IN PLANTING MEDIA

The planting media, composed of a mixture of overburden, nickel slag, manure, and topsoil with various treatment compositions, was used for tree and cover crop experiments in the greenhouse of the Silviculture Laboratory, Department of Silviculture, Faculty of Forestry and Environment, IPB University, Indonesia.

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Nutrient content in tree planting media

The nutrient content for tree planting media is presented in Table 3. All media types produced a pH around 7, indicating neutral soil reaction. Sand content increased while dust content decreased in media types M_t1–M_t5 compared to M_t0. Available phosphorus (P) was very high in M_t1–M_t4, while M_t5 showed high available P levels, suggesting that the addition of nickel slag + manure + topsoil (20:15:15%) to overburden soil resulted in lower available P compared to other nickel slag mixtures. The highest available P was found in M_t2 and M_t3, exceeding 30 ppm. The highest nitrogen (N) content was observed in M_t4 at 0.19%, while the lowest was in M_t1 at 0.12%, categorised as low.

Potassium (K) levels were low in M_t1, M_t2, and M_t5, while moderate in M_t0, M_t3, and M_t4. Calcium (Ca) levels were high in M_t0, but ranged from low to moderate in media types M_t1–M_t4, with the lowest Ca concentration in M_t1 at 3 $cmol^{(+)} \cdot kg^{-1}$. This indicates that adding nickel slag while reducing manure and topsoil in overburden soil results in lower Ca levels compared to adding only manure + topsoil (30:20%). Magnesium (Mg) levels were categorised as high across all media types. These results suggest that adding up to 40% nickel slag and 10% manure to overburden soil yields Mg levels comparable to those achieved by adding manure + topsoil (30:20%).

Nutrient content in cover crop planting media

The nutrient content for cover crop planting media is shown in Table 4. Media types $M_{cc}0$–$M_{cc}3$ and $M_{cc}5$ produced neutral soil reactions, while $M_{cc}3$ showed a slightly alkaline reaction. Sand content increased in $M_{cc}1$–$M_{cc}5$ compared to $M_{cc}0$, while dust and clay content decreased. Sand content progressively increased from $M_{cc}0$ to $M_{cc}5$, with the highest sand content in $M_{cc}3$. Organic carbon and total nitrogen levels were low across all media types, except for $M_{cc}1$, which had very low C-organic. Media types $M_{cc}2$ and $M_{cc}5$ had higher organic carbon and total nitrogen levels than $M_{cc}0$. Available P was very high in all media types, with $M_{cc}3$–$M_{cc}4$ showing higher levels than $M_{cc}0$. Potassium (K) levels were low in $M_{cc}0$–$M_{cc}3$, and moderate in $M_{cc}4$–$M_{cc}5$. Magnesium (Mg) and iron (Fe) levels were high in all media types ($M_{cc}0$–$M_{cc}5$), while sodium (Na) levels were low and copper (Cu) levels were adequate.

GROWTH OF TREE PLANTS

The test results indicate that plant species significantly affect changes in stem diameter, plant height, and leaf count in tree plants. Species P_t2 showed the greatest increase in stem diameter, while species P_t1 exhibited the highest increase in plant height and number of leaves. As indicated in Table 5, plant species significantly affect tree growth.

The test results indicate that the composition of the planting media had no significant effect on changes in stem diameter, plant height, or leaf count over the 20 weeks after planting (WAP), as shown in Table 6.

Based on the test results, the interaction between plant species and planting media composition had not significant effect on changes in stem diameter, plant height, and leaf count in tree plants over the 20 weeks after planting (WAP), as presented in Table 7.

Based on Figure 1, all tree species exhibited increases in stem diameter, height, and leaf count up to 20 weeks after planting (WAP). Species P_t2 showed a greater increase in stem diameter compared to the others, with an average diameter of 5.04 mm at week 20. Meanwhile, species P_t1 demonstrated the highest average growth in plant height and leaf count over the 20-week period, reaching 53.26 cm and 89 leaves, respectively.

GROWTH OF COVER CROP PLANTS

The test results (Tab. 8) indicate that the type of cover crop significantly influences changes in stem diameter, plant height, and leaf count. Species $P_{cc}2$ showed the greatest increase in stem diameter, while species $P_{cc}1$ exhibited the highest increase in plant height and number of leaves.

The test results (Tab. 9) also show that the composition of the planting media significantly affects changes in leaf count, with the highest values observed in $M_{cc}2$, $M_{cc}3$, $M_{cc}4$, and $M_{cc}5$, and the lowest in $M_{cc}1$. However, media composition did not significantly affect changes in stem diameter or plant height.

The test results also indicate a significant interaction between plant species and planting media composition and its effect on leaf count, while no significant influence was observed on changes in stem diameter and plant height (Tab. 10).

Based on Figure 2, all cover crop species exhibited increasing plant height growth up to 17 weeks after planting (WAP). Species $P_{cc}2$ showed greater stem diameter growth compared to other types, with an average diameter of 6.04 mm at week 17. Meanwhile, species $P_{cc}1$ demonstrated the highest average plant height and leaf count at 17 WAP, reaching 133.27 cm and 26 leaves, respectively. The growth of tree and cover crop species in the greenhouse is shown in Photo 1.

SOCIAL ACCEPTANCE AND EXPERT PERCEPTIONS OF NICKEL SLAG UTILISATION AS SOIL IMPROVER

Social acceptance of nickel slag utilisation as a soil improver in post-mining land reclamation is a critical aspect in assessing the social feasibility and practical implementation of this approach. To examine the extent of stakeholder support and response, this study not only relied on a literature review but also collected data through structured interviews and questionnaires distributed among representatives from academia (lecturers and researchers), government officials (ministries and related agencies), and industry practitioners (mining companies).

The findings indicate positive acceptance of nickel slag utilisation, driven by its technical effectiveness, cost efficiency, environmental aspects, and social contribution. Support from experts across academia, government, and industry provides a strong foundation for both technical and social dimensions of nickel slag application in land reclamation.

Nickel slag is regarded as a relevant and strategic innovation for sustainable industrial waste management. According to representatives of the Ministry of Energy and Mineral Resources (ESDM), Ministry of Environment and Forestry (KLHK), Coordinating Ministry for Maritime Affairs and Investment (Kemenko Marves), North Maluku Provincial Environmental Agency (BLH), and other technical officials, this innovation holds great potential to replace natural materials, enhance economic value, and expand field application provided it is supported by

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Table 3. Nutrient analysis results of planting media for trees

Parameter	Unit	M_t0	Criteria[1)]	M_t1	Criteria[1)]	M_t2	Criteria[1)]	M_t3	Criteria[1)]	M_t4	Criteria[1)]	M_t5	Criteria[1)]
pH in H_2O	–	7.11	neutral	7.14	neutral	7.13	neutral	7.15	neutral	7.17	neutral	7.09	neutral
CEC	$cmol^{(+)}·kg^{-1}$	13.21	low	4.92	very low	7.59	low	11.25	low	9.10	low	7.22	low
Al	$cmol^{(+)}·kg^{-1}$	undetected		undetected		undetected		undetected		undetected		undetected	
Sand	%	27.45		43.47		39.01		37.88		39.54		28.02	
Silt	%	51.15		40.97		39.41		43.35		41.70		48.01	
Clay	%	21.40		15.56		21.58		18.77		18.76		23.97	
Macronutrients													
Organic C	%	1.55	low	0.96	very low	0.96	very low	1.18	low	1.31	low	1.02	low
Total N	%	0.16	low	0.12	low	0.14	low	0.16	low	0.19	low	0.14	low
Total P	ppm	106.1	very low	72.7	very low	86.9	very low	138.0	very low	110.2	very low	52.9	very low
Available P	ppm	26.4	very high	24.2	very high	31.4	very high	30.3	very high	20.9	very high	14.6	high
K	$cmol^{\backslash(+)}·kg^{-1}$	0.54	moderate	0.20	low	0.30	low	0.41	moderate	0.43	moderate	0.22	low
Micronutrients													
Ca	$cmol^{(+)}·kg^{-1}$	11.98	high	3.25	low	4.43	low	9.52	moderate	8.29	moderate	3.49	low
Mg	$cmol^{(+)}·kg^{-1}$	5.80	high	3.00	high	3.89	high	5.11	high	4.68	high	3.39	high
Na	$cmol^{(+)}·kg^{-1}$	0.21	low	0.12	low	0.15	low	0.20	low	0.17	low	0.12	low
Fe	ppm	17.3	high	19.5	high	25.9	high	20.1	high	25.1	high	26.3	high
Cu	ppm	1.27	adequate	0.96	adequate	1.26	adequate	1.28	adequate	1.31	adequate	0.94	adequate
Zn	ppm	0.60	marginal	0.68	marginal	0.70	marginal	0.65	marginal	1.02	adequate	0.65	marginal
Mn	ppm	12.92	high	10.06	high	12.80	high	13.12	high	13.12	high	10.35	high

[1)] Acc. to Prasetyo, Santos and Laniyani Retno (2009).

Explanations: *CEC* = cation exchange capacity, M_t0 = 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil, M_t1 = 50% overburden soil + 40% nickel slag + 10% manure + 0% topsoil, M_t2 = 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil, M_t3 = 50% overburden soil + 20% nickel slag + 30% manure + 0% topsoil, M_t4 = 50% overburden soil + 20% nickel slag + 20% manure + 10% topsoil, M_t5 = 50% overburden soil + 20% nickel slag + 15% manure + 15% topsoil; the nutrient data for treatments M_t0, M_t1, and M_t3 were previously published by Handayani S *et al.* (2025).

Source: own study.

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Table 4. Nutrient analysis results of planting media for cover crops

Parameter	Unit	$M_{cc}0$	Criteria[1)]	$M_{cc}1$	Criteria[1)]	$M_{cc}2$	Criteria[1)]	$M_{cc}3$	Criteria[1)]	$M_{cc}4$	Criteria[1)]	$M_{cc}5$	Criteria[1)]
pH in H_2O	–	7.04	neutral	7.16	neutral	6.71	neutral	7.79	slightly alka-line	7.53	neutral	7.48	neutral
CEC	$cmol^{(+)} \cdot kg^{-1}$	8.98	low	6.83	low	12.12	low	3.66	very low	14.18	low	14.41	low
Al	$cmol^{(+)} \cdot kg^{-1}$	undetected		undetected		undetected		undetected		undetected		undetected	
Sand	%	24.93		34.45		44.81		86.86		76.71		74.13	
Silt	%	51.45		47.77		36.31		8.18		12.12		14.80	
Clay	%	23.63		17.78		18.89		4.96		11.17		11.07	
Macronutrients													
Organic C	%	1.24	low	0.86	very low	1.77	low	1.03	low	1.21	low	1.46	low
Total N	%	0.12	low	0.11	low	0.16	low	0.13	low	0.13	low	0.16	low
Total P	ppm	76.0	very low	80.7	very low	124.9	very low	289.2	moderate	228.5	moderate	282.8	moderate
Available P	ppm	38.2	very high	38.1	very high	24.9	very high	44.0	very high	50.6	very high	37.2	very high
K	$cmol^{(+)} \cdot kg^{-1}$	0.29	low	0.30	low	0.32	low	0.17	low	0.48	moderate	0.58	moderate
Micronutrients													
Ca	$cmol^{(+)} \cdot kg^{-1}$	4.73	low	4.53	low	5.56	low	2.13	low	10.87	high	11.71	high
Mg	$cmol^{(+)} \cdot kg^{-1}$	3.00	high	4.19	high	2.73	high	0.90	low	4.46	high	5.67	high
Na	$cmol^{(+)} \cdot kg^{-1}$	0.22	low	0.15	low	0.14	low	0.17	low	0.28	low	0.20	low
Fe	ppm	23.8	high	24.1	high	38.2	high	18.5	high	22.6	high	28.0	high
Cu	ppm	1.27	adequate	0.93	adequate	1.95	adequate	1.90	adequate	2.43	adequate	2.71	adequate
Zn	ppm	0.78	marginal	0.55	marginal	1.12	adequate	0.72	marginal	0.91	marginal	0.92	marginal
Mn	ppm	14.59	high	9.70	high	31.48	very high	13.44	high	17.01	high	18.87	high

[1)] Acc. to Prasetyo, Santos and Laniyani Retno (2009).
Explanations: $M_{cc}0$ = 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil, $M_{cc}1$ = 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil, $M_{cc}2$ = 0% overburden soil + 30% nickel slag + 20% manure + 50% topsoil, $M_{cc}3$ = 0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil, $M_{cc}4$ = 0% overburden soil + 70% nickel slag + 30% manure + 0% topsoil, $M_{cc}5$ = 0% overburden soil + 60% nickel slag + 40% manure + 0% topsoil; the nutrient data for treatments $M_{cc}0$, $M_{cc}1$, and $M_{cc}5$ were previously published by Handayani S *et al.* (2025).
Source: own study.

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Table 5. The effect of plant species on growth changes in tree plants

Plant species	Stem diameter (mm)	Plant height (cm)	Leaf count
	mean ±*SD*		
P_t1	4.14 ±0.92[b]	53.26 ±16.03[a]	88.53 ±21.81[a]
P_t2	5.04 ±0.96[a]	31.65 ±8.90[b]	0.60 ±1.34[b]
P_t3	1.89 ±1.69[c]	14.18 ±15.92[c]	−1.30 ±2.67[d]
P_t4	1.85 ±0.73[c]	3.06 ±2.40[d]	3.05 ±1.58[c]
***p*-value**	**<0.0001***		

Explanations: numbers followed by different letters within the same column indicate significant differences among plant species, *SD* = standard deviation, * significant effect at the 5% significance level (*p*-value < 0.05), P_t1 = cajuput (*Melaleuca leucadendron*), P_t2 = red jabon (*Anthocephalus macrophyllus*), P_t3 = jeungjing (*Falcataria moluccana*), P_t4 = nutmeg (*Myristica fragrans*).
Source: own study.

Table 6. The effect of planting media composition on growth changes in tree plants

Planting medium	Stem diameter (mm)	Plant height (cm)	Leaf count
	mean ±*SD*		
M_t0	3.25 ±2.00[a]	25.61 ±25.39[a]	23.83 ± 41.83[a]
M_t1	2.85 ±1.51[a]	22.54 ±19.90[a]	21.13 ±37.65[a]
M_t2	3.32 ±2.16[a]	27.49 ±26.85[a]	22.95 ±41.94[a]
M_t3	3.42 ±1.77[a]	26.83 ±22.16[a]	23.33 ±41.61[a]
M_t4	3.34 ±1.73[a]	26.70 ±21.53[a]	21.50 ±37.24[a]
M_t5	3.19 ±1.60[a]	24.06 ±19.53[a]	23.60 ±39.81[a]
***p*-value**	**0.4991**[ns]	**0.8372**[ns]	**0.3856**[ns]

Explanations: numbers followed by different letters within the same column indicate significant differences among plant species, *SD* = standard deviation, [ns] = not significant at the 5% level (*p*-value ≥ 0.05), M_t0 = 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil, M_t1 = 50% overburden soil + 40% nickel slag + 10% manure + 0% topsoil, M_t2 = 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil, M_t3 = 50% overburden soil + 20% nickel slag + 30% manure + 0% topsoil, M_t4 = 50% overburden soil + 20% nickel slag + 20% manure + 10% topsoil, M_t5 = 50% overburden soil + 20% nickel slag + 15% manure + 15% topsoil.
Source: own study.

adequate regulations and technical guidelines. The classification of nickel slag as non-hazardous waste (non-B3), as stipulated in Government Regulation No. 22/2021 (Peraturan, 2021), strengthens its legal basis for utilisation.

Environmental concerns are central to the implementation of this innovation. Respondents emphasised the importance of laboratory testing and field trials to ensure material stability and prevent potential heavy metal release into the environment. Identified challenges include high costs of transportation from smelter sites, limited land for management, lack of supporting technology, and suboptimal industrial utilisation, leading to material accumulation in disposal areas. Strategic recommendations include developing technical guidelines, conducting laboratory and field-scale trials, and involving communities in collective slag management based on precautionary principles. Cross-sector and multi-stakeholder coordination is key to successful, systemic, and sustainable implementation.

Table 7. The interaction between plant species and planting media composition and its effect on tree plant growth

Plant species	Planting media	Stem diameter (mm)	Plant height (cm)	Leaf count
		mean ±*SD*		
P_t1	M_t0	4.57 ±0.67	60.98 ±11.51	93.10 ±21.08
	M_t1	3.73 ±0.74	47.59 ±12.10	82.90 ±21.66
	M_t2	4.41 ±0.96	61.77 ±16.76	90.80 ±27.84
	M_t3	4.25 ±1.01	52.30 ±17.16	91.40 ±24.85
	M_t4	4.18 ±1.20	51.69 ±17.72	83.10 ±19.06
	M_t5	3.68 ±0.69	45.21 ±16.08	89.90 ±18.45
P_t2	M_t0	5.29 ±0.87	30.84 ±9.93	0.80 ±1.75
	M_t1	4.40 ±0.85	28.84 ±7.78	0.70 ±1.42
	M_t2	5.57 ±1.09	34.71 ±8.54	0.20 ±1.48
	M_t3	4.99 ±0.68	31.84 ±9.17	1.20 ±1.14
	M_t4	4.86 ±0.85	31.77 ±8.76	0.20 ±1.40
	M_t5	5.13 ±1.13	31.91 ±10.34	0.50 ±0.71
P_t3	M_t0	1.45 ±1.68	8.39 ±14.26	−1.90 ±2.69
	M_t1	1.94 ±1.12	11.78 ±12.92	−1.70 ±2.63
	M_t2	1.42 ±2.02	10.15 ±20.39	−2.30 ±2.41
	M_t3	2.22 ±2.17	20.24 ±17.48	−1.60 ±2.76
	M_t4	2.20 ±2.01	18.87 ±16.48	−1.00 ±2.16
	M_t5	2.09 ±1.03	15.67 ±12.97	0.70 ±2.87
P_t4	M_t0	1.70 ±0.65	2.24 ±1.68	3.30 ±1.34
	M_t1	1.32 ±0.58	1.96 ±1.10	2.60 ±1.43
	M_t2	1.88 ±0.91	3.31 ±2.60	3.10 ±1.45
	M_t3	2.23 ±0.79	2.93 ±3.37	2.30 ±1.77
	M_t4	2.10 ±0.55	4.47 ±2.69	3.70 ±2.11
	M_t5	1.85 ±0.67	3.46 ±2.00	3.30 ±1.16
***p*-value**		**0.6309**[ns]	**0.3967**[ns]	**0.5019**[ns]

Explanations: *SD* = standard deviation, [ns] = not significant at 5% level (*p*-value ≥ 0.05), M_t0 = 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil, M_t1 = 50% overburden soil + 40% nickel slag + 10% manure + 0% topsoil, M_t2 = 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil, M_t3 = 50% overburden soil + 20% nickel slag + 30% manure + 0% topsoil, M_t4 = 50% overburden soil + 20% nickel slag + 20% manure + 10% topsoil, M_t5 = 50% overburden soil + 20% nickel slag + 15% manure + 15% topsoil, P_t1 = cajuput (*Melaleuca leucadendron*), P_t2 = red jabon (*Anthocephalus macrophyllus*), P_t3 = jeungjing (*Falcataria moluccana*), P_t4 = nutmeg (*Myristica fragrans*).
Source: own study.

Academics noted that slag management has begun, but current approaches remain passive and not yet systematically integrated at the industrial level. Key challenges include limited applied research, lack of value-added exploration, and negative

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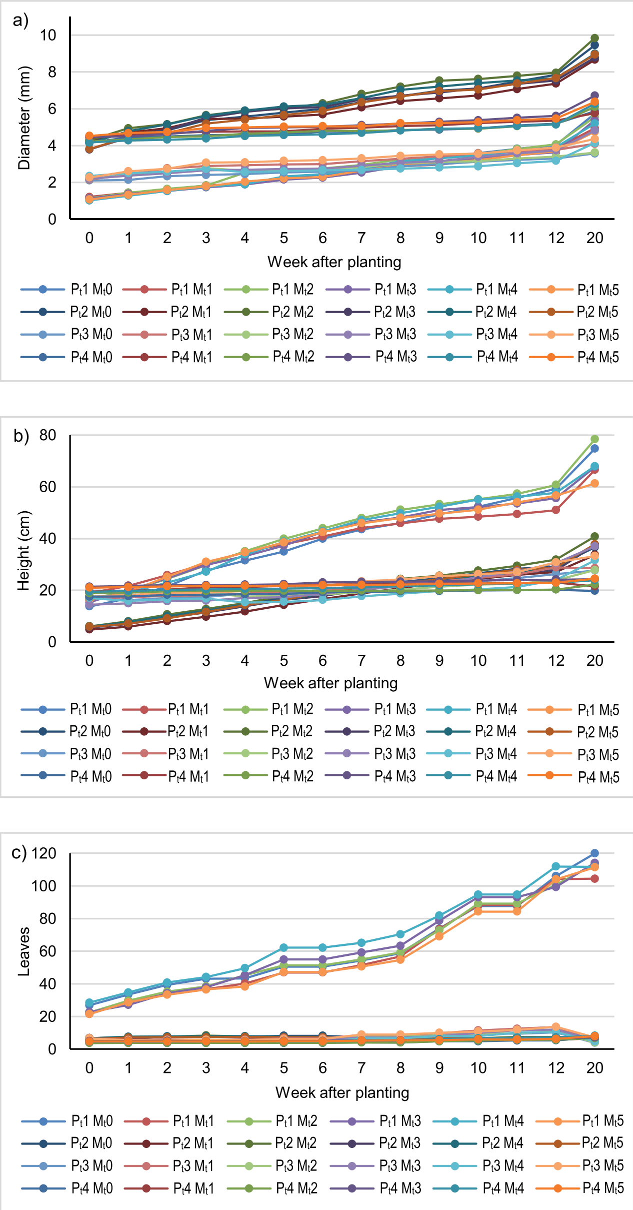

Fig. 1. Tree plant growth: a) average diameter growth in tree plants, b) average growth of plant height in tree plants, c) average leaf growth in tree plants; P_t1 = cajuput (*Melaleuca leucadendron*), P_t2 = red jabon (*Anthocephalus macrophyllus*), P_t3 = jeungjing (*Falcataria moluccana*), P_t4 = nutmeg (*Myristica fragrans*); M_t0 = 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil, M_t1 = 50% overburden soil + 40% nickel slag + 10% manure + 0% topsoil, M_t2 = 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil, M_t3 = 50% overburden soil + 20% nickel slag + 30% manure + 0% topsoil; M_t4: 50% overburden soil + 20% nickel slag + 20% manure + 10% topsoil; M_t5: 50% overburden soil + 20% nickel slag + 15% manure + 15% topsoil; source: own study

perceptions of slag as hazardous waste. Therefore, interdisciplinary research involving universities and research institutions is needed to comprehensively study the physical and chemical characteristics of slag. Nickel slag is known to contain iron oxide and possess high physical strength, making it a promising material for construction and soil improver in post-mining reclamation. However, chemical aspects such as element stability and soil interaction require further investigation to ensure safety and effectiveness. Academics advocate for innovation development based on literature review and field practices to ensure

Table 8. The effect of plant species on cover crop growth parameters

Plant species	Stem diameter (mm)	Plant height (cm)	Leaf count
	mean ±*SD*		
$P_{cc}1$	1.50 ±1.25^b	133.27 ±64.72^a	26.02 ±15.37^a
$P_{cc}2$	6.04 ±4.07^a	129.65 ±33.89^a	4.85 ±3.44^c
$P_{cc}3$	0.91 ±0.84^b	72.66 ±41.93^b	12.27 ±8.08^b
***p*-value**	**0.0001***	**0.0001***	**0.0001***

Explanations: numbers followed by different letters within the same column indicate significant differences among plant species, *SD* = standard deviation, * significant effect at 5% level (*p*-value < 0.05), $P_{cc}1$ = centro beans (*Centrocema pubescens*), $P_{cc}2$ = citronella (*Cymbopogon nardus*), $P_{cc}3$ = bede grass (*Brachiaria decumbens*).
Source: own study.

Table 9. The effect of planting media composition on cover crop growth parameters

Planting media	Stem diameter (mm)	Plant height (cm)	Leaf count
	mean ±*SD*		
$M_{cc}0$	3.18 ±3.54^a	99.48 ±42.57^a	11.83 ±8.38^{ab}
$M_{cc}1$	2.18 ±3.25^a	97.12 ±55.52^a	8.47 ±7.28^b
$M_{cc}2$	3.25 ±3.59^a	119.48 ±56.93^a	17.40 ±16.09^a
$M_{cc}3$	2.89 ±3.33^a	118.04 ±61.40^a	17.23 ±16.11^a
$M_{cc}4$	2.65 ±2.84^a	118.82 ±52.98^a	15.47 ±14.33^a
$M_{cc}5$	2.76 ±3.87^a	118.23 ±62.70^a	15.87 ±14.29^a
***p*-value**	**0.6205^{ns}**	**0.7857^{ns}**	**0.0179***

Explanations: numbers followed by different letters within the same column indicate significant differences among plant species, *SD* = standard deviation, ^{ns} = not significant at 5% level (*p*-value ≥ 0.05); * = significant effect at 5% level (*p*-value < 0.05), $M_{cc}0$: 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil; $M_{cc}1$: 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil; $M_{cc}2$: 0% overburden soil + 30% nickel slag + 20% manure + 50% topsoil; $M_{cc}3$: 0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil; $M_{cc}4$: 0% overburden soil + 70% nickel slag + 30% manure + 0% topsoil; $M_{cc}5$: 0% overburden soil + 60% nickel slag + 40% manure + 0% topsoil.
Source: own study.

technical feasibility, environmental safety, and adequate social acceptance.

Industry representatives argue that nickel slag must be optimally utilised, especially given the increasing volume resulting from the expansion of nickel processing industries using RKEF technology. While some parties consider nickel slag non-risky if systematically managed, concerns about material accumulation persist. Currently, nickel slag is used in various construction and infrastructure products such as bricks, box culverts, wave-breaking concrete, cement raw materials, and mine void fillers. Some companies also highlight its potential as a soil amendment, particularly for peat soil neutralisation and magnesium nutrient supply.

Nevertheless, the implementation process still faces technical and regulatory challenges. Transportation costs, lack of

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Table 10. Interaction test between plant species and planting media composition and its effect on cover crop growth

Plant species	Planting media	Stem diameter (mm)	Plant height (cm)	Leaf count
		mean ±*SD*		
$P_{cc}1$	$M_{cc}0$	1.25 ±0.12^{a}	100.56 ±40.12^{a}	16.90 ±7.67^{bc}
	$M_{cc}1$	1.13 ±0.41^{a}	89.12 ±68.57^{a}	11.00 ±9.70^{cdefg}
	$M_{cc}2$	1.29 ±0.32^{a}	162.47 ±47.08^{a}	34.10 ±15.47^{a}
	$M_{cc}3$	1.49 ±0.57^{a}	156.68 ±65.20^{a}	33.20 ±17.49^{a}
	$M_{cc}4$	1.62 ±0.40^{a}	149.25 ±49.15^{a}	31.60 ±10.54^{a}
	$M_{cc}5$	2.22 ±2.94^{a}	141.55 ±83.64^{a}	29.30 ±14.86^{ab}
$P_{cc}2$	$M_{cc}0$	7.30 ±3.40^{a}	137.78 ±15.87^{a}	4.10 ±2.02^{gh}
	$M_{cc}1$	4.29 ±4.94^{a}	137.38 ±18.51^{a}	5.60 ±3.57^{efgh}
	$M_{cc}2$	7.59 ±3.06^{a}	129.14 ±19.87^{a}	5.10 ±2.13^{efgh}
	$M_{cc}3$	6.28 ±3.98^{a}	118.76 ±54.25^{a}	5.50 ±4.90^{efgh}
	$M_{cc}4$	5.66 ±3.08^{a}	133.59 ±15.82^{a}	5.10 ±4.20^{fgh}
	$M_{cc}5$	5.13 ±5.37^{a}	121.27 ±54.59^{a}	3.70 ±3.33^{h}
$P_{cc}3$	$M_{cc}0$	0.99 ±0.65^{a}	60.11 ±25.01^{a}	14.50 ±7.78^{cd}
	$M_{cc}1$	1.12 ±1.44^{a}	64.86 ±43.12^{a}	8.80 ±6.89^{defgh}
	$M_{cc}2$	0.86 ±0.79^{a}	66.84 ±50.96^{a}	13.00 ±9.50^{cdef}
	$M_{cc}3$	0.89 ±0.52^{a}	78.69 ±39.65^{a}	13.00 ±7.10^{cde}
	$M_{cc}4$	0.67 ±0.79^{a}	73.61 ±53.25^{a}	9.70 ±9.32^{defgh}
	$M_{cc}5$	0.93 ±0.66^{a}	91.86 ±36.13^{a}	14.60 ±7.69^{cd}
***p*-value**		**0.4371^{ns}**	**0.1666^{ns}**	**0.0056***

Explanations: numbers followed by different letters within the same column indicate significant differences among plant species, *SD* = standard deviation, ^{ns} = not significant at 5% level (*p*-value ≥ 0.05), * = significant at 5% level (*p*-value < 0.05), P1 = centro beans (*Centrocema pubescens*), $P_{cc}2$ = citronella (*Cymbopogon nardus*), $P_{cc}3$ = bede grass (*Brachiaria decumbens*), $M_{cc}0$ = 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil, $M_{cc}1$ =50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil, $M_{cc}2$ = 0% overburden soil + 30% nickel slag + 20% manure + 50% topsoil, $M_{cc}3$ = 0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil, $M_{cc}4$ = 0% overburden soil + 70% nickel slag + 30% manure + 0% topsoil, $M_{cc}5$ = 0% overburden soil + 60% nickel slag + 40% manure + 0% topsoil.
Source: own study.

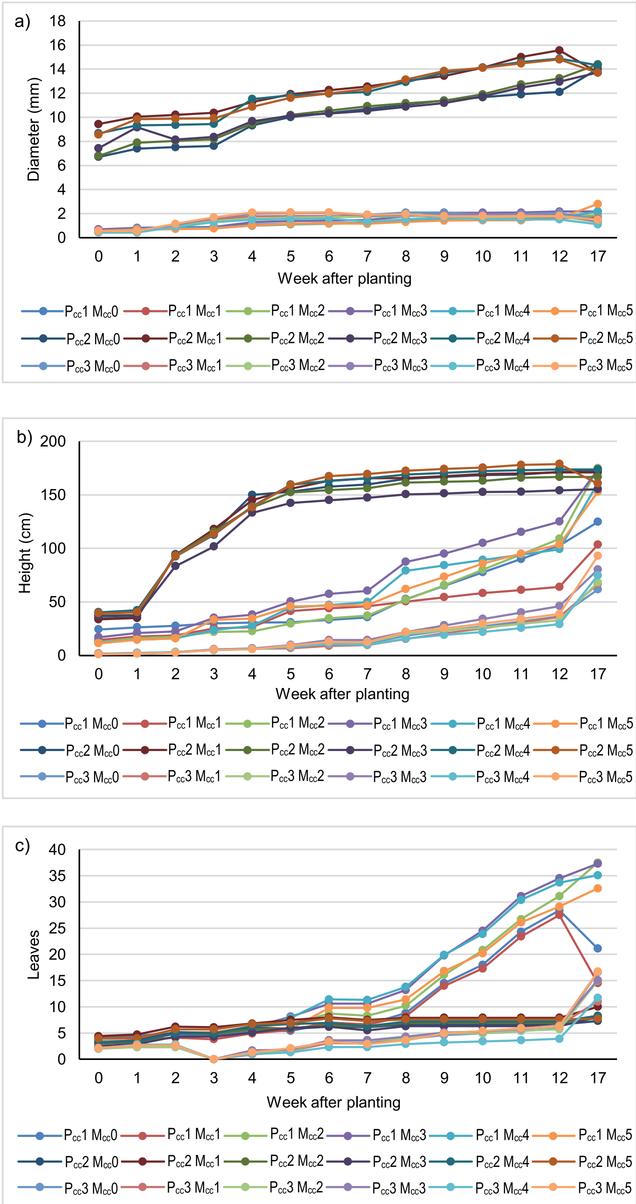

Fig. 2. Growth of cover crop plants: a) average diameter growth in cover crops, b) average plant height growth in cover crops, c) average leaf growth in cover crops; $P_{cc}1$ = centro beans (*Centrocema pubescens*), $P_{cc}2$ = citronella (*Cymbopogon nardus*), $P_{cc}3$ = bede grass (*Brachiaria decumbens*), $M_{cc}0$: 50% overburden soil + 0% nickel slag + 30% manure + 20% topsoil, $M_{cc}1$ = 50% overburden soil + 30% nickel slag + 20% manure + 0% topsoil, $M_{cc}2$ = 0% overburden soil + 30% nickel slag + 20% manure + 50% topsoil, $M_{cc}3$ = 0% overburden soil + 80% nickel slag + 20% manure + 0% topsoil, $M_{cc}4$ = 0% overburden soil + 70% nickel slag + 30% manure + 0% topsoil, $M_{cc}5$ = 0% overburden soil + 60% nickel slag + 40% manure + 0% topsoil; source: own study

processing technology and supporting equipment are major barriers. In addition, incomplete regulatory support and limited outreach hinder innovation development. The growing volume of slag also demands extensive storage land, while utilisation rates lag behind production. The government has contributed by removing slag from the hazardous waste category. From an economic and sustainability perspective, nickel slag has significant potential as an efficient and environmentally friendly reclamation medium. To support broader implementation, companies recommend pilot trials at various mine sites, workforce training, and development of adaptive technologies. Cross-sector support and multi-stakeholder coordination are essential to drive systemic and sustainable nickel slag utilisation. Synergy between government regulation, academic research, and industrial initiatives demonstrates that this approach is not only socially accepted but also considered feasible as part of a sustainable reclamation strategy.

ECONOMIC VALUE OF NICKEL SLAG UTILISATION AS SOIL IMPROVER IN RECLAMATION ACTIVITIES

Utilising nickel slag as a soil improver in mine land reclamation contributes significantly to cost efficiency, particularly by reducing the use of manure. Research findings show that nickel

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Photo 1. Growth of trees and cover crops in the greenhouse (phot.: *R.D. Handayani S*)

slag has substantial potential as a soil improver in post-mining reclamation. Its use in mixtures with manure – 80% nickel slag and 20% manure for cover crops, and 40% nickel slag and 10% manure for pioneer plants – can reduce manure requirements.

With the 4:1 ratio, manure use was reduced by 21 $Mg \cdot ha^{-1}$, from an initial 20,000 kg to 5,000 kg for cover crops and from 8,000 kg to 2,000 kg for trees. At a manure price of IDR[1]2,500·kg^{-1}, this reduced the reclamation cost to IDR 110,716,000·ha^{-1} and generated a cost saving of IDR 52,500,000·ha^{-1}, equivalent to about 32%. This efficiency demonstrates that nickel slag can serve as an economical and effective soil improver. The comparison of reclamation costs using manure versus nickel slag is presented in Table 11.

Table 11. Comparison of reclamation costs using manure vs. nickel slag

Activity	Description	Cost with manure (IDR)	Cost with nickel slag (IDR)
Cover crop planting	seeds, manure, other materials, and labour	89,832,000	52,332,000
Pioneer planting	seeds, manure, other materials, and labour	50,346,000	35,346,000
Local planting	seedlings, materials, and labour	17,538,000	–
Supporting equipment	procurement of tools and supporting materials	5,500,000	–
Total		**163,216,000**	**110,716,000**

Source: own study.

[1] Exchange rate as of 6th March 2026 (USD1 ≈ IDR16,886; Bank Indonesia, subject to change)

This cost efficiency supports the notion that nickel slag not only serves as a sustainable reclamation material but also offers economic benefits. Overall, this approach promotes sustainability through industrial waste utilisation while delivering significant economic value for reclamation. These findings reinforce the potential of nickel slag as a strategic solution for efficient, sustainable, and locally resource-based post-mining land management.

DISCUSSION

Soil properties that influence plant growth include physical, chemical, mineralogical, and biological aspects (Gardner, Pearce and Mitchell, 1991; Widiatmaka *et al.*, 2010; Nadalia and Bagus Pulunggono, 2020). In nickel mining areas, overburden soil is characterised by low organic matter content, very low available phosphorus (P), low cation exchange capacity, very low exchangeable calcium (Exch-Ca), low exchangeable potassium (Exch-K), but high exchangeable magnesium (Exch-Mg). Widiatmaka, Suwarno and Kusmaryandi (2010) explained that revegetation efforts face challenges, as the growth of tree species such as albizia, white acacia (*Acacia villosa*, local name: tirotasi), large-leaf acacia (*Acacia mangium*), and small-leaf acacia (*Acacia auriculiformis*) is poor due to deficiencies in Ca, Fe, Cu, or Mn.

Slag used as fertiliser significantly increases soil pH and concentrations of P, Ca + Mg, Si, Cu, Mn, Zn, and Fe, while reducing potential acidity (H + Al) with long-term effects (Preston *et al.*, 2021). In addition, the combined use of slag and rice husk bokashi can reduce P retention while maintaining the beneficial physical properties of Andisol soil at rates of up to 7.5% of soil weight (Devnita *et al.*, 2014). Slag application in apple growing media can also increase Mg content and result in a low shoot-to-root ratio (Kumashiro, 1959). Furthermore, slag at doses that raise pH to ≥6.0 can serve as a liming agent replacing dolomite or calcite for pakchoy (*Brassica chinensis* L.) on Andisol soil, and for soybean (*Glycine max* L. Merr.) and sorghum (*Sorghum vulgare* Pers.) on Ultisol soil, resulting in greater dry plant weight (Suwarno, 2010).

Application of 2 $mg \cdot ha^{-1}$ slag and NPK in rice farming can improve soil physical-chemical and biological properties, as well as crop yield (Das *et al.*, 2020). Slag application up to 10 $Mg \cdot ha^{-1}$ does not inhibit rice growth or yield, and a dose of 1,000 g per tree steel slag is optimal for *Acacia crassicarpa* on peat soil. In arsenic-contaminated growing media for radish (*Raphanus sativa* L.), steel slag application of up to 8 $mg \cdot ha^{-1}$ can inhibit As uptake and improve yield (Gutierrez *et al.*, 2010). In addition, a 5% steel slag dose provides the lowest P retention value after incubation in Andisol soil for two months (Rosidah *et al.*, 2019). Suwardi (2019) stated that the slag dose to be applied depends on soil properties such as exchangeable Al, pH, organic matter, and soil texture. Several studies on slag use as fertiliser for plant growth have shown positive effects.

The addition of nickel slag to the planting media enhances the availability of nitrogen (N) and phosphorus (P) nutrients, although plant growth responses vary depending on species and media composition (Handayani S *et al.*, 2025). Phosphorus (P) concentration increases in planting media with nickel slag addition, as seen in two treatment compositions for pioneer and cover crop media. Pioneer media treatments include mixtures of 50% overburden soil + 30% nickel slag + 20% manure and 50% overburden soil + 20% nickel slag + 30% compost. Cover crop media treatments include 80% nickel slag + 20% manure and 70%

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nickel slag + 30% manure. Rosalina, Tjahyandari and Darmawan (2018) found that nickel slag has potential as an ameliorant for red-yellow podzolic soil when combined with humic acid, improving soil pH and nutrient availability of N, P, and Mg. When nickel slag is combined only with manure, Ca and Mg concentrations increase at slag percentages up to 70%, as observed in the cover crop media in this study.

Pioneer plants such as cajuput, red jabon, jeungjing, and nutmeg can grow on overburden soil amended with nickel slag, manure, or topsoil. Cover crops such as centro beans, citronella, and bede grass also grow under these conditions. Moreover, cover crops in this study were able to grow in media containing only nickel slag and manure. Therefore, selected pioneer and cover crop species are suitable for post-mining land revegetation.

Plant growth in media containing nickel slag is influenced by the high Si and Mg content in the slag at the study site. This is consistent with other studies reporting that nickel slag can be reused for agricultural development (Rembah and Novianti, 2021). This aligns with research indicating that soil improver can be derived from mixed mining slag materials (Rosalina, Tjahyandari and Darmawan, 2018; Benassi *et al*., 2019). These findings are supported by Handayani S *et al*. (2025), who reported that red jabon exhibited higher fresh and dry weights of shoots and roots, total biomass, and shoot-to-root ratio compared to cajuput, jeungjing, and nutmeg when grown in media composed of 40% nickel slag and 10% manure. Citronella showed optimal growth in media containing 80% nickel slag and 20% manure, as indicated by superior biomass and shoot-to-root ratio compared to centro beans and bede grass.

Revegetation aims to cover the soil surface with plant canopy, with coverage increasing as the revegetated plants mature (Pratiwi *et al*., 2021). Tree species selection criteria for post-mining land, as described by Susilo *et al*. (2010), include local pioneer species and those with good root systems. In this study, cajuput produced greater height and leaf count than red jabon, jeungjing, or nutmeg. Centro beans had the highest values for height and leaf count compared to citronella and bede grass. Thus, cajuput and centro beans can be selected as alternatives for improving overburden soil conditions.

Cajuput showed superior height and leaf count compared to other pioneer species across planting media containing up to 40% nickel slag. This indicates that cajuput can be used for revegetation by first improving soil physical-chemical properties using planting media with up to 40% nickel slag, without adding topsoil. This is supported by Handayani S *et al*. (2025) who found that the addition of nickel slag to the planting medium increased the availability of N and P, although plant responses varied depending on species and soil type. Cajuput also produced the highest number of secondary roots, with an average of 25. Moreover, centro beans grown in a mixture of 80% nickel slag and 20% compost showed greater increase in leaf count.

Expert perceptions indicate that nickel slag is environmentally safe and economically promising soil improver. Its use can also support community empowerment programmes through socialisation and training on nickel slag utilisation. This study also highlights social support by stakeholders, which aligns with the social acceptance dimension of sustainable development (Daly, 1990; Brown, 1991).

Sustainable development often involves the introduction of new technologies and innovations, and social acceptance helps ensure these are adopted by communities (Schweizer-Ries, 2008; Peek *et al*., 2014). Promoting community participation in technology development helps identify and consider social implications, while strong social acceptance contributes to long-term sustainability. With community support, projects more likely to endure and continue providing benefits to society (Peek *et al*., 2014; Cousse, 2021).

Using nickel slag can reduce reclamation costs, consistent with other studies showing its economic benefits (Cosme, Fernandes and Pinto Fernandes, 2021; Kumar *et al*., 2021; Pratiwi *et al*., 2022). This study also demonstrates economic gains, aligning with the economic aspect of sustainable development. This is reinforced by the theory that economic benefit is essential for sustainability (Daly, 1990; Brown, 1991).

Sustainable development must consider several influencing aspects, including environmental, economic, ecological quality, and social dimensions. The use of nickel slag across social, economic, and environmental aspects aligns with sustainability principles. This is consistent with other studies stating that mining by-products can be reused for sustainable reclamation (Jawadand and Randive, 2021; Pavloudakis, Roumpos and Spanidis, 2022; Nigéus *et al*., 2023). This study shows that using nickel slag as a soil improver fulfils all the three pillars of sustainable development, in accordance with the theory proposed by Brown (1991) and Daly (1990). The conceptual sustainability scheme for nickel slag utilisation as a soil improver is presented in Figure 3.

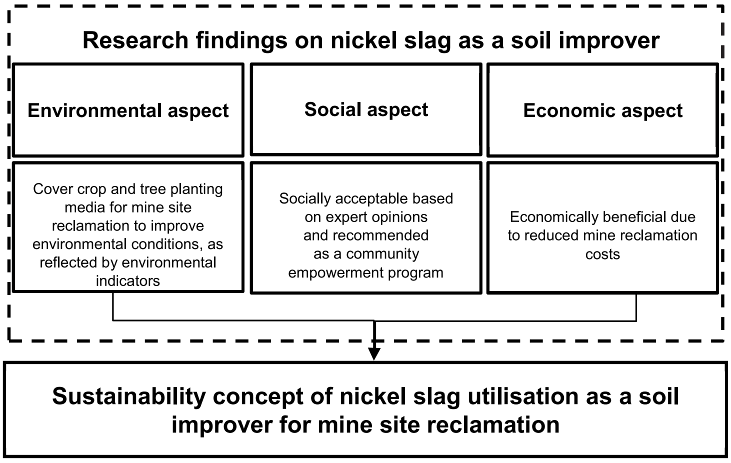

Fig. 3. Sustainability concept of nickel slag utilisation; source: own study

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CONCLUSIONS

This study demonstrates that nickel slag holds significant potential as a soil improver in post-mining land reclamation activities, from technical, social, and economic perspectives. The addition of nickel slag has been proven to enhance the availability of essential nutrients such as phosphorus (P), magnesium (Mg), and calcium (Ca), improve soil pH, and support the growth of pioneer and cover crops such as cajuput (*Melaleuca leucadendron*) and centro beans (*Centrocema pubescens*).

Overburden soil, which is initially has poor nutrient content, can be improved through planting media formulations based on nickel slag and manure, in some cases without the need for topsoil. This effectiveness is supported by good plant growth outcomes and significant reclamation cost efficiency. Cajuput has shown superior height growth and leaf production compared to other pioneer species, regardless of planting media composition, with nickel slag additions up to 40%. It can be used in revegetation efforts by first improving the soil's physical and chemical properties using planting media with up to 40% nickel slag, without adding topsoil. Centro beans grown in a medium composed of 80% nickel slag and 20% compost produced better leaf development.

Economically, the use of nickel slag can reduce reclamation costs by up to 32%, primarily by lowering the need for manure. The mixture of nickel slag and manure for cover and pioneer crops provides a cost efficiency of IDR 52,500,000 per hectare, making it an economical and environmentally friendly alternative. From a social standpoint, the use of nickel slag has received positive support from experts and is considered environmentally safe. This innovation also has the potential to be integrated into community empowerment programs through training and outreach.

Overall, the use of nickel slag as a soil improver fulfils the three pillars of sustainable development – environmental, social, and economic – and can serve as a sustainable concept for nickel slag utilisation in systematic reclamation strategies that prioritise responsible use of local resources.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

INSTITUTIONAL REVIEW BOARD STATEMENT

This research did not involve human or animal subjects.

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