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HEAP LEACH: A GREEN HYDROMETALLURGY PROCESS ALTERNATIVE FOR INDONESIA NICKEL LATERITE ORE CONSERVATION AND ITS GEOMETALLURGY APPROACH

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Abstract

The increasing demand for nickel has driven the rapid expansion of RKEF-based processing for stainless steel production, thereby accelerating the depletion of high-grade saprolite reserves in Indonesia. Currently available nickel processing methods in Indonesia, specifically the smelting process (RKEF/Blast Furnace) and high-pressure acid leaching (HPAL), pose considerable environmental and economic challenges, including high energy intensity, a high carbon footprint, and complex tailings management. Heap leach technology offers a sustainable alternative, particularly for low-grade saprolite ores, which are typically excluded from conventional processing routes such as RKEF or HPAL. Through a geometallurgical approach, critical geological and metallurgical parameters are identified to optimize ore selection for heap leaching, thereby maximizing resource value. Heap leach technology's low operational risk, low energy intensity, and reduced carbon footprint make it viable under Indonesian conditions, thereby lowering freshwater requirements and producing a stable, non-hazardous residue. This approach not only aligns with Indonesia's environmental commitments but also provides an avenue for Indonesia to supply "green nickel" that meets global sustainability standards.

Keywords: Nickel Laterites, Heap Leach, Hydrometallurgy, Battery Material, Geometallurgy, Ore Conservation, Sustainable, Green Nickel

Introduction – Global & Indonesia Nickel Laterite Production

Nickel laterite deposits are a critical source of nickel, primarily used in stainless steel production and, increasingly, in EV batteries (Oxley et al., 2016). Indonesia, home to the world's largest nickel reserves, plays a pivotal role in meeting global demand. The projected growth in global nickel demand is shown in Figure 1 (Nursahan et al., 2024). However, the focus on high-grade saprolite ores for pyrometallurgical processes has led to the rapid depletion of high-grade saprolite reserves. While low-grade ores remain largely untapped (Bahfie et al., 2022; Oxley et al., 2016). This imbalance underscores the need for innovative and sustainable processing methods.

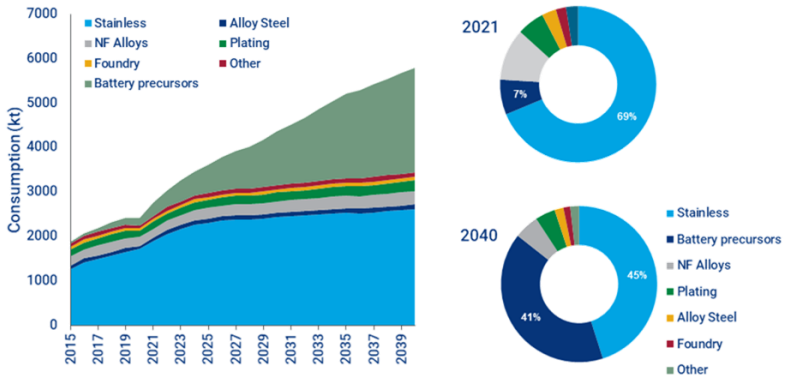


Figure 1. Global Nickel Demand Projection (Mitchell, 2022)

The global nickel market is projected to grow at a compound annual growth rate (CAGR) of 7.1% from 2021 to 2028, driven by the EV revolution. (Smith & Brown, 2021). Indonesia, contributing over 30% of global nickel production, is under pressure to adopt environmentally responsible practices while meeting demand. A traditional method like RKEF, though effective for high-grade ores, is energy-intensive, emits significant greenhouse gases (Oxley et al., 2016). Another way, like HPAL, also presents environmental challenges, particularly regarding tailings management.

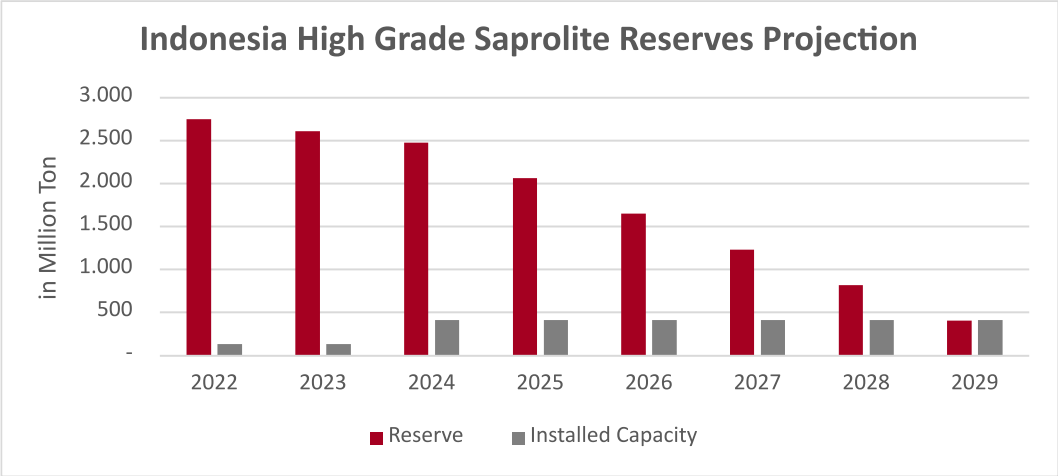


Figure 2. High Grade Nickel Ore Reserves Projection (Nursahan et al., 2024).

On the other hand, the development of nickel smelter projects in Indonesia in recent years has been predominantly driven by Rotary Kiln-Electric Furnace (RKEF) technology. This type of smelter utilizes high-grade nickel ore as feedstock to produce Nickel Pig Iron (NPI) and Ferronickel (FeNi), primarily as raw materials for stainless steel production (Bahfie et al., 2022). The rapid proliferation of RKEF smelters in Indonesia has led to an influx of nickel supply into the global market, resulting in an oversupply condition that has contributed to the decline in nickel prices in 2024. Additionally, the widespread expansion of RKEF smelters has raised concerns regarding the depletion of high-grade nickel ore reserves, which are projected to last only for the next ten years (Figure 2) due to the significant growth of RKEF-based smelting capacity in recent years.

Given these conditions, heap leaching emerges as an alternative technological option for nickel processing in Indonesia. This technology has been successfully applied to the processing of gold and copper and has potential for application to different types of nickel laterite ores. Therefore, this study aims to evaluate the potential of heap leaching as an alternative processing route for the utilization and conservation of Indonesian nickel laterite resources, particularly lower-grade saprolite and transition ores, based on a review of the existing literature and nickel-processing practices. The study also examines the geometallurgical characteristics that influence heap leach amenability, including ore type, mineralogical composition, degree of laterization and serpentinization, permeability, and nickel extraction performance. The integration of these geological and metallurgical characteristics is intended to provide a scientific basis for evaluating ore suitability and the potential for heap leaching in Indonesian nickel laterite resources.

Method

This study employed a literature review and comparative analysis to evaluate the potential of heap leaching for Indonesian nickel laterite ores. Relevant information was compiled from peer-reviewed scientific publications, government reports, technical reports, and publicly available data from nickel processing projects.

The comparative analysis focused on the differences among nickel processing routes, particularly RKEF, HPAL, and heap leaching. The comparison considered ore suitability, processing characteristics, energy intensity, carbon emissions, capital expenditure (CAPEX), operating expenditure (OPEX), and environmental considerations. In addition, reported heap leach performance was examined in relation to geological and mineralogical characteristics of nickel laterite ores, including ore type, degree of laterization, mineralogical composition, degree of serpentinization, permeability, and nickel extraction.

The reviewed information was then integrated to assess the relationship between the geological and mineralogical characteristics of nickel laterite ores and their amenability to heap leaching. This approach was used to identify ore characteristics and processing considerations relevant to the potential utilization of heap leaching for Indonesian nickel laterite resources.

Recent Nickel Laterite Projects in Indonesia

The current nickel laterite processing routes in Indonesia can be broadly classified into hydrometallurgical and pyrometallurgical pathways, depending on the ore characteristics and the targeted nickel product. The main processing routes and their corresponding intermediate and final products are summarized in Figure 3.

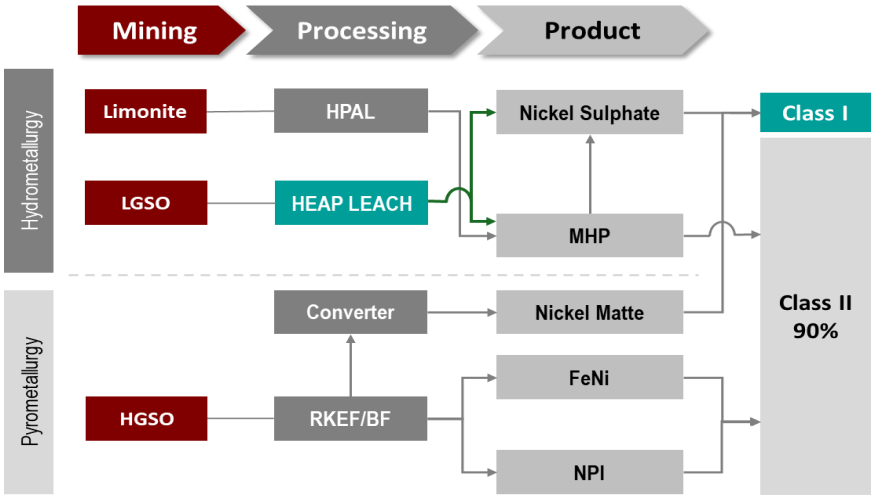


Figure 3. Current nickel laterite processing routes in Indonesia. LGSO: Low-Grade Saprolite Ore; HGSO: High-Grade Saprolite Ore; HPAL: High-Pressure Acid Leaching; MHP: Mixed Hydroxide Precipitate; RKEF: Rotary Kiln–Electric Furnace; BF: Blast Furnace; FeNi: Ferronickel; NPI: Nickel Pig Iron.

As shown in Figure 3, Indonesia's nickel laterite processing routes include both hydrometallurgical and pyrometallurgical pathways. Pyrometallurgical technologies, such as rotary kiln–electric furnace (RKEF) and blast furnace (BF) processing, have traditionally been applied mainly to higher-grade saprolite ores, producing ferronickel (FeNi) and nickel pig iron (NPI), which are primarily used in stainless steel production. Hydrometallurgical processing, particularly high-pressure acid leaching (HPAL), is used to treat lower-grade nickel laterite ores and can produce a mixed hydroxide precipitate (MHP) and nickel sulfate for battery-related applications. Nickel products are commonly classified into Class I and Class II based on nickel purity. Class I nickel contains at least 99.8% Ni, whereas Class II products generally contain less than 99.8% Ni and include products such as ferronickel and nickel pig iron.

Saprolite ores can be further differentiated according to their nickel grade into high-grade saprolite ore (HGSO) and low-grade saprolite ore (LGSO) (Asmiani et al., 2024). HGSO refers to saprolite ore with a relatively higher nickel concentration, whereas LGSO refers to saprolite ore with a comparatively lower nickel concentration. Both are derived from the saprolite zone of nickel laterite deposits, but they differ primarily in nickel grade and, consequently, in their suitability for different processing routes. HGSO has traditionally been preferred as feed for pyrometallurgical processes, such as RKEF and blast-furnace smelting. In contrast, LGSO represents a lower-grade saprolite resource that may require alternative processing approaches, including hydrometallurgical methods such as heap leaching. The specific grade boundaries between HGSO and LGSO are deposit- and operation-dependent and therefore should not be considered universal. The major pyrometallurgical plants operating in Indonesia, together with their principal nickel

products, production capacities, and locations, are summarized in Table 1. The listed plants predominantly produce ferronickel (FeNi) and nickel pig iron (NPI), which are primarily used as feedstocks for stainless steel production.

Table 1. Major Pyrometallurgical Nickel Processing Plants in Indonesia, Including Principal Products, Production Capacities, and Locations (Indonesian Ministry of Energy and Mineral Resources, 2022).

No	Company name	Product	Capacity Output ('000 ton Ni)	Location
1	COR Industri Indonesia	FeNi	100	Morowali, Sulawesi Tengah
2	Vale Indonesia	Ni Matte	80	Sulawesi Selatan
3	Tsingshan Steel	NPI	500	Morowali, Sulawesi Tengah
4	Aneka Tambang	FeNi	90	Kolak, Sulawesi
5	Virtue Dragon	NPI	1000	Konawe, Sulawesi
6	Weda Bay Nickel	NPI	300	Halmahera, Maluku
7	Fajar Bhakti Lintas Nusantara	NPI	120	Halmahera, Maluku
8	Wanatiara Persada	NPI	160	Halmahera, Maluku
9	Century Metalindo	FeNi	25	Banten
10	Sulawesi Resources	NPI	150	Morowali, Sulawesi Tengah
11	Wanxiang Nickel Indonesia	FeNi	350	Morowali, Sulawesi Tengah
12	Ang and Fang Brother	NPI	130	Morowali, Sulawesi Tengah
13	Arthabumi Sentra Industri	NPI	75	Morowali, Sulawesi Tengah
14	Ceria Nugraha Indotama	FeNi	250	Kolaka, Sulawesi Tenggara
15	Mapan Asri Sejahtera	NPI	21	Kolaka, Sulawesi Tenggara
16	Bintang Smelter Indonesia	NPI	250	Konawe, Sulawesi
17	Mahkota Konaweeha	FeNi	62	Kendari, Sulawesi
18	Macika Mineral Industri	NPI	93	Konawe, Sulawesi
19	Artha Mining Industry	FeNi	200	Bombana, Sulawesi
20	Sinar Deli Bantaeng	NPI	238	Bantaeng, Sulawesi
21	Aneka Tambang	FeNi	160	Halmahera Timur
22	Aneka Tambang	FeNi	64	Halmahera Timur
23	Teka Mining Resources	FeNi	300	Halmahera Tengah
24	Smelter Nikel Indonesia	NPI	76	Banten

The hydrometallurgical nickel processing plants reported in Indonesia, including their principal products, production capacities, and locations, are summarized in Table 2. The listed facilities predominantly produce mixed hydroxide precipitate (MHP), an intermediate product for further processing of nickel and cobalt.

Table 2. Hydrometallurgical Plant in Indonesia (Indonesian Ministry of Energy and Mineral Resources, 2022).

No	Company name	Product	Capacity Output ('000 ton Ni)	Location
1	Halmahera Persada Lygend	MHP	365	Obi Island, North Maluku
2	Huayue Nickel Cobalt	MHP	60	Morowali, Sulawesi Tengah
3	Huafei Nickel Cobalt	MHP	120	IMIP, Morowali
4	Huashan Nickel Cobalt	MHP	120	South Sulawesi
5	Vale Indonesia Huayou Ford	MHP	120	Pomalaa, East Sulawesi
6	Vale Indonesia Huayou	MHP	60	Sorowako, South Sulawesi
7	Aneka Tambang - CATL	MHP	50	North Maluku
8	Aneka Tambang - LGES	MHP	50	North Maluku

The energy consumption and carbon emissions of selected nickel processing projects are compared in Figure 4. The HPAL projects shown in the figure have energy consumption ranging from 10.16 to 14.89 MWh/tNi, whereas the RKEF projects range from 34.94 to 41.52 MWh/tNi. In terms of carbon emissions, HPAL is reported to be 27 tCO_2/tNi, while NPI produced via RKEF is associated with approximately 50 tCO_2/tNi. In comparison, the BMR heap leach project shows an energy consumption of 5.58 MWh/tNi and carbon emissions of 16 tCO_2/tNi (Trinanda et al., 2026). These data indicate that the BMR heap leach project has lower energy consumption and carbon emissions than the HPAL and RKEF projects presented in Figure 4.

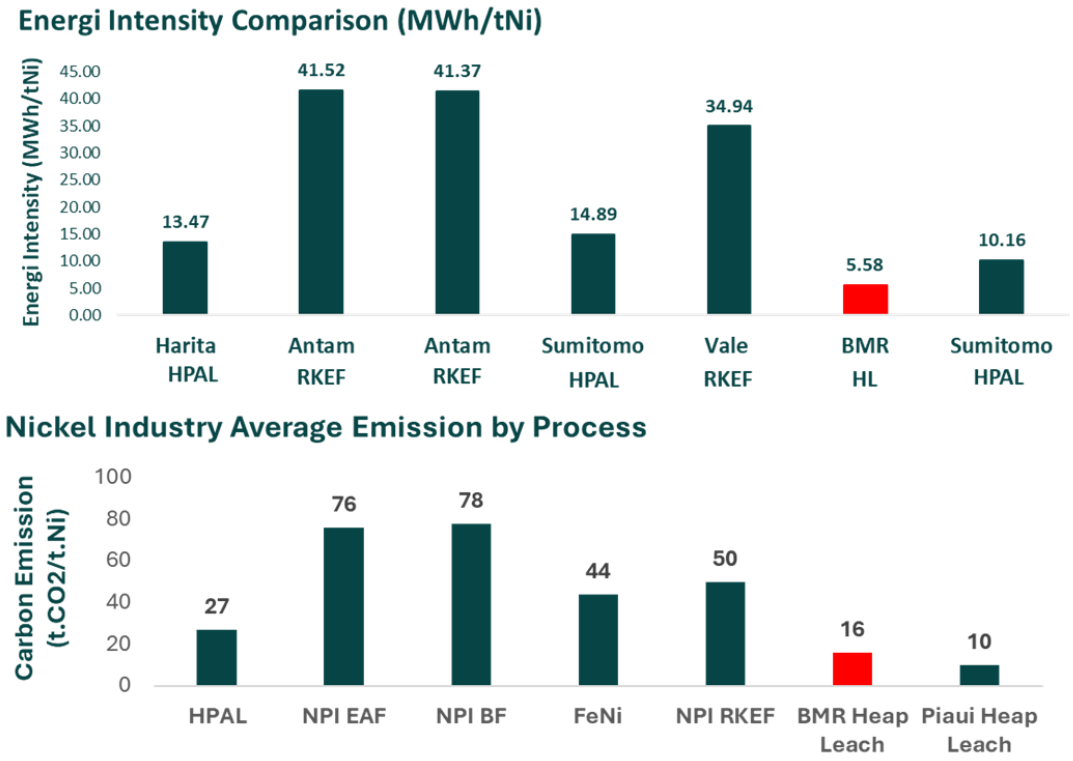


Figure 4. Energy Intensity and Emission of the Various Nickel Projects (Trinanda et al., 2026).

High-pressure acid leaching (HPAL) plants, designed to process limonite and lower-grade ores, have also been introduced in Indonesia (McDonald & Whittington, 2008). While HPAL can

produce battery-grade nickel sulfate, it faces criticism for its environmental impacts, particularly tailing disposal and water consumption. These challenges highlight the need for alternative technologies that address sustainability concerns while utilizing underexplored ore grades, such as low-grade saprolite.

Heap Leaching and Its Benefits

Heap leaching is a hydrometallurgical process that involves stacking crushed ore onto a lined pad and applying a leaching solution (typically sulfuric acid) to dissolve nickel and cobalt. The pregnant leach solution (PLS) is then collected and processed to recover the metals (McDonald & Whittington, 2008; Oxley et al., 2016). Its application to nickel laterites presents an opportunity to address the challenges associated with conventional processing methods. Heap leaching offers several distinct advantages:

- *Proven and Low-Risk Technology*



Figure 5. Heap Leach Commercial plants around the world: A) Brazilian Nickel (Brazil), B) Hellenic Minerals (Cyprus), C) Bukit Makmur Resources (Indonesia) (Trinanda et al., 2026).

  Extensively used in other metals, it requires lower operational complexity and avoids the need for high-temperature and high-pressure systems (Oxley et al., 2016). Heap leaching has been successfully implemented in various mining operations worldwide, including Brazilian Nickel in Brazil and Hellenic Minerals in Cyprus. Its operational simplicity and lower capital expenditure make it an attractive option for Indonesia. Examples of commercial heap leach plants are shown in Figure 5.
- *Lower Carbon and Energy Footprint*
  Heap leaching consumes significantly less energy compared to RKEF and HPAL, with energy requirements as low as 5.58 MWh/tNi and carbon emissions of 16 tCO_2/tNi (Figure 4) (World Bank, 2021). This aligns with global efforts to reduce carbon footprints in mining operations.
- Environmentally Friendly
  Heap leaching provides an alternative route for processing selected lower-grade nickel laterite ores that may be less suitable for conventional processing routes (McDonald & Whittington, 2008; Oxley et al., 2016). This maximizes resource utilization and extends the lifespan of nickel reserves. The distribution of ore types relevant to heap leach processing is illustrated in Figure 6.

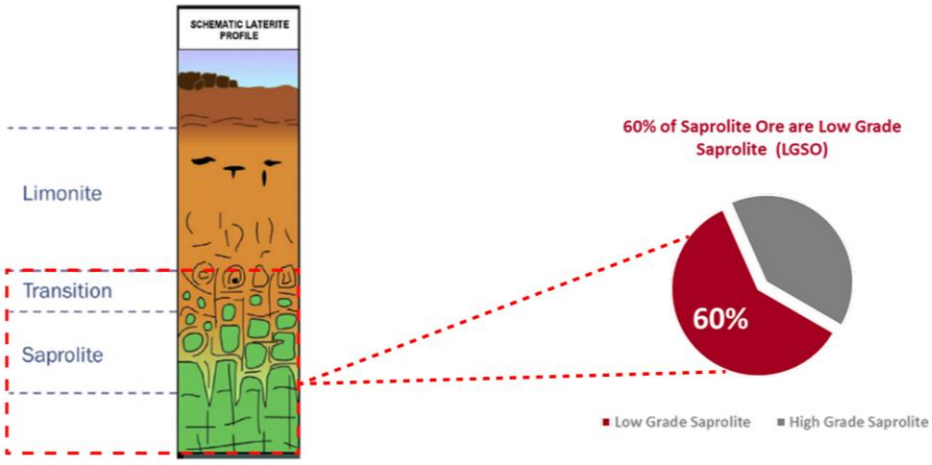


Figure 6. Ore Type Processed in Heap Leach and its typical proportion in the mine (Brand et al., 1998).

- Efficient Resource Utilization
  Heap leaching reduces freshwater consumption by up to 50% compared to HPAL and eliminates the need for hazardous tailings dams. The residues produced are stable and non-hazardous, minimizing environmental risks. The environmental characteristics of the residue generated from heap leaching were evaluated using the Toxicity Characteristic Leaching Procedure (TCLP). Table 3 presents the TCLP results for selected anions and inorganic elements in the tested heap leach residue, together with the corresponding TCLP-A, TCLP-B, and TCLP-C threshold values.

Table 3. Toxicity Characteristic Leaching Procedure (TCLP) Test Results for Heap Leach Residue, Including Selected Anion and Inorganic Element Concentrations and the Corresponding TCLP-A, TCLP-B, and TCLP-C Threshold Values

No.	Test Description	Satuan	Hasil	TCLP-A	TCLP-B	TCLP-C
TCLP Anions						
1	Chloride, Cl-	mg/L	147	75000	12500	5000
2	Cyanide (Total), CN-	mg/L	<0,005	21	4	1,4
3	Fluoride	mg/L	0,21	450	75	30
4	Nitrate, NO_3 _N	mg/L	0,042	40	5	1000
5	Nitrite, NO_2-N	mg/L	<0,001	900	150	60
TCLP Inorganic						
1	Antimony, Sb	mg/L	<0,0005	6	1	0,4
2	Arsenic, As	mg/L	<0,0005	3	0,5	0,2
3	Barium, Ba	mg/L	<0,1	210	35	14
4	Beryllium, Be	mg/L	<0,01	4	0,5	0,2
5	Boron, B	mg/L	<0,1	150	25	10
6	Cadmium, Cd	mg/L	<0,005	0,9	0,15	0,06
7	Chromium Hexavalent, Cr^{6+}	mg/L	<0,002	15	2,5	1
8	Copper, Cu	mg/L	<0,01	60	10	4
9	Iodide,	mg/L	<0,01	40	5	2

10	Lead, Pb	mg/L	<0,05	3	0,5	0,2
11	Mercury, Hg	mg/L	<0,00005	0,3	0,05	0,02
12	Molybdenum, MO	mg/L	<0, 1	21	3,5	1,4
13	Nickel, Ni	mg/L	0,26	21	3,5	1,4
14	Selenium, Se	mg/L	<0,0005	3	0,5	0,2
15	Silver, Ag	mg/L	<0,02	40	5	2
16	Tributyl Tin Oxide (as Organotins) **	mg Sn/L	<0,005	0,4	0,05	0,02
17	Zinc, Zn	mg/L	0,064	300	50	20

Source: Trinanda et al. (2026) for test results; Government of the Republic of Indonesia (2021), Appendix XIII, for TCLP threshold values.

The TCLP results presented in Table 3 show the concentrations of selected anions and inorganic elements in the tested heap leach residue relative to the corresponding TCLP threshold values. These results indicate the leaching characteristics of the residue and can be used to evaluate its potential environmental risk.

- Cost-Effective
  The economic characteristics of heap leach projects can be evaluated by comparing their estimated capital requirements and planned production capacities. Table 4 summarizes selected nickel heap leach projects reported in the literature, including their estimated CAPEX, planned nickel production capacity, and corresponding CAPEX intensity (Oxley et al., 2016).

Table 4. Heap Leach Project List (Oxley et al., 2016).

Project	**Country**	**Owner**	**Estimated CAPEX (US$ Million)**	**Planned Capacity (t.Ni/year)**	**CAPEX Intensity (US$/t.Ni)**
Piaui	Brazil	BRN	450	22,000	20,455
NiWest	Australia	GME	400	14,000	28,571
Cerro Matoso	Colombia	BHPB	750	20,000	37,500
Caldag	Turkey	ENK	450	20,000	22,500
	Guatemala	BHPB	2550	79,500	32,075
Pearl	Indonesia	BHPB	800	32,000	25,000
Gag Island	Indonesia	BHPB	800	27,300	29,304
Cleopatra	USA	RFN	475	21,500	22,093
Acoje	Philippines	ENK	498	24,500	20,327

The selected projects in Table 4 show variation in CAPEX intensity, ranging from approximately US$20,327 to US$37,500 per tonne of planned annual nickel capacity (Oxley et al., 2016). This variation indicates that the capital requirements of heap leach projects can differ substantially among projects. The differences may be associated with project scale, location, infrastructure requirements, and site-specific ore and processing conditions. Therefore, the CAPEX values presented in Table 4 should be considered as project-specific estimates rather than universal cost benchmarks for heap leaching.

To place the economic characteristics of heap leaching in the context of other nickel processing technologies, the reported CAPEX and OPEX intensities can be compared with those of conventional processing routes. Table 5 compares the typical processing capacity, CAPEX intensity, and OPEX intensity of smelting, high-pressure acid leaching (HPAL)/atmospheric leaching (AL), and heap leaching.

Table 5. CAPEX intensity of Nickel Processing Projects (Oxley et al., 2016).

Process Technology	Typical Capacity (kt.Ni/year)	CAPEX Intensity (US$/t.Ni Capacity)	OPEX Intensity (US$/t.Ni)
Smelting	18-60	48,000-90,000	4,400-8,000
HPAL/AL	10-60	42,000-140,000+	5,400-22,000
Heap Leach	10-60	18,000-30,000	4,400-6,000

Table 5 shows that heap leaching has a lower reported CAPEX intensity than smelting and HPAL/AL, with a typical range of US$18,000–30,000 per tonne of annual nickel capacity. The reported OPEX intensity of heap leaching, at US$4,400–6,000 per tonne of nickel, is also lower than the reported range for HPAL/AL and falls within the range reported for smelting (Oxley et al., 2016). These data indicate that heap leaching may offer an economic advantage in terms of capital intensity compared with the other processing routes presented. However, these cost ranges should not be interpreted as universal economic advantages because actual project economics depend on ore characteristics, acid consumption, nickel recovery, heap permeability, processing scale, infrastructure, and site-specific conditions. Therefore, CAPEX and OPEX intensity should be evaluated together with metallurgical performance and ore suitability when assessing heap leaching as an alternative processing route.

Geometallurgy Approach

Geometallurgy integrates geological and metallurgical data to optimize ore processing and resource utilization. In the context of heap leaching, geometallurgical studies are important for identifying and evaluating ore characteristics that influence heap leach amenability. The assessment involves characterizing ore properties, evaluating permeability and heap stability, and determining nickel extraction performance through metallurgical testing. The general workflow used to evaluate heap leach amenability is presented in Figure 7.

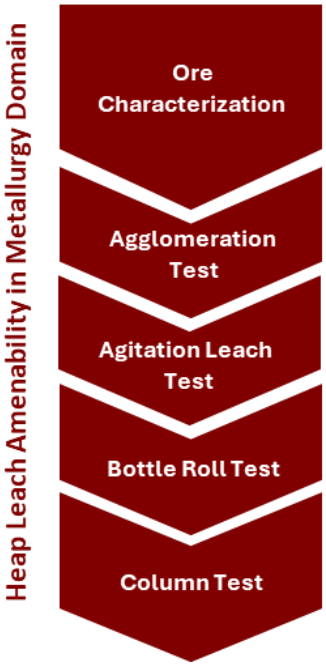
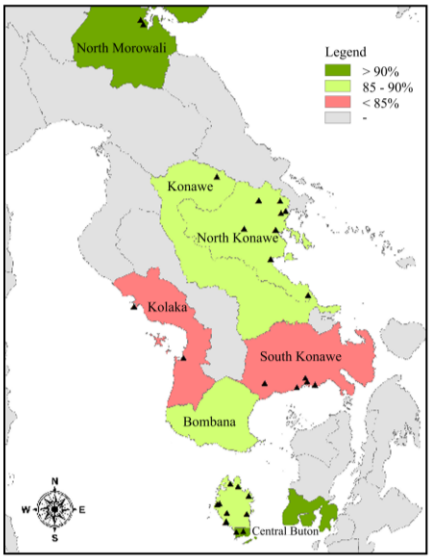


Figure 7. Heap Leach Amenability Test Scheme



Region	Number of Concession
North Morowali	2
North Konawe	8
Konawe	1
Central Buton	2
Bombana	9
Kolaka	2
South Konawe	3

Figure 8. Sample locations and spatial distribution of nickel extraction ranges obtained from heap leach amenability tests.

The locations of the investigated samples and the spatial distribution of nickel extraction obtained from the heap leach amenability tests are presented in Figure 8. The values >90%, 85–90%, and <85% in the map legend represent nickel extraction ranges obtained from the amenability tests. The >90% category indicates high nickel extraction, the 85–90% category represents intermediate extraction, and the <85% category indicates relatively lower extraction. The spatial distribution of these extraction categories provides an overview of variation in heap-leach performance across the investigated areas.

- *Ore Characterization*
  Geochemical assays, mineralogical analysis, and particle size distribution (PSD) tests are conducted to assess laterization and serpentinization levels (Watling et al., 2011). These parameters influence the ore's reactivity and permeability, which are crucial for heap leaching.
- *Permeability and Stability*
  Agglomeration and column leaching tests are performed to evaluate the ore's ability to form stable, permeable heaps. Poor permeability can lead to channeling, reducing metal recovery rates (Oxley et al., 2016).
- *Metal Extraction Efficiency*
  Agitation and column leach tests are conducted to determine nickel extraction rates under varying conditions, such as acid concentration and leaching duration. The geological regions investigated in relation to heap leach performance are shown in Figure 9.

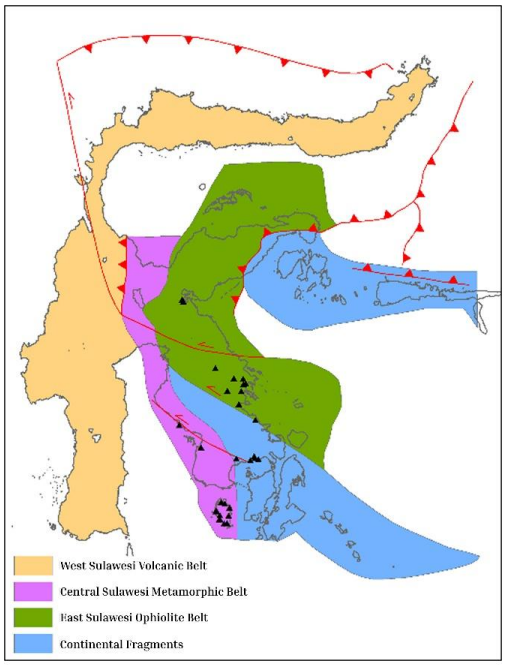


Figure 9. Geological Regions Investigated in Relation to Heap Leach Performance (modified from Surono & Hartono, 2013).

The relationship between geological setting and heap leach performance was further evaluated by comparing nickel extraction among the investigated geological regions. The number of investigated concessions, nickel extraction ranges, and corresponding average extraction values for the ophiolite, metamorphic, and continental terranes are summarized in Table 6.

Table 6. Extraction Profile for Each Region

Geology Region	Number of Concessions	%Nickel Extraction		
		Min	Max	Average
Ofiolit	11	80.0	94.0	86.7

Malihan	13	75.0	95.5	86.2
Continental Terrane	5	73.0	87.5	83.1

The reported amenability test results show that the ophiolite and metamorphic regions have slightly higher average nickel extraction than the continental terrane, with average extraction values of 86.7%, 86.2%, and 83.1%, respectively. The difference in average extraction between the ophiolite and metamorphic regions is relatively small, whereas the continental terrane shows a lower average extraction. This variation may reflect differences in mineralogical composition, degree of laterization, serpentinization, permeability, and other ore characteristics among the investigated areas. However, the extraction ranges overlap among the geological regions, indicating that geological setting alone may not be sufficient to predict heap leach performance. Therefore, ore-specific mineralogical and geometallurgical characterization remains necessary when evaluating the suitability of nickel laterite ores for heap leaching.

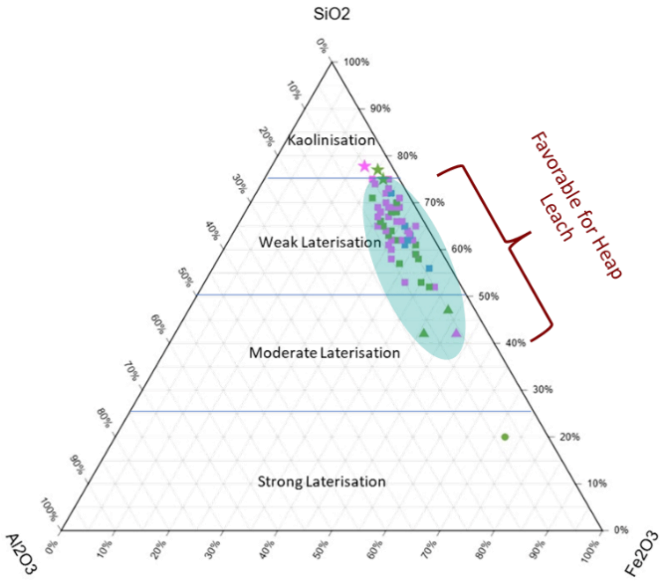


Figure 10. Ore Type Clustering for Heap Leach Processing.

The chemical composition of nickel laterite ores can indicate their degree of laterization. It may be used as one of the parameters in evaluating their suitability for heap leaching. Figure 10 illustrates the relationship between the relative proportions of SiO_2, Al_2O_3, and Fe_2O_3 in the investigated lateritic nickel ores and their corresponding degree of laterization. The highlighted area represents the range identified in this study as favorable for heap leach processing. Ores within this range are associated with weak to moderate laterization and may exhibit chemical characteristics favorable for acid leaching. However, oxide composition alone is insufficient to determine heap-leach amenability and should be evaluated alongside mineralogical characteristics, serpentinization, permeability, and metallurgical extraction performance.

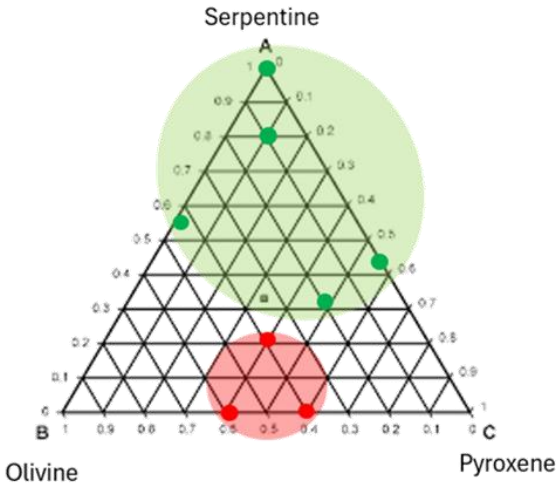


Figure 11. Ternary Diagram of Serpentine, Olivine, and Pyroxene Mineral Composition Showing Heap Leach Performance: Green Region Indicates Ore Types Associated with Higher Nickel Extraction and Favorable Heap Leach Performance, Whereas Red Region Indicates Olivine-Rich Ore Types Associated with Lower Nickel Extraction and Poor Leaching Performance.

The ternary diagram in Figure 11 illustrates the mineralogical composition of the investigated nickel-bearing lateritic ores in terms of serpentine, olivine, and pyroxene. The green region indicates ore compositions associated with higher nickel extraction and favorable heap leach performance. In contrast, the red region represents olivine-rich ore compositions associated with lower nickel extraction and poorer leaching performance. These results indicate that mineralogical composition is an important factor influencing the response of nickel laterite ores to heap leaching. However, the observed relationship should be evaluated alongside other geometallurgical parameters, including the degree of serpentinization, permeability, particle-size distribution, and leaching conditions.

Ores within this favorable region are rich in serpentine, a mineral that enhances nickel recovery due to its better dissolution kinetics. In contrast, the red-marked region, which represents olivine-rich ores, exhibits poor leaching performance. High olivine content leads to lower nickel recovery due to its slow dissolution rate. This analysis shows that selecting ore with a higher serpentine composition significantly improves the viability and efficiency of heap-leach processing for nickel extraction.

$$\text{Deegre of Serpentinization} = \frac{\%\ Serpentine}{\%Serpentine\ +\ \%Olivine\ +\ \%\ Pyroxene} \qquad (1)$$

Further mineralogical analysis was conducted by examining the degree of serpentinization. The degree of serpentinization is determined by the proportion or percentage of serpentine minerals relative to other minerals, namely olivine and pyroxene (Equation 1), resulting in a ratio that represents the degree of serpentinization.

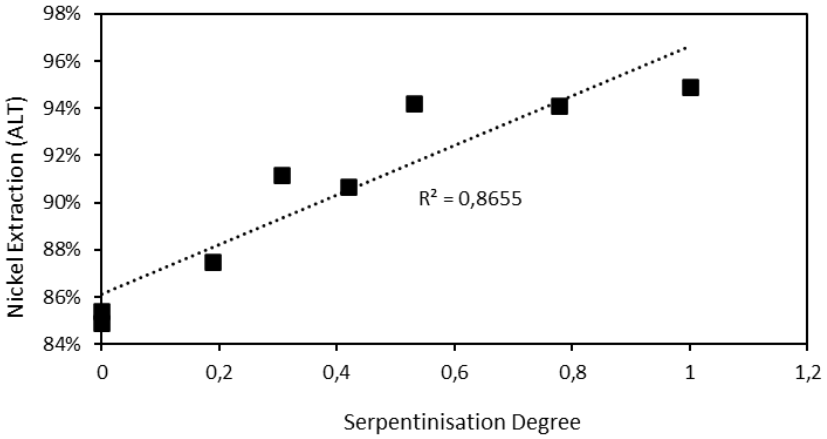


Figure 12. Relationship between Degree of Serpentinization and Nickel Extraction Efficiency Obtained from Agitation Leaching Tests (ALT), Showing a Positive Correlation with $R^2 = 0.8655$.

Further mineralogical analysis was conducted by examining the relationship between the degree of serpentinization and nickel extraction efficiency, as shown in Figure 12. The graph presents the relationship between the degree of serpentinization and nickel extraction obtained from the Agitation Leaching Test (ALT). A positive correlation is observed between the two variables, as indicated by the trend line with an R^2 value of 0.8655. The results show that nickel extraction increases with the degree of serpentinization, with extraction values exceeding 96% across the investigated samples. This observation is consistent with previous studies showing that mineralogical characteristics can influence the leaching behavior of nickel laterite ores (Watling et al., 2011). However, the empirical relationship represented by the trend line is specific to the dataset analyzed in this study. It should be validated using independent experimental data before being applied to other deposits or ore types.

$$\%Ni\ Ext = (8{,}403\ x\ Degree\ of\ Serpentinization) + 85{,}47 \qquad (2)$$

Equation 2 provides an empirical relationship between nickel extraction and the degree of serpentinization, based on the dataset investigated. Given the observed correlation, the equation may be used as an initial empirical estimate of nickel extraction within the range of conditions represented by the dataset. However, its predictive applicability to other deposits or ore types requires validation using independent experimental data.

Conclusions

This review indicates that heap leaching has potential as an alternative processing route for selected Indonesian nickel laterite ores, particularly low-grade saprolite and transition ores that are less suitable for conventional pyrometallurgical processing. The comparative assessment shows that heap leaching can provide lower energy consumption and carbon emissions than the conventional processing routes considered in this study, while offering an opportunity to utilize lower-grade nickel resources. However, the applicability of heap leaching is strongly dependent on ore characteristics and cannot be determined solely by nickel grade.

The geometallurgical assessment highlights the importance of laterization, mineralogical composition, serpentinization, permeability, and metallurgical extraction performance in determining heap leach amenability. The reviewed extraction data indicate differences among

ophiolite, metamorphic, and continental geological regions, with average nickel extraction of 86.7%, 86.2%, and 83.1%, respectively. In addition, the observed positive relationship between the degree of serpentinization and nickel extraction, with an R^2 value of 0.8655, indicates that mineralogical characteristics are important factors influencing leaching performance. These findings demonstrate the importance of integrating geological, mineralogical, and metallurgical information in the selection of nickel laterite ores for heap leaching.

Therefore, the implementation of heap leaching in Indonesia should be based on ore-specific geometallurgical characterization and amenability testing rather than on ore grade alone. The reviewed evidence supports heap leaching as a potentially suitable option for selected nickel laterite resources; however, further investigation is required to validate its performance under representative Indonesian ore and operating conditions. Future studies should include systematic column leaching tests, assessment of long-term permeability and heap stability, evaluation of acid consumption, and integrated techno-economic and environmental assessments to establish the technical and economic feasibility of heap leaching at the deposit scale.

References

Asmiani, N., Thamsi, A. B., Nompo, S., Bakri, S., Tukloy, M. Y. A., & Harmitun. (2024). Model of Laterite Nickel Deposits Based on LGSO and HGSO Values PT Mitra Karya Agung Lestari. *JGE (Jurnal Geofisika Eksplorasi)*, *10*(1), 16–23. https://doi.org/10.23960/jge.v10i1.305

Bahfie, F., Manaf, A., Astuti, W., Nurjaman, F., Prastyo, E., & Herlina, U. (2022). Development of Laterite Ore Processing and Its Applications. *Indonesian Mining Journal*, *25*(2), 89–104. https://doi.org/10.30556/imj.Vol25.No2.2022.1261

Brand, N. W., Butt, C. R. M., & Elias, M. (1998). Nickel laterites: classification and features. *AGSO Journal of Australian Geology and Geophysics*, *17*(4), 81–88.

Indonesian Ministry of Energy and Mineral Resources. (2022). *Nickel Production and Sustainability in Indonesia*.

McDonald, R. G., & Whittington, B. I. (2008). Atmospheric acid leaching of nickel laterites review Part I. Sulphuric acid technologies. *Hydrometallurgy*, *91*(1–4), 35–55. https://doi.org/10.1016/j.hydromet.2007.11.009

Mitchell, A. (2022). *Nickel and copper: building blocks for a greener future*. https://www.woodmac.com/news/opinion/nickel-and-copper-building-blocks-for-a-greener-future/

Nursahan, I., Heditama, D. M., Hilman, P. M., Mulyadi, A. D., Eddy, H. R., Sunuhadi, D. N., Juarsa, A., Wibisono, S. A., Ibrahim, M. A., Oktaviani, P., Hidayat, R., & Fatimah. (2024). *Neraca Sumber Daya dan Cadangan Mineral, Batubara dan Panas Bumi Indonesia Tahun 2023* (M. Awaludin & E. B. Cahyono, Eds.). Pusat Sumber Daya Mineral Batubara dan Panas Bumi (PSDMBP), Badan Geologi. http://geologi.esdm.go.id/publikasi/laporan-dan-buku/neraca-sumber-daya-dan-cadangan-mineral-batubara-dan-panas-bumi-indonesia-tahun-2023

Oxley, A., Smith, M. E., & Caceres, O. (2016). Why heap leach nickel laterites? *Minerals*

Engineering, *88*, 53–60. https://doi.org/10.1016/j.mineng.2015.09.018

Pemerintah Republik Indonesia. (2021). *Peraturan Pemerintah Republik Indonesia Nomor 22 Tahun 2021 tentang Penyelenggaraan Perlindungan dan Pengelolaan Lingkungan Hidup* (Peraturan Pemerintah Nomor 22 Tahun 2021). https://peraturan.bpk.go.id/Details/161852/PP-No-16-Tahun-2021

Smith, J., & Brown, A. (2021). *Sustainable Mining Practices: A Global Perspective*. Springer.

Surono, & Hartono, U. (2013). *Geologi Sulawesi* (1st ed.). LIPI Press.

Trinanda, A., Lestari, R., Juliansyah, M., Maharani, R., & Nugraha, N. (2026). Eco-Efficient Nickel: Heap Leaching as a Game-Changer for Indonesia's Nickel Industry. *E3S Web of Conferences*, *693*. https://doi.org/10.1051/e3sconf/202669302003

Watling, H. R., Elliot, A. D., Fletcher, H. M., Robinson, D. J., & Sully, D. (2011). Ore mineralogy of nickel laterites: Controls on processing characteristics under simulated heap-leach conditions. *Australian Journal of Earth Sciences*, *58*(7), 725–744. https://doi.org/10.1080/08120099.2011.602986

World Bank. (2021). *The Role of Nickel in the Global Energy Transition*. https://www.worldbank.org/nickel-report