

# Eco-Efficient Nickel: Heap Leaching as a Game-Changer for Indonesia's Nickel Industry

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**Abstract.** Indonesia, home to the world's largest nickel laterite reserves, plays a vital role in global stainless steel and EV battery supply chains. Traditionally dominated by energy and capital-intensive pyrometallurgical methods (RKEF and BF), the industry has recently introduced hydrometallurgical HPAL technology to meet EV battery demand. However, both methods are environmentally burdensome and leave parts of laterite reserves unutilized, fueling Indonesia's image as a "dirty nickel" producer. Heap leaching offers a compelling alternative: a low-cost, scalable, and eco-efficient hydrometallurgical process well-suited to Indonesia's tropical laterites and low-grade ores. It improves ore utilization, reduces emissions and operational costs, and generates more stable tailings suitable for rehabilitation or use as plantation media. The process also enables recovery of by-products like magnesium sulfate, supporting circular economy practices and unlocking new revenue. Operational flexibility allows heap leaching to produce nickel for both stainless steel and battery-grade markets. Compared to conventional methods, it offers advantages in emissions, water use, waste management, economics, and local knowledge transfer. Embracing this technology could redefine Indonesia's nickel sector, positioning the country as a leader in clean and responsible mineral extraction.

## 1 Introduction

Indonesia holds the world's largest reserves of nickel laterite, making it a key player in the global supply chains for stainless steel and electric vehicle (EV) batteries. Over the past two decades, the country's nickel industry has been driven primarily by pyrometallurgical processes, such as Rotary Kiln-Electric Furnace (RKEF) and Blast Furnace (BF), which produce ferronickel and nickel pig iron for stainless steel production. More recently, the emergence of EV battery demand has led to the introduction of High-Pressure Acid Leach (HPAL) technology to produce battery-grade nickel.

While both pyrometallurgy and HPAL have enabled Indonesia to industrialize its nickel resources, they come at a significant environmental and economic cost. These methods are capital-intensive, energy-consuming, and generate high volumes of carbon emissions and hazardous tailings. As a result, Indonesia's nickel has been increasingly associated with the label of "dirty nickel," a perception that threatens the industry's long-term competitiveness. This reputation has begun to influence global trade dynamics, with environmentally conscious markets, particularly in Europe and North America, placing greater scrutiny on the carbon footprint and sustainability of raw material imports.

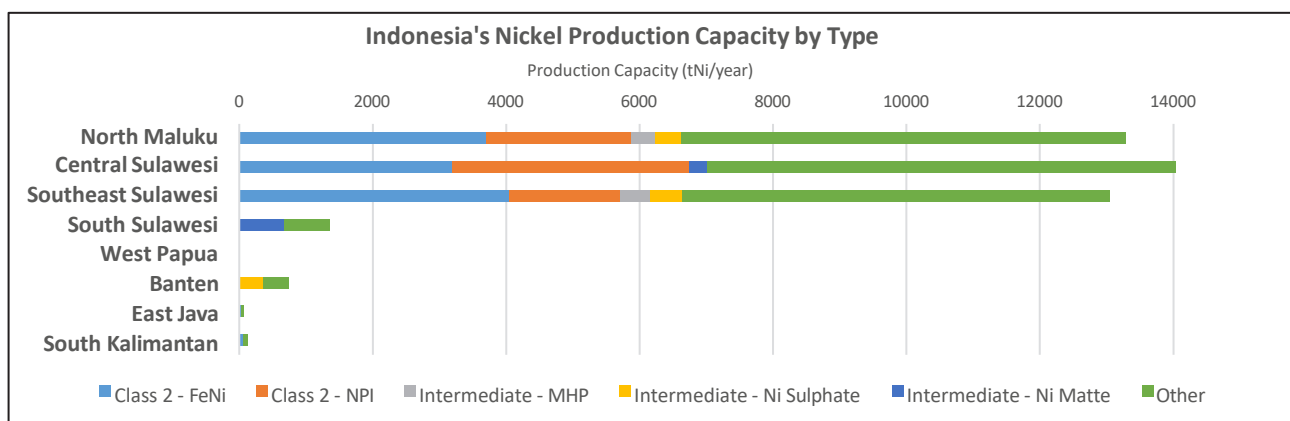
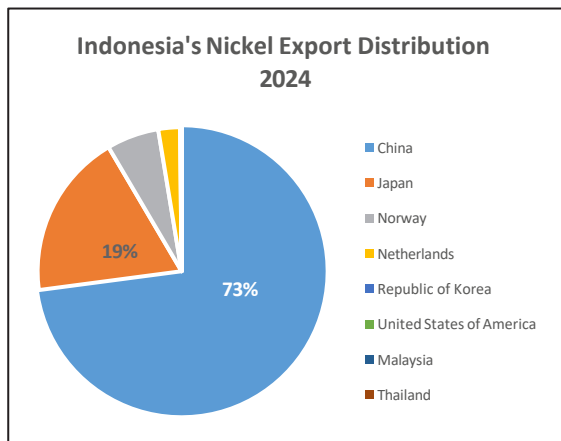


Fig. 1. Nickel Production Capacity by Type [1]

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Some buyers have already begun prioritizing “green nickel” from jurisdictions with lower environmental impact, which could marginalize Indonesia’s market position and limit its access to premium pricing or strategic partnerships.



**Fig. 2.** Indonesia’s Nickel Export Countries [2].

Moreover, these extraction technologies are selective in the types of ore they can process efficiently, leaving significant portions of low-grade laterite resources underutilized or discarded. This not only reduces the overall resource efficiency but also increases the environmental footprint per ton of nickel produced.

In this context, heap leaching has emerged as a compelling alternative technology. It is a low-cost, environmentally friendly, and scalable hydrometallurgical method that is well-suited to Indonesia’s tropical climate and laterite ore profiles. Unlike conventional methods, heap leaching offers improved ore utilization, reduced greenhouse gas emissions, and the ability to generate more stable tailings that can be rehabilitated or repurposed for sustainable land use. The technology also presents opportunities to extract valuable by-products such as magnesium sulfate, supporting a more circular and resource-efficient mining model.

This paper examines the potential of heap leaching to transform Indonesia’s nickel sector into a cleaner, more inclusive, and more sustainable industry. It evaluates the environmental, economic, and social advantages of heap leaching, compares its performance with existing technologies, and discusses its role in helping Indonesia transition away from “dirty nickel” toward a greener and more resilient mining future.

## 2 Methods

This study employs a combined experimental-comparative research approach to evaluate the technical, environmental, and economic feasibility of heap leaching for Indonesian nickel laterites. Unlike purely literature-based assessments, this work is grounded in original metallurgical testwork conducted on representative Indonesian laterite ores, followed by systematic upscaling and benchmarking against established

processing routes. The methodology integrates Laboratory- and pilot- scale heap leach experiments (column, crib, and cell tests) and Comparative assessment versus RKEF and HPAL technologies using some indicators such as Energy intensity (MWh/t Ni), CO<sub>2</sub> emissions (t CO<sub>2</sub>/t Ni), CAPEX and OPEX intensity (US\$/t Ni)



**Fig. 3.** The Nickel Heap Leaching Test Stages from a) Column Test, b) Crib and c) Cell Sized Test

Heap leach performance was evaluated through a staged experimental program. The Parameter and Feed used for the testwork can be seen in the Table 1 & 2.

### 2.1 Column Leach Tests

Column leach tests were conducted to establish baseline leach kinetics, acid consumption, and nickel recovery under controlled conditions. Cylindrical columns with a diameter of approximately 20 cm and a height of 3.5 m were used, representing typical industrial heap lift heights. Agglomerated ore was irrigated with sulfuric acid solution at ambient temperature.

### 2.2 Crib Size Tests

Crib tests were performed to simulate intermediate-scale heap behavior, incorporating agglomeration effects, solution distribution, and percolation characteristics. The cribs had a plan area of approximately 3 × 3 m and a heap height of 3.5 m

### 2.3 Cell Size Tests

Heap cell tests represented the largest experimental scale and were designed to closely approximate commercial heap leach conditions. The heap cells had plan dimensions of approximately 26 × 45 m, with a heap height of 3.5 m

**Table 1.** Parameter Used During The Experiment

Parameter	Unit	Column	Crib	Cell
Acid concentration in lixiviant	g/L	50	50	50
Heap height	m	3.5	3.5	3.5
Estimated True SG	t/m <sup>3</sup>	2.5	2.5	2.5
Ore dry weight	kg	82	26,750	1,559,000
Target flux rate	L/h·m <sup>2</sup>	8	8	8

**Table 2.** Ore Feed Grade

Parameter	Unit	Column	Crib	Cell
Feed Grade :				
- Al	%	1.51	1.51	3.3
- Co	%	0.04	0.04	0.03
- Cr	%	0.87	0.87	0.69
- Cu	ppm	0.37	0.37	0.45
- Fe	%	17.79	17.77	14.81
- Mg	%	12.23	12.21	11.04
- Mn	%	0.29	0.29	0.26
- Ni	%	1.5	1.5	1.52
- Fe/Mg		1.45	1.45	1.34

### 2.4 TCLP Test

The residues were air-dried and subjected to Toxicity Characteristic Leaching Procedure (TCLP) testing in accordance with applicable regulatory standards. TCLP results were compared against national regulatory limits (TCLP-A, TCLP-B, and TCLP-C criteria), providing a quantitative basis for residue management, disposal options, and post-mining land use considerations.

Results from column, crib, and cell tests were used to define realistic operating windows and to validate scale-up assumptions.

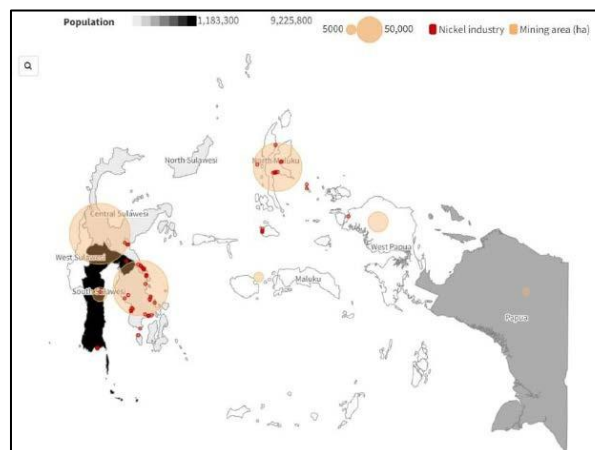
## 3 Results and discussion

### 3.1 Indonesia’s Current Industry

The downstream development of natural resources is central to Indonesia’s national agenda for sustaining economic growth and realizing the Golden Indonesia 2045 Vision. As the nation nears its centennial, strategic efforts are underway to transition into a developed economy and escape the middle-income trap.

Among key sectors, nickel stands out due to its rapid export growth. Global demand has risen ~7% annually from 2.44 million tons in 2019 to 3.36 million tons in 2024[3], prompting Indonesia to boost output from 0.2 million tons in 2016 to 0.76 million tons in 2020, nearly 30% of global production. The country’s largest nickel reserves are concentrated in eastern Indonesia, with 143 million tons of ore and 49 million tons of metal resources. By June 2021, 338 active licenses had been issued, and facility expansion continues, especially in Southeast and Central Sulawesi and North Maluku.

Indonesia’s nickel deposits consist mostly of laterite ores: limonite (0.8 – 1.5% Ni, high iron) and saprolite (1.5 – 3% Ni, 0.1 – 0.2% Co). The Geological Agency estimates limonite reserves will last 34 years and saprolite 15 years. Historically, the sector has focused on Class 2 Nickel, Ferronickel (FeNi) and Nickel Pig Iron (NPI), produced from saprolite via pyrometallurgical processes (BF and RKEF). The export ban on raw ore has driven domestic downstreaming, increasing the value chain and use of Class 2 products for stainless steel and as feedstock for Class 1 Nickel required in EV batteries, renewables, and superalloys.



**Fig. 4.** Distribution map of Indonesia’s current nickel industry across Eastern Indonesia [1].

Limonite is processed hydrometallurgically via HPAL, producing MHP and MSP intermediates. These can be further refined into Nickel Sulphate (21% Ni), Nickel Hydroxide (40% Ni), and Nickel Matte (80% Ni), which also derives from RKEF routes. These materials are critical for battery cell production.

According to the IEA, Indonesia is now the world’s leading center for nickel mining and refining, supplying stainless steel and battery-grade commodities like FeNi, NPI, MHP/MSP, Nickel Sulphate, Hydroxide, and Matte [4]. At the 2023 APEC Summit, President Joko Widodo announced plans for domestic EV production starting in 2024, aiming for 600,000 units annually by 2030, alongside a 30,000-hectare green industrial zone.

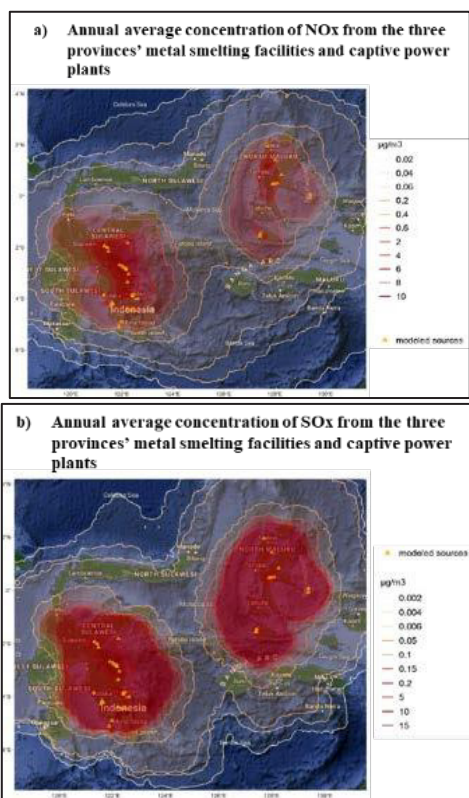
### 3.2 Opportunities and challenges

The extractive industry is highly energy-intensive and emission-heavy, with Indonesia’s reliance on coal for downstream operations being a major concern. Around 76% of its captive coal power, 8.2 GW out of 10.8 GW is dedicated to metal processing [5], yet remains largely absent from national energy and climate strategies.

The Just Energy Transition Partnership’s (JETP) Comprehensive Investment and Policy Plan (CIPP), finalized in November 2023, confirms that off-grid captive coal plants are outside its current scope. Given this, achieving the 2030 emissions peak target of 290 million tons CO<sub>2</sub> appears highly challenging [6]. Decarbonising the metal sector is hindered by conflicting economic priorities, limited affordable clean energy, and a fragile national grid.

China dominates Indonesia’s captive coal sector, holding over 70% ownership across 14 companies in mining and metals. International partners could accelerate decarbonisation by aligning Indonesia with global or even China’s stricter domestic emissions standards.

Despite existing regulations, rapid nickel industry expansion has triggered major environmental issues, from seawater discoloration near Obi Island to heavy metal pollution in Halmahera’s bays, offshore dumping by IMIP, land degradation in North Konawe, and air pollution affecting communities near the Konawe Industrial Park [7].



**Fig. 5.** Annual average concentration of NOx (a) and Sox (b) from the three provinces’ metal smelting facilities and captive power plants [1]

The Coral Triangle, home to 76% of the world’s shallow-water coral species, faces growing threats as Indonesia’s nickel mining and processing rapidly expand. Environmental groups and lawmakers warn that industry growth could pressure regulators to ease controls on deep-sea tailings disposal, raising concerns over potential illegal dumping. In response, Maritime Affairs and Investment Minister Luhut Binsar Pandjaitan reiterated in July 2023 that waste disposal is limited to approved methods like engineered containment or dry stacking [8].

Nickel mining has also driven large-scale deforestation and biodiversity loss in Sulawesi and North Maluku. Over 500,000 hectares have been cleared, legally and illegally, while more than 75% of the one million hectares of mining concessions overlap with forested land [9].

Social and governance concerns are mounting. From 2019 to 2023, 32 community members were criminally charged in disputes with mining companies, with several reports of abuse. Activists have criticized revisions to Article 162 of Law No. 3/2020 as a tool to silence environmental defenders.

Worker safety is also under scrutiny. A smelter explosion on December 24, 2023, at PT Indonesia Tsingshan and PT Gunbuster Nickel killed 21 people [10]. It was not an isolated case, Trend Asia recorded 65 fires and explosions between 2015 and 2023, with 53 worker deaths during 2015 – 2022.

These incidents reflect systemic failures in occupational safety and enforcement. The December tragedy highlights the urgent need for stronger oversight and regulation. Reform is critical to ensuring that Indonesia’s metal industry aligns with

environmental and social responsibility, supporting a fair, sustainable energy transition through accountability across the nickel supply chain.

### 3.3 Heap Leach Testworks Results

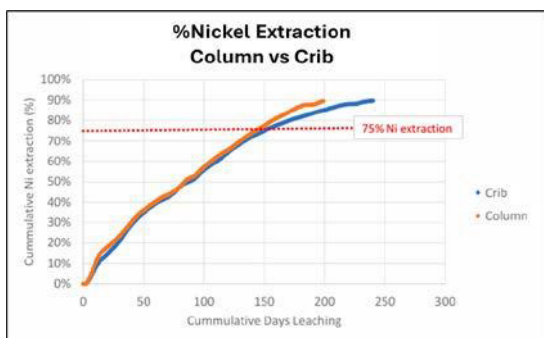
Nickel heap leaching was evaluated through a staged testwork program progressing from laboratory to column and pilot-scale trials. Laboratory tests confirmed the fundamental leachability of Indonesian laterite ores, providing baseline data on nickel recovery, acid consumption, and leach kinetics. Column leach tests then simulated heap percolation behavior and leach cycle duration, demonstrating technically meaningful recoveries while identifying key operational challenges such as solution distribution and impurity dissolution, particularly iron. These findings informed pilot-scale heap tests, where larger ore volumes were irrigated under near-commercial conditions, generating critical data on long-term recovery performance, reagent consumption, and heap stability. Collectively, the results validate the technical feasibility of nickel heap leaching and establish a sound basis for scale-up, while highlighting agglomeration quality, acid management, and heap hydraulics as critical optimization factors for commercial deployment.

The result of heap leach test at column and crib scale are summarized below

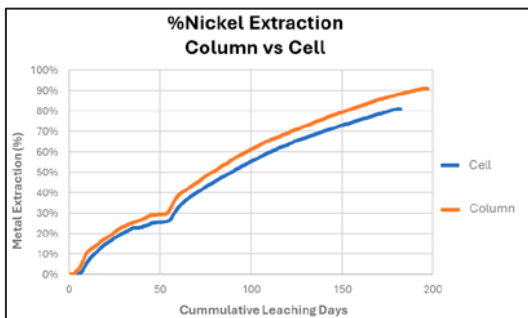
Table 3. Test Result Summary at 75% Nickel Extraction

Parameter	Unit	Column	Crib	Cell
Leaching duration	days	143	150	162
Metal Extraction:				
- Al	%	34.6	31.5	63.6
- Co	%	83.3	78.7	96.0
- Cr	%	16.4	22.1	23.3
- Cu	%	54.7	49.6	86.0
- Fe	%	38.2	39.2	7.8
- Mg	%	56.8	54.7	61.5
- Mn	%	84.2	74.5	86.7
- Ni	%	75	75	75
- Acid consumption	kg/t ore	539	522	663
- Acid consumption	kg/kg Ni Ext	52	49	44

The data in Table 3 show consistent heap leach performance across column, crib, and cell-scale tests, with nickel extraction remaining stable at approximately 75% and only minor variation in acid consumption and solution-to-ore ratios. Similar impurity extraction trends and leaching durations were observed across all test scales, indicating controlled solution distribution and stable leach kinetics as heap size increased. The low deviation in recovery and reagent efficiency between scales demonstrates that the heap leach process is technically robust and scalable, supporting its potential for larger-capacity commercial application.

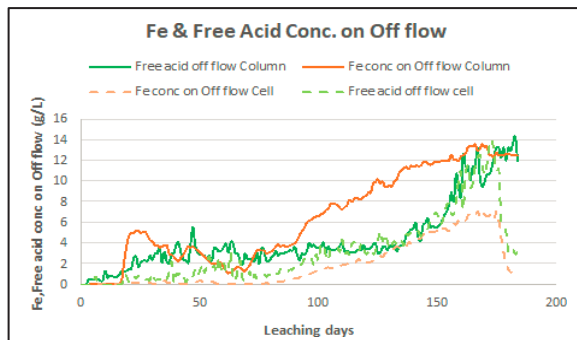


**Fig. 6.** Comparison of %Nickel Extraction of Cribs and Column



**Fig. 7.** Comparison of %Nickel Extraction of Cell and Column

Fig. 6 & 7 shows the nickel extraction curves for column, crib, and cell tests show similar leaching kinetics and converge toward a final recovery of approximately 75%. This consistency across test scales demonstrates stable heap leach performance and supports the technical feasibility of upscaling the process to commercial capacity.



**Fig. 8.** Iron and Free Acidity Concentration Profiles in Column and Cell leaching

The iron and free acidity concentration profiles in the off-flow or pregnant leach solution (Fig. 8) indicate that iron dissolution remains low during the early stages of nickel heap leaching, increasing only at later leaching periods as acid strength and exposure time rise. This behavior demonstrates the inherent selectivity of heap leaching toward nickel over iron under atmospheric conditions, resulting in a relatively cleaner pregnant leach solution during the critical recovery phase. The reduced early-stage iron extraction simplifies downstream purification and reagent consumption, highlighting a key processing advantage of heap leaching compared to less selective hydrometallurgical routes.

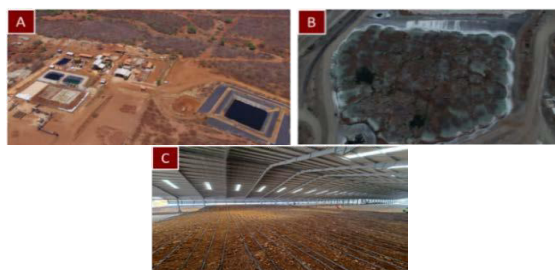
### 3.4 Heap Leach Technology as the Game Changer

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.

Heap leaching is a hydrometallurgical process that has been successfully employed for gold, silver, and copper extraction [11]. Its adaptation for nickel laterites presents an opportunity to address the challenges faced by conventional methods. Heap leaching involves stacking crushed ore onto a lined pad, followed by the application of a leaching solution to dissolve nickel and cobalt, which are subsequently recovered from the solution. Heap leaching offers several distinct advantages:

#### 3.4.1 Proven and Low-Risk Technology

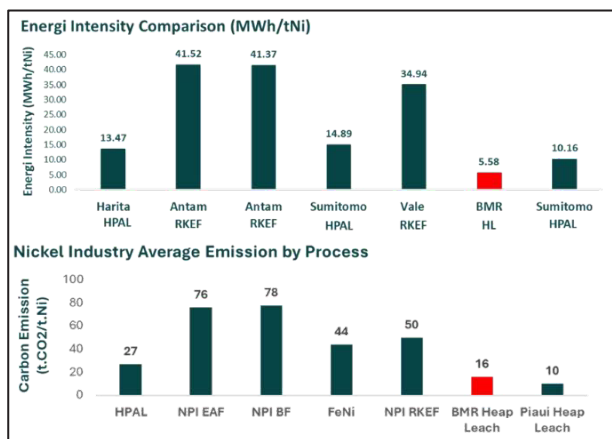
Extensively used in other metals, it requires lower operational complexity and avoids the need for high-temperature and high-pressure systems. Heap leaching has been successfully implemented in various mining operations worldwide, including Brazilian Nickel in Brazil and Hellenic Minerals in Cyprus. Its operational simplicity and lower capital expenditure make it an attractive option for Indonesia



**Fig. 9.** Heap Leach Commercial plants around the world; A) Brazilian Nickel (Brazil), B) Hellenic Minerals (Cyprus), C) Bukit Makmur Resources (Indonesia).

#### 3.4.2 Lower Carbon and Energy Footprint

As mentioned before, many nickel projects that has been done in Indonesia which focus on pyrometallurgical technologies such as rotary kiln electric furnaces (RKEF), producing ferronickel (FeNi) and nickel pig iron (NPI) primarily for stainless steel. Despite their efficiency for high-grade ores, these methods are energy-intensive and result in significant carbon emissions.



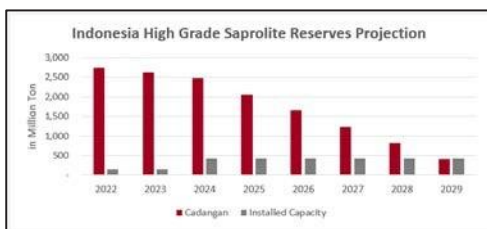
**Fig. 10.** Energy Intensity and Emission of various Nickel Project Efficient Resource Utilization.

Fig. 10 highlights the stark contrast in energy consumption and carbon emissions between traditional methods and heap leaching. HPAL and RKEF consume 25 – 30 MWh/tNi and emit 40 – 50 tCO<sub>2</sub>/tNi, whereas heap leaching consumes only 5.5 MWh/tNi and emits 16 tCO<sub>2</sub>/tNi [12]. These findings underscore heap leaching's potential as a low-carbon alternative.

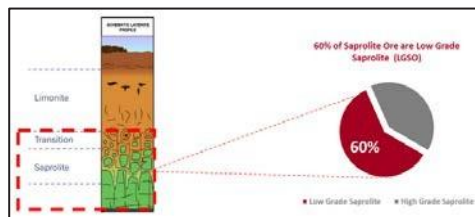
Heap leaching consumes significantly less energy compared to RKEF and HPAL, with energy requirements as low as 5.5 MWh/tNi and carbon emissions of 16 tCO<sub>2</sub>/tNi [12]. This aligns with global efforts to reduce carbon footprints in mining operations.

### 3.4.3 Efficient Resource Utilization

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). 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 (Fig. 11) due to the significant growth of RKEF-based smelting capacity in recent years.



**Fig. 11.** High Grade Nickel Ore Reserves Projection [13]



**Fig. 12.** Ore Type Processed in Heap Leach and its typical proportion in mine [14].

Heap leaching enables the processing of low-grade saprolite and ferruginous ores, which are unsuitable for traditional methods. This maximizes resource utilization and extends the lifespan of nickel reserves.

### 3.4.4 Environmentally Friendly

The residues produced from the heap leach process are stable and non-hazardous, minimizing environmental risks. Table 4 shows the TCLP result of Heap Leach. All measured parameters, including Chloride (147 mg/L), Cyanide (<0.005 mg/L), Fluoride (0.21 mg/L), Nitrate (0.042 mg/L), Nitrite (<0.001 mg/L), and heavy metals like Arsenic (<0.0005 mg/L), Cadmium (<0.001 mg/L), Chromium (<0.005 mg/L), Nickel (<0.005 mg/L), and Zinc (0.064 mg/L), fall significantly below the regulatory limits for TCLP-A, TCLP-B, and TCLP- C standards. This indicates that the residue does not leach hazardous levels of contaminants and is classified as non-hazardous, compliant for standard waste disposal without special hazardous waste treatment requirements.

**Table 4.** TCLP Test Result of Bukit Makmur Resources Heap Leach Residue.

Ion	Unit	Result	TCLP-A	TCLP-B	TCLP-C
Cl <sup>-</sup>	mg/L	147	75000	12500	5000
CN <sup>-</sup>	mg/L	<0,005	21	4	1,4
F <sup>-</sup>	mg/L	0,06	450	75	30
NO <sub>3</sub> -N	mg/L	0,042	40	5	1000
	mg/L	<0,001	900	150	60
Sb	mg/L	<0,0005	6	1	0,4
As	mg/L	<0,0005	3	0,5	0,2
Ba	mg/L	<0,1	210	35	14
Be	mg/L	<0,01	4	0,5	0,2
B	mg/L	<0,1	150	25	10
Cd	mg/L	<0,005	0,9	0,15	0,06
Cr <sup>6+</sup>	mg/L	<0,002	15	2,5	1
Cu	mg/L	<0,01	60	10	4
I	mg/L	<0,01	40	5	2
Pb	mg/L	<0,05	3	0,5	0,2
Hg	mg/L	<0,00005	0,3	0,05	0,02
Mo	mg/L	<0,1	21	3,5	1,4
Ni	mg/L	0,26	21	3,5	1,4
Se	mg/L	<0,0005	3	0,5	0,2
Ag	mg/L	<0,02	40	5	2
Tributyltin oxide (TBTO)**	mg Sn/L	<0,005	0,4	0,05	0,02
Zn	mg/L	0,064	300	50	20



**Fig. 13.** Plantation Trial on Bukit Makmur Resources Heap Leach Residue.

### 3.4.5 Cost-Effective

Heap leaching avoids the need for expensive infrastructure like rotary kiln and electrical furnace in RKEF or autoclaves and high-pressure systems in HPAL, reducing capital and operational costs. Table shows some heap leach projects CAPEX around the world.

**Table 5.** Heap Leach Project List [15]

Project	Owner	Estimated CAPEX (US\$ Million)	Planned Capacity (t.Ni/year)	CAPEX Intensity (US\$/t.Ni)
Piaui	BRN	450	22,000	20,455
NiWest	GME	400	14,000	28,571
Cerro Matoso	BHPB	750	20,000	37,500
Caldag	ENK	450	20,000	22,500
	BHPB	2550	79,500	32,075
Pearl	BHPB	800	32,000	25,000
Gag Island	BHPB	800	27,300	29,304
Cleopatra	RFN	475	21,500	22,093
Acoje	ENK	498	24,500	20,327
Kabaena	BMR	260	10,000	26,000

**Table 5.** Heap Leach Project List [15]

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

Heap leach is not as mature as HPAL in nickel hydrometallurgy, which has been developed over the past 50 years. However, the CAPEX of heap leach projects at this stage can be considered low compared to HPAL projects during their early development phases. There are still many efficiency opportunities that can be pursued if heap leach is later operated on a commercial scale.

## 4 Conclusion

Heap leaching presents a transformative opportunity for Indonesia's nickel industry. By utilizing low-grade saprolite and transition ores, the process addresses critical resource conservation needs while meeting the growing demand for "green nickel." Its low carbon footprint, minimal environmental impact, and adaptability to Indonesian ore conditions make it a compelling alternative to conventional methods.

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