INTAN Jurnal Penelitian Tambang
Journal Homepage : www.jurnal-intan.ac.id
e-issn: 2723-2727, p-issn: 2655-3473
OPEN ACCESS

CONTRASTING LATERITIC NICKEL ORE CHARACTERISTICS IN EASTERN INDONESIA: THE URGENCY OF SHIFTING FROM RKEF TO HPAL

Renny Cahyaningtyas[1*], Nurkhamim[1], Eddy Winarno[1]

[1]Master of Mining Engineering Program, UPN "Veteran" Yogyakarta,
Jl. Padjadjaran, Sleman, Yogyakarta, Indonesia.
[*]Corresponding author: cahyanyrenny@gmail.com

ARTICLE INFO

Article history:
Received January 28th 2026
Received in revised from May 18th 2026
Accepted May 22nd 2026
Available online May 2026

Keywords:
Geometallurgical Mismatch
High Pressure Acid Leaching (HPAL)
Nickel Laterite
Rare Earth Elements
Resource Sustainability
Rotary Kiln Electric Furnace (RKEF)

ABSTRACT

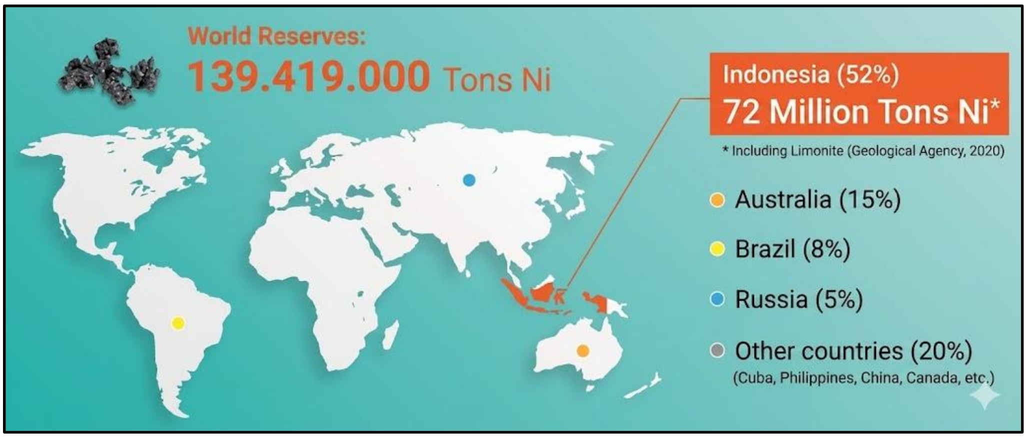
While Indonesia holds a strategic position in the global electric vehicle (EV) supply chain, with 19.16 billion tons of nickel resources, this dominance is threatened by a critical mismatch between geological realities and the downstream industrial structure. This paper analyzes the disparity within the national ore balance and assesses the urgency of transitioning processing technologies to secure long-term sustainability. Using an economic geology approach, we conducted a geometallurgical characterization of regional deposits (Sulawesi, Maluku, Papua) and a mass balance analysis based on the 2025 Mineral Resource and Reserve Balance. Findings indicate that 58% of national resources are limonite (Ni <1.5%) and are predominantly located in Eastern Indonesia (Maluku and Papua). Crucially, these eastern limonite profiles are enriched in cobalt, scandium, and a comprehensive spectrum of rare earth elements (REE). In stark contrast, the industry remains heavily skewed toward pyrometallurgy (RKEF) for producing intermediate stainless steel products, resulting in massive consumption of saprolite ore (Ni ≥ 1.5%). Reserve life projections indicate that high-grade saprolite could be depleted within eight years at current extraction rates. Consequently, this study advocates for a moratorium on RKEF expansion and accelerated investment in hydrometallurgy (HPAL). This strategic pivot toward Class I nickel production is imperative to valorize the massive limonite inventory and underpin the national EV battery ecosystem. Furthermore, this paper emphasizes that the HPAL transition must be tightly coupled with robust environmental, social, and governance (ESG) practices to mitigate ecological risks, particularly regarding tailings management and biodiversity protection in fragile small-island environments.

How to Cite This Article: Cahyaningtyas, R., dkk. (2026). Contrasting Lateritic Nickel Ore Characteristics in Eastern Indonesia: The Urgency of Shifting from RKEF to HPAL. *INTAN: Jurnal Penelitian Tambang*, 9(1), 24–37. https://doi.org/10.56139/intan.v9i1.371

INTRODUCTION

Nickel, a transition metal classified as a critical mineral, plays a pivotal role across diverse industrial applications. These range from traditional stainless-steel production to its increasingly vital role in lithium-ion (Li-ion) battery cathodes, which are the cornerstone of electric vehicles (EVs) and renewable energy storage systems [1]. As the global energy transition accelerates, the International Energy

Agency (2023) projects a surge in demand for chemical-grade (battery-grade) nickel [2]. This trajectory is propelled by the EV revolution and the expanding needs of the renewable energy sector [3]. Within this landscape, Indonesia has cemented its status as a strategic global player. Data from the Nickel Booklet (2020) and the 2025 Mineral Resource and Reserve Balance indicate that Indonesia ranks first worldwide in nickel reserves, holding a dominant market share over major competitors such as the Philippines and Russia. (Figure 1)[4,5].



Source: Kementrian ESDM, 2023[4]

Figure 1. Global Nickel Reserve Rankings

As noted by the Indonesia Business Post (2024), Indonesia's geological endowment is characterized by extensive nickel laterite deposits in the eastern region, specifically Sulawesi and North Maluku, resulting from the intense chemical weathering of ultramafic bedrock in a tropical environment [6]. These resources are hosted in lateritic profiles formed over ultramafic rocks (peridotite) within the ophiolite belts that stretch from Sulawesi through Halmahera to Papua [7]. Nevertheless, from an economic-geology perspective, this dominance harbors a fundamental vulnerability. The latest data from the USGS 2025 Mineral and Coal Resource and Reserve Balance (status: December 2024) highlights a substantial surge in total nickel ore resources to 19.16 billion tons [8]. Although this figure underscores Indonesia's status as a global supply hub, it also introduces complex resource management challenges concerning the long-term sustainability of reserves.

A critical challenge for the national nickel industry stems from the heterogeneous nature of regional laterite deposits. The Indonesian laterite profile is typically stratified into two principal mineralization zones exhibiting contrasting geochemical signatures: the overlying limonite zone (Ni <1.5%, Fe-rich) and the underlying saprolite zone (Ni ≥1.5%, Mg-rich). The latest balance data exposes a severe disparity: 58% of the national nickel inventory, totaling 11.12 billion tons, is hosted in limonite, while saprolite, the current industrial backbone, comprises only 8.04 billion tons. Moreover, a spatial mismatch exists; vast limonite reserves are concentrated in Maluku and Papua, whereas the center of the current processing industry is in Sulawesi.

This mismatch between a limonite-dominated geology and an industrial structure reliant on rotary kiln electric furnace (RKEF) technology creates a critical supply vulnerability. Stringent geometallurgical constraints generally bind RKEF technology; it requires high-grade saprolite with specific chemistry for technical and economic viability and is poorly suited to processing iron-rich limonite. As a result, limited saprolite reserves are facing over-exploitation. This imbalance poses a long-term supply risk, particularly given rapidly increasing rates of saprolite consumption driven by the proliferation of RKEF smelters across the Sulawesi and North Maluku corridors. In response, the Indonesian government progressively implemented a downstreaming policy (hilirisasi), banning raw nickel ore exports since January 2020 to accelerate the construction of domestic processing facilities [9].

The transformation of Indonesia's nickel industry was catalyzed by this ban on raw nickel ore exports, shifting the sector away from its historical reliance on raw ore exports. This move represents a core component of the nation's resource nationalism strategy, mandating downstreaming to capture greater domestic value-added [10]. Moreover, through the Grand Strategy for Mineral and Coal Commodities, the Indonesian government envisions a trajectory extending beyond intermediate products (e.g., NPI/FeNi) toward the high-value EV battery ecosystem. This strategic roadmap prioritizes the development of hydrometallurgy (HPAL) to process limonite ore into Mixed Hydroxide Precipitate (MHP) and nickel sulfate, critical precursors for battery cathodes. While this strategy is geologically aligned with Indonesia's abundant limonite resources, its execution entails significantly higher technological and investment barriers compared to the conventional pyrometallurgical pathway.

Consequently, this research investigates these economic-geological dynamics by comprehensively characterizing regional laterite deposits and formulating strategic implications to accelerate the shift from RKEF to HPAL technologies. This assessment is pivotal for securing the long-term sustainability of national reserves and optimizing economic value creation, aligning with the objectives of Indonesia's national downstreaming agenda.

METHODS

Research Approach

This research employs a descriptive-quantitative methodology grounded in an economic geology perspective. The framework is structured to assess the mass balance equilibrium between geological supply (regional deposit characteristics) and industrial demand (processing capacity). Central to this analysis is the quantification of reserve-life disparity resulting from the strict geometallurgical constraints of RKEF technology, relative to the heterogeneity of laterite ores across Sulawesi, Maluku, and Papua.

The aggregated data were then subjected to systematic analysis to identify underlying patterns, trends, and critical information gaps. This approach enables a comprehensive assessment of Indonesia's nickel potential and provides a foundation for formulating evidence-based strategic plans. Data validity was verified by cross-referencing information from multiple sources and comparing findings with published literature. The research workflow is illustrated in Figure 2.

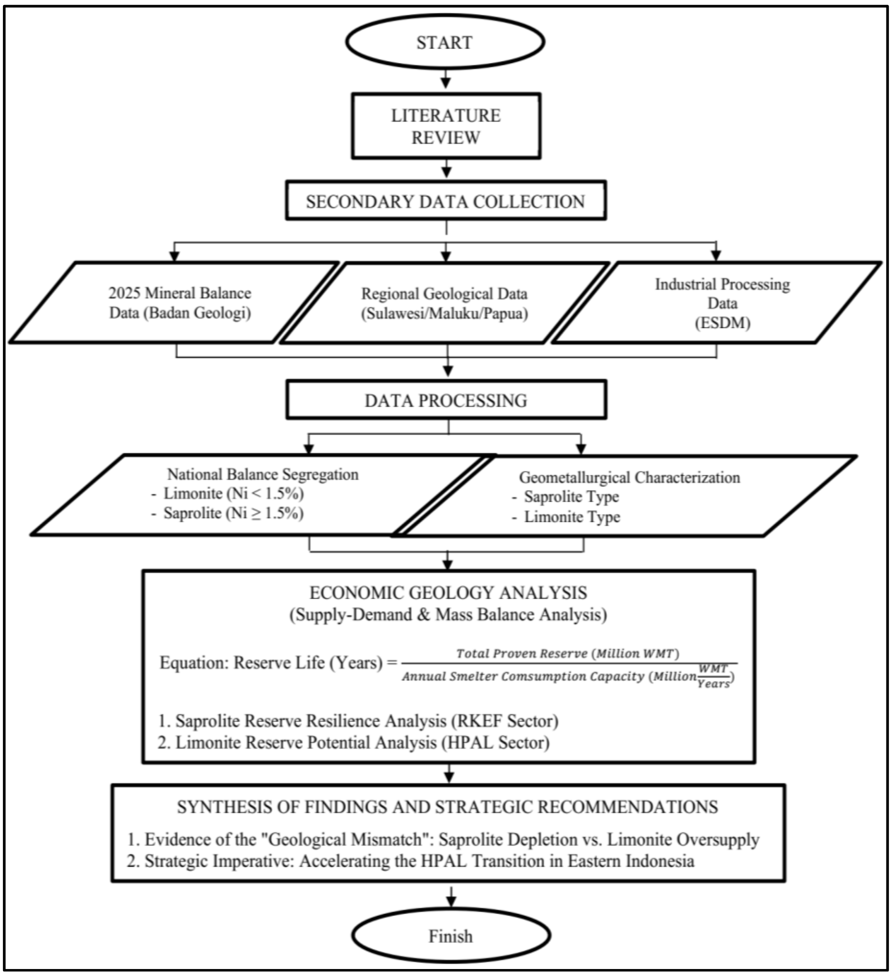


Figure 2. Flow Chart of Research Stages

Data Sources and Collection

This study integrates national quantitative data with qualitative data derived from regional geological case studies.

1. Macro Balance Data (Quantitative).

These data were sourced from:

a. The 2025 Mineral Resource and Reserve Balance (status as of December 2024), issued by the Geological Agency, to obtain tonnage data for limonite and saprolite ores.

b. The Grand Strategy for Minerals and Coal, for national policy targets.

2. Regional Characteristic Data (Qualitative/Case Studies).

Data regarding laterite profiles, mineralogy, and geochemistry were collected from technical reports of representative locations:

a. Sulawesi: Drill hole and geochemical assay data from North Kolaka, Morowali, and Palangga (South Konawe). These locations were selected to represent RKEF feedstock characteristics.
b. Maluku: Laterite profile data from Obi Island and Gebe Island, including REE potential. These locations were selected to represent HPAL feedstock potential.
c. Papua: Geological data from Gag Island and Kawei Island (Raja Ampat). Data from Kawei Island illustrate the vertical geochemical distribution, in which Ni, Fe, and Co grades show significant enrichment in the laterite zone relative to the bedrock. This location represents the eastern ophiolite deposit model, which is characterized by abundant associated minerals.

Data Analysis

The collected data were analyzed through three distinct stages.

Stage 1: Regional geometallurgical characterization.

This stage analyzes vertical deposit profiles from secondary regional data to determine the dominant ore typology in each region:

a. Type A (saprolite-dominant): Areas characterized by thick saprolite horizons and high Ni grades (e.g., Morowali, Kolaka).
b. Type B (limonite-dominant or multi-commodity): Areas characterized by thick limonite horizons or containing valuable associated minerals such as REE (e.g., Gebe, Obi, Kawei).

Stage 2: National balance segregation.

This stage segregates the total national nickel balance (Geological Agency 2025 Data) based on technological cut-off grades:

a. Limonite (Ni < 1.5%): Potential feedstock for HPAL.
b. Saprolite (Ni ≥ 1.5%): Potential feedstock for RKEF.

Stage 3: Reserve life and policy gap analysis.

This stage calculates reserve life by dividing the total proven reserves of each ore type by the national smelter consumption capacity (sourced from the Nickel Booklet). The results are then compared with the Grand Strategy for Minerals and Coal to demonstrate the urgency of shifting investment towards HPAL in Eastern Indonesia.

RESULTS AND DISCUSSION

RESULTS

1. Geological Potential of Indonesian Nickel Resources

Characteristics of Indonesian Nickel Laterite Deposits

Indonesian nickel laterites are typically hosted in ophiolite complexes emplaced during the Phanerozoic, specifically within the Cretaceous-Miocene timeframe. The fundamental source of these deposits is the weathering of ultramafic protoliths. In Indonesia, significant distributions of these ultramafic assemblages are found on the islands of Kalimantan, Sulawesi, Maluku, and Papua (Figure 3).

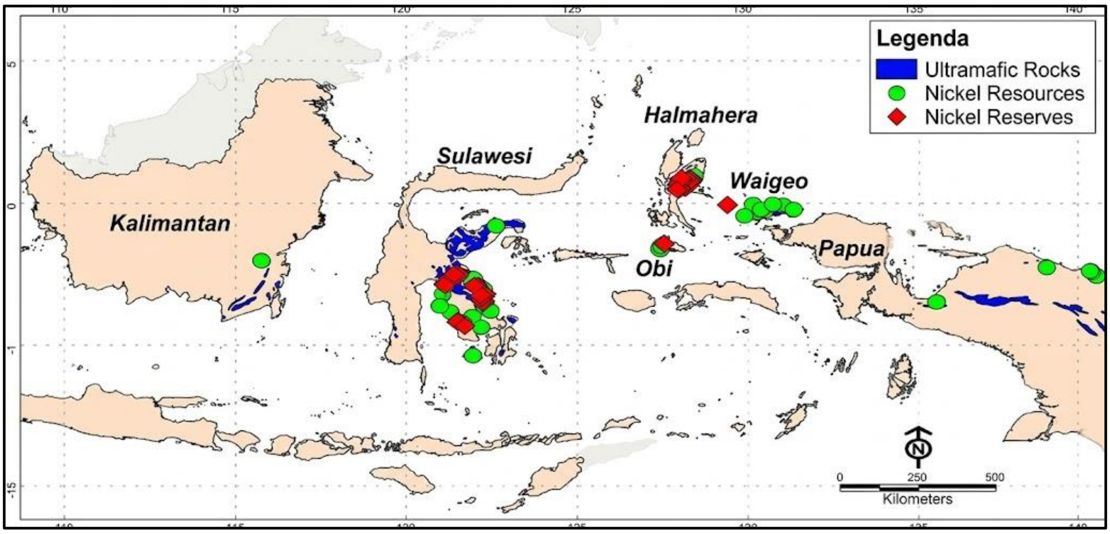
Hosting the world's largest nickel laterite deposits, Indonesia holds total resources of 17.7 billion tons of ore (177.8 million tons of metal) and accessible reserves of 5.2 billion tons of ore (57 million tons of metal) [6]. These deposits originate from the intensive chemical weathering of ultramafic protoliths, specifically peridotite and harzburgite, within a tropical environment with high precipitation [11]. The typical Indonesian laterite profile is stratified into three distinct horizons: the limonite zone (Ni < 1.5%), the saprolite zone (Ni 1.5–2.7%), and the bedrock. Mineralogically, the saprolite zone is dominated by nickel-bearing silicates such as serpentine, garnierite, and olivine, while the limonite zone is composed primarily of iron oxides like goethite and hematite.

This study characterizes laterite deposits across three key metallogenic provinces in eastern Indonesia: Sulawesi, Maluku, and Papua. Each region exhibits distinct geological settings and weathering intensities. Analysis of the regional data reveals significant variability in laterite profiles among these provinces, a factor with direct strategic implications for selecting appropriate processing technologies.

a. Sulawesi Region: Saprolite Dominance and Overburden Constraints

The Sulawesi ultramafic belt represents the backbone of Indonesia's pyrometallurgical nickel supply chain, primarily known for its extensive development of nickel-rich silicate (saprolite) horizons. However, given the continuous genetic process of lateritization, it would be geologically inaccurate to assume the absence of the upper oxide zone in this region. Empirical lithological profiles across major Sulawesi deposits confirm that the limonite horizon is consistently associated with the underlying saprolite. For instance, stratigraphic investigations in North Kolaka demonstrate a well-developed laterite profile consisting of a topsoil zone (approximately 2 m), a significant limonite zone (approximately 6 m), and an underlying saprolite zone (approximately 11 m) [13]

.



Source: Pardianto et al., 2013; Arif, 2022 [12]

Figure 3. Distribution of Ultramafic Rocks and Nickel Laterite Deposits In Indonesia

Similarly, well-defined weathering profiles derived from harzburgite bedrocks are well documented in the Palangga area of Southeast Sulawesi, exhibiting a continuous geochemical transition from iron-rich limonite caps to magnesium-nickel silicates [14], a trend further supported by continuous profiling within the lateritic frameworks of North Morowali [15].

The critical issue in the Sulawesi region is not the geological absence of limonite, but rather its industrial classification as a major "overburden constraint" within the current pyrometallurgical paradigm. Because conventional RKEF smelters strictly demand high-grade saprolite ore (Ni ≥ 1.5%), the overlying millions of tons of limonite must be physically stripped away and stored as non-economic waste, creating substantial environmental liabilities and mining inefficiencies. Furthermore, this overburden constraint is exacerbated by the island's unique structural settings. Geological mapping in Tinanggea, Southeast Sulawesi, reveals that certain laterite profiles are unconformably buried beneath post-orogenic sedimentary covers, specifically the Early Miocene Celebes Molasse [16]. The preservation of laterite under such thick molasse sediments imposes dual structural and lithological overburden constraints [16]. Therefore, accelerating the transition to HPAL technology in Sulawesi is highly urgent, not only to utilize the massive limonite layers that are currently discarded as mining waste, but also to optimize project economics when dealing with deep-seated or heavily concealed laterite resources.

b. Maluku Region: Limonite Endowment and Co-products

The North Maluku archipelago exhibits significant intra-regional geometallurgical heterogeneity, challenging simplistic regional assumptions. While the laterite profiles are recognized as hubs of hydrometallurgical potential, they vary considerably due to local geomorphological and erosional controls. For instance, investigations on Obi Island demonstrate an eroded profile heavily skewed toward the lower horizon; the limonite zone is relatively thin (1–5 m) due to intense surficial erosion, while the underlying saprolite zone reaches an exceptional thickness of up to 16 m derived from dunite weathering [17].

Conversely, neighboring Gebe Island preserves a fully developed laterization profile. At the base, it hosts a high-grade saprolite zone in which the presence of garnierite significantly enhances nickel concentrations in finer-grained fractions [18]. Above this framework, Gebe retains prominent, well-preserved red and yellow limonite caps. Geochemical scanning of these limonite layers detects a comprehensive spectrum of REE, including Light REE (LREE) such as La, Ce, Pr, Nd, Sm, and Eu, alongside heavy REE (HREE) like Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu [19].

While these general REEs serve as critical geochemical tracers for advanced lateritization stages, they typically do not achieve standalone economic cut-off grades in these settings [19]. Instead, the primary economic value in these thick eastern limonite horizons lies in enrichment in Cobalt (Co) and Scandium (Sc), with Sc showing a robust correlation with alumina (Al_2O_3) minerals [19]. This highlights the critical structural mismatch: current operations often bypass or discard these thick, Sc-enriched limonite caps to access the saprolite below. Transitioning to HPAL technology is imperative to unlock the full economic and multi-commodity potential of these fully preserved laterite profiles.

c. Papua Region: The Strategic Eastern Ophiolite Profile

The eastern frontier of Indonesia's nickel endowment, located within the classic ophiolite terranes of the West Papua and Southwest Papua archipelagoes (such as Gag and Kawei Islands), represents a strategically critical geometallurgical domain. Geologically, these deposits are hosted within structurally complex ophiolite suites composed predominantly of ultramafic rocks, including harzburgite, serpentinite, and pyroxenite [20]. Driven by intense tropical chemical weathering, these ultramafic complexes undergo profound supergene alteration, leading to the development of deeply developed and exceptionally well-preserved laterite profiles [20]. Stratigraphic and geochemical mapping on Kawei Island demonstrates that these fully preserved profiles can reach vertical thicknesses of up to 16 m, displaying a continuous and systematic geochemical transition from the baseline bedrock up to the surficial horizons [21]. Advanced X-ray Fluorescence (XRF) profiling in this region reveals a sharp elemental segregation: elements with low vertical mobility, such as Ni, Fe, Co, MnO, and Al_2O_3, undergo intense residual accumulation within the upper limonite cap, while highly mobile constituents like MgO and SiO_2 are thoroughly depleted upward and enriched downward within the underlying silicate framework [21].

This distinct preservation of the complete weathering profile provides the Papua region with a powerful dual-ore advantage, making it a highly relevant case study for optimizing the transition from RKEF to HPAL technology. Rather than hosting an isolated single-ore type, islands like Gag showcase a modern crossroads of concurrent metallurgical processes: the upper, iron-rich limonite zones are dynamically extracted to supply HPAL plants for the EV battery sector, while the deeper, magnesium-rich saprolite zones continue to feed traditional RKEF operations for ferronickel (FeNi) manufacturing [22].
However, the strategic imbalance identified in this study remains prevalent. Despite the proven multi-commodity potential of these eastern profiles, historical mining infrastructures remain disproportionately focused on pyrometallurgical processing. Expanding hydrometallurgical infrastructure in the Papua region is imperative; it enables the simultaneous vertical co-extraction of saprolite and the massive, Co-Sc-enriched limonite overburden within a single, highly efficient mining footprint, thereby preventing valuable oxide reserves from being permanently sterilized as non-economic waste.

While this study highlights specific regions based on their dominant economic potential and technological suitability, such as Sulawesi for RKEF and Maluku/Papua for HPAL, it is critical to emphasize that saprolite and limonite horizons are genetically associated and coexist across all these terrains as products of continuous ultramafic weathering. As detailed in Table 1, the regional distinctions lie in the volumetric proportions and preservation of these horizons rather than their exclusive presence. For instance, while Sulawesi is renowned for its saprolite, it still contains a limonite zone (0–6 m thick), though it is often discontinuous or eroded. Conversely, while Maluku and Papua are prioritized in this study for their exceptionally thick, HPAL-ready limonite caps (enriched with Co, Sc, and a broader distribution of REE), they simultaneously host massive saprolite resources. Obi Island in Maluku, for example, exhibits exceptionally thick saprolite horizons reaching up to 16 m, and Kawei Island in Papua retains a high-grade saprolite base (1.5%–2.8% Ni) beneath its thick limonite overburden. Therefore, the regional mismatch addressed in this study pertains to the industrial overexploitation of the saprolite fraction and the underutilization of the massive limonite inventory, rather than a geological absence of either horizon.

Table 1. Comparative characteristics of nickel laterite deposits in Sulawesi, Maluku, and Papua.

Geological parameters	Sulawesi (Kolaka, Konawe, Morowali)	Maluku (Obi Island, Gebe Island)	Papua (Gag Island, Kawei Island)
Bedrock	Dominated by harzburgite and lherzolite peridotites.	Weakly to strongly serpentinized dunite and harzburgite.	Jurassic ophiolite complex, dominated by harzburgite and dunite.
Overburden characteristics	Unique feature: In certain areas (e.g., Tinanggea, Palangga), the laterite profile is unconformably overlain by Molasse sediments and limestone cover.	Generally standard organic topsoil.	Organic-rich overburden containing iron oxide nodules.
Limonite zone	- Thickness: 0–6 m (Variable). - Mineralogy: Rich in goethite and hematite.	- Thickness: 1–5 m. - Geochemistry: Rich in Iron (Fe) and Alumina (Al_2O_3). - Zonation: Differentiated into	- Thickness: Very thick (up to 7 m). - Geochemistry: High Iron content (Fe>30-50%) and

Geological parameters	Sulawesi (Kolaka, Konawe, Morowali)	Maluku (Obi Island, Gebe Island)	Papua (Gag Island, Kawei Island)
	- Distribution: Discontinuous; locally absent due to erosion or lack of development.	Red limonite ($Fe > 70\%$) and yellow limonite.	low Magnesium (MgO).
Saprolite zone (Ore)	- Ni Grade: 1.4% – 3.4% (High Grade). - Key minerals: Rich in garnierite and chrysoprase. - Topographic Control: Well-developed on steep slopes (gradient of approx. 29.4%).	- Thickness: Exceptionally thick (up to 16 m on Obi Island). - Enrichment: Strong supergene enrichment concentrated in the fine fraction (<1 cm). - Grade Potential: Nickel grades in fines can exceed 4%.	- Ni Grade: ~1.5% – 2.8%. - Texture: Relict rock textures are distinctly preserved. - Mineralogy: Abundant garnierite occurring as fracture fillings.
Potential of associated elements	Cobalt (Co) exhibits an inverse relationship with Nickel (Ni).	High Potential: Indications of Scandium (Sc) associated with Fe- and Al-bearing minerals.	Cobalt (Co) is associated with the limonite zone, making it suitable for hydrometallurgical extraction.
Technological implications	Predominant feedstock for RKEF facilities (High-Grade Saprolite).	- RKEF: Viable due to thick saprolite horizons. - HPAL: Highly prospective due to thick limonite overburden and associated REE/Sc enrichment.	- Limonite: Designated for HPAL (Battery Precursors). - Saprolite: Designated for RKEF (Ferronickel/FeNi).

As synthesized in Table 1 Indonesia's nickel endowment is defined by distinct geological heterogeneity. The Maluku and Papua regions display intensive weathering profiles marked by substantial limonite thickness and high-potential co-products (Scandium & REE). These findings confirm that a monolithic national downstreaming strategy focused exclusively on pyrometallurgy (RKEF) is geologically inadequate. It is therefore strategically imperative to prioritize HPAL deployment in Maluku and Papua to valorize the limonite and associated critical minerals, transforming materials currently discarded as overburden into strategic assets.

Indonesian Nickel Resources and Reserves Balance

As of 2024, Indonesia's total nickel ore resources stand at 19.16 billion tons, with proven reserves totaling 5.9 billion tons. In terms of contained metal, these reserves equate to 62 million tons of nickel metal [5]. Meanwhile, national nickel ore production, as of December 2024, reached 173.6 million tons [5].

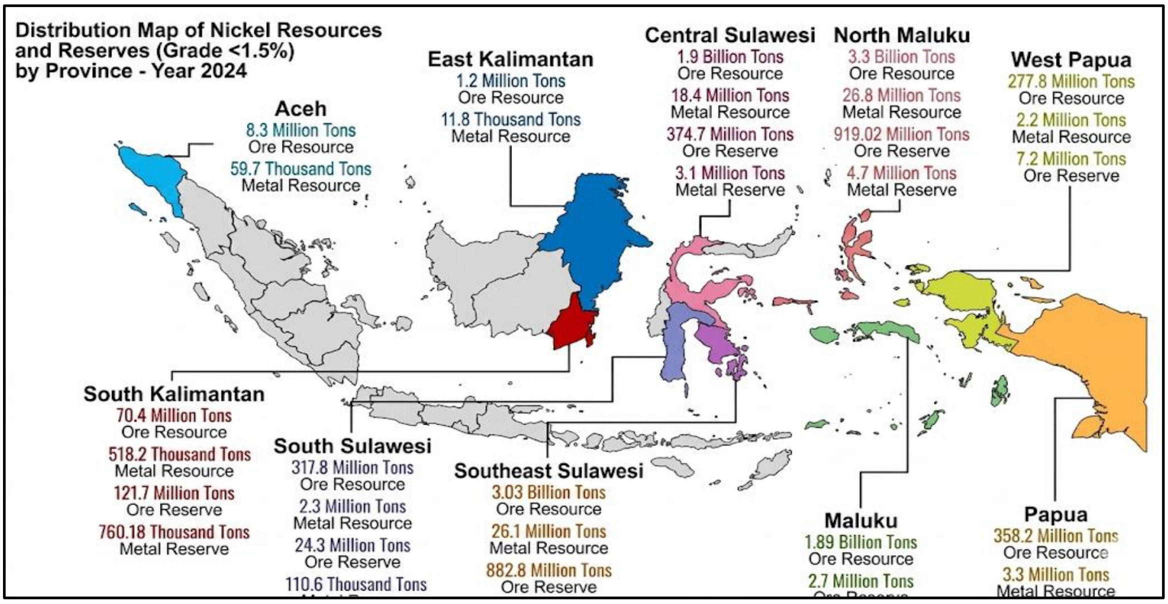
The recapitulation of resources and reserves by province shows that the highest concentrations are in three key provinces: Southeast Sulawesi, North Maluku, and Central Sulawesi. Based on the updated resource and reserve balance data (status: December 2024), the nickel grades reported by mining entities vary significantly, ranging from 0.5% to 2.73% Ni [5]. The spatial distribution of resources and reserves, segregated by grade classification, limonite ($Ni < 1.5\%$) and saprolite ($Ni \geq 1.5\%$), across Indonesian provinces is presented in Figure 4 and Figure 5.

Referring to the updated data from the 2025 Mineral Resource and Reserve Balance (status as of December 2024), Indonesia's total nickel ore resources amount to 19.16 billion tons [5]. The tonnage distribution, classified by ore typology, is presented in Table 2. Table 2 indicates a notable disparity: despite limonite representing 58% of the total resource endowment, the current proven reserve inventory remains skewed towards saprolite, which totals 3.58 billion tons [5].

Table 2. Indonesian nickel balance by ore typology

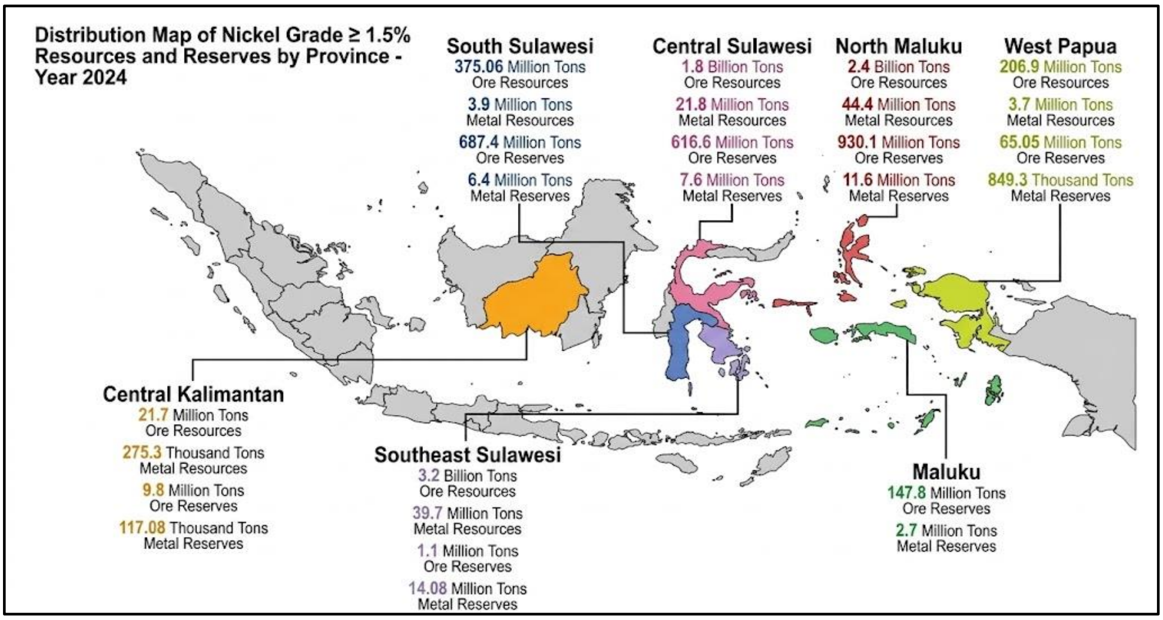
Ore Typology	Cut-Off Grade (Ni)	Total Resources (million WMT)	Total Reserve (million WMT)	Percentage of Resources (%)
Limonite	< 1.5%	**11.12**	2.33	**58%**
Saprolite	≥1.5%	8.04	**3.58**	42%

Source: Data processed from Badan Geologi, 2025



Source:. Badan Geologi, 2025 [5]

Figure 4. Provincial distribution of low-grade nickel resources and reserves (Limonite, Ni <1.5%) in 2024.



Source: Badan Geologi, 2025 [5]

Figure 5. Provincial distribution of high-grade nickel resources and reserves (Saprolite, Ni >1.5%) in 2024.

1. Development of the Nickel Downstreaming Industry

Implementation of the Export Ban Policy

The raw nickel ore export ban, effective as of January 2020, accelerated the timeline originally set for 2022 [9]. The primary objective of this policy was to compel investors to establish domestic refining facilities, thereby shifting the value chain from raw material export to the production of higher-value-added semi-finished and finished goods [23].

The impact of this policy on the transformation of the Indonesian nickel industry has been profound. Before the ban, Indonesia exported approximately 64 million metric tons of nickel ore annually. Post-implementation, exports plummeted to near-zero levels, with the supply redirected to meet domestic smelter demand. Consequently, the policy successfully attracted over US$30 billion in investment, predominantly from Chinese entities, for the construction of smelters [9], [23].

Smelter Capacity Expansion

The number of nickel smelters in Indonesia has grown rapidly, surging from only two facilities in 2014 to over 44 by 2024. With an additional 19 projects under construction and 7 facilities in the feasibility study stage, the national total is projected to reach 70 nickel processing plants [23].

Of the 44 operational smelters, 40 (91%) utilize RKEF technology to process high-grade saprolite ore into Nickel Pig Iron (NPI) and stainless steel. In stark contrast, only 4 (9%) facilities employ HPAL technology to process low-grade limonite into mixed hydroxide precipitate (MHP) for EV batteries [4], [24].

2. Nickel Processing Technologies

Pyrometallurgy: Rotary Kiln Electric Furnace (RKEF)

RKEF technology has emerged as the predominant choice for nickel processing in Indonesia due to its compatibility with the specific characteristics of the available laterite ore profile. The RKEF process entails a multi-stage thermal treatment: drying the ore at 200-300°C, calcination/reduction at 700-750°C, and final smelting in an electric furnace at temperatures up to 1,600°C [24].

The primary advantages of RKEF include relatively lower capital expenditure (CAPEX), operational simplicity manageable by the domestic workforce, and high suitability for Indonesian saprolite ore. However, the major drawback lies in its high carbon intensity, despite the implementation of waste heat recovery systems, and the production of an intermediate product (NPI) that requires further refinement for high-end applications [24].

Hydrometallurgy: High Pressure Acid Leaching (HPAL)

HPAL technology utilizes a high-pressure acid leaching process to extract nickel and cobalt from low-grade limonite ore [25]. This process involves heating the laterite slurry to elevated temperatures under pressures of 4-5 MPa, with the addition of sulfuric acid within an autoclave reactor [24].

HPAL yields intermediate products such as MHP and final products including nickel sulfate and cobalt sulfate, which serve as direct precursors for EV battery cathodes. This technology boasts high nickel-cobalt recovery rates and effectively valorizes low-grade ores previously classified as overburden [24], [25].

PT Halmahera Persada Lygend (HPL) pioneered the application of HPAL technology in Indonesia by commencing nickel sulfate production in March 2023, establishing Indonesia as the region’s first producer of EV battery raw materials [26]. To provide a comprehensive overview of the technological dichotomy within Indonesia's nickel sector, a comparative analysis is summarized in Table 3. This table delineates the fundamental differences in feedstock requirements, operational parameters, and end-product specifications between the established pyrometallurgical (RKEF) route and the emerging hydrometallurgical (HPAL) route. These technical distinctions are the primary drivers of the geological-industrial mismatch discussed in this study.

Table 3. Technical comparison of RKEF vs. HPAL technologies

Parameters	Pyrometallurgy (RKEF)	Hydrometallurgy (HPAL)
Feedstock	High-Grade Saprolite (Ni ≥ 1.5%)	Low-Grade Limonite (Ni < 1.5%)
Process Condition	High Temp (1,600°C), Atmospheric P	Medium Temp (250°C), High Pressure
Key Reagent	Coal / Electricity (Reductant)	Sulfuric Acid (Leaching Agent)
Primary Output	NPI / FeNi (Stainless Steel)	MHP / Sulfate (Battery)
Co-Product	None (Co lost in slag/alloy)	Cobalt & Sc Recovery
Carbon Footprint	High	Low – Medium
Status	Dominant (40+ Smelters)	Emerging (Pioneer: PT HPL)

3. Electric Vehicle (EV) Ecosystem Development Strategy

Value Chain Integration Plan

The Government of Indonesia has formulated a comprehensive strategy to establish a fully integrated EV ecosystem, spanning from upstream extraction to downstream manufacturing. This strategy entails integrating diverse mineral assets distributed across the archipelago: nickel in Sulawesi and North Maluku, copper in Papua and Sumbawa, bauxite in West Kalimantan and the Riau Islands, and tin in the Bangka Belitung Islands [4].

The government aims to develop the battery-based electric motor vehicle industry, targeting production of 400,000 units by 2025 and 1 million units by 2035 [23]. To sustain these ambitious targets, Indonesia requires a domestic battery production capacity of up to 140 GWh by 2030 [4,23].

Investment in the Battery Industry

Despite possessing abundant nickel feedstocks, domestic battery production capacity remains significantly constrained, estimated at merely 10 GWh in 2024, representing less than 0.4% of the global capacity of 2,800 GWh (Bloomberg, 2024).

This figure highlights a substantial disparity between upstream nickel production, which has increased eightfold since 2015, and the lagging development of the midstream battery manufacturing sector [23].

Several major projects are under construction to bridge this gap, including battery facilities in Karawang and Morowali, which are projected to increase national MHP capacity by 120,000 metric tons per annum. Furthermore, incoming investments from global automotive entities such as BYD and VinFast are expected to bolster the Indonesian EV ecosystem further and accelerate its integration into the global clean energy supply chain [3].

DISCUSSION

This section evaluates the implications of the study's data on the long-term sustainability of the national nickel sector, with a particular focus on technological suitability and reserve security.

Analysis of Geometallurgical Mismatch

The regional characterization reveals a critical technical dichotomy that fundamentally conflicts with the prevailing industrial structure. The need to shift from RKEF to HPAL technology is strongly supported by recent geometallurgical evaluations across Indonesia's ultramafic belts.

a. Pyrometallurgical Constraints (RKEF)

RKEF operations are mandated by the need for high-grade saprolite with specific basicity ratios (MgO/SiO_2). However, relying exclusively on this pyrometallurgical paradigm inherently treats the overlying limonite horizon as uneconomic overburden. This practice contradicts the continuous genetic nature of laterite profiles, which are universally observed. For instance, well-preserved saprolite-limonite transitions in North Kolaka [13] and North Morowali [15] demonstrate that limonite is geologically ubiquitous. Furthermore, accessing the required saprolite often involves significant stripping costs. Geological constraints in areas such as Tinanggea and Palangga, where thick Celebes Molasse sediments unconformably overlie laterite profiles, demonstrate that mining saprolite poses severe structural and lithological overburden challenges [14], [16]. Moreover, the thick limonite profiles dominant in Maluku and Papua are processed with high inefficiency by RKEF; the excessive iron content (Fe >40%) results in unmanageable slag volumes and thermal inefficiency.

b. Hydrometallurgical Opportunities (HPAL)

In contrast, the elevated cobalt (Co) content and associations with scandium (Sc) in the Maluku and Papua limonite horizons are favorable for HPAL applications. Previous studies consistently highlight that these eastern limonite caps are not mere waste but rather critical multi-commodity reservoirs. Geochemical profiling on Gebe Island confirms substantial enrichment of Co and Sc alongside a broad spectrum of other REE within the red and yellow limonite zones [19]. Crucially, HPAL enables the valorization of these co-product resources that are historically discarded in conventional "saprolite-centric" mining operations. As demonstrated by the operational dynamics on Gag Island, where limonite is extracted for battery-grade HPAL processing while the underlying saprolite feeds RKEF operations [20], [22], maximizing the complete vertical profile of the laterite deposit is the only sustainable pathway. Therefore, deploying HPAL is not merely a technological upgrade but a strategic necessity to optimize the extraction of multi-commodity critical minerals from the massive eastern limonite inventory [21].

Reserve Life Analysis and Sustainability Projection

a. National Ore Consumption Trends (2024)

Estimates for Indonesia's 2024 nickel ore consumption indicate a significant surge, reaching hundreds of millions of tons. According to industry tracking and parliamentary economic reports, domestic ore consumption has followed an aggressive trajectory: rising from approximately 65 million tons in 2021 to 101 million tons in 2022, nearly 200 million tons in 2023, and projected to reach approximately 265 million tons in 2024 [23]. It is critical to note that these figures represent the aggregate consumption of nickel ore (laterite) and do not include official differentiation between saprolite and limonite fractions.

Corroborating this trend, the 2024 Work Plan and Budget (RKAB) approved a nickel ore production quota of approximately 272 million wet metric tons (wmt), aligning closely with the smelter demand projections [23]. While some reports suggest demand could approach 300 million tons, these figures refer to total ore volume, not exclusively saprolite.

b. Saprolite-Specific Consumption and Reserve Life

Technical documents and academic studies underscore that the vast majority of pyrometallurgical smelters (RKEF and blast furnace) in Indonesia rely exclusively on high-grade saprolite (>1.5–1.7% Ni). Capacity-based scenario analyses suggest that if all existing and planned RKEF capacities operate at full utilization, saprolite demand could surge to a maximum scenario of 450 million tons per annum [4]. While this 450-million-ton figure represents a medium-term capacity scenario rather than a confirmed 2024 realization, it serves as a critical stress-test metric for sustainability. Official government data typically publishes aggregate ore figures, necessitating the derivation of saprolite estimates from the operating smelter composition [4].

The Reserve-Resource Anomaly: Referring to Table 2, a significant anomaly is observed: Proven Saprolite Reserves (3.58 billion tons) are recorded as higher than Limonite Reserves (2.33 billion tons), despite the geological resource reality being the inverse, where limonite comprises 58% of the total resource endowment [5]. This discrepancy indicates a historical exploration bias targeting saprolite to feed the RKEF boom [5].

Reserve Life Calculation: By integrating the industrial consumption data (Nickel Booklet) with the massive proliferation of RKEF smelters, the critical reserve life can be estimated. Assuming a "maximum capacity scenario" where national saprolite consumption reaches 450 million tons/year, the resilience of saprolite reserves is calculated as follows:

$$\text{Reserve Life Saprolite} = \frac{\text{Total Proven Saprolite Reserves}}{\text{Annual Saprolite Consumption Rate}} \qquad (1)$$

$$= \frac{3.58 \text{ Million Tons}}{0.45 \text{ Million Tons/Years}}$$

$$= 7.96 \text{ Years}$$

This calculation demonstrates that Indonesia’s Tier-1 (high-grade) reserves have entered a critical phase of depletion, reflecting global mining mega-trends where accelerated high-grade extraction intensifies resource depletion and strains long-term mineral sustainability [1]. In stark contrast, the substantial limonite inventory of 11.12 billion tons guarantees long-term supply security (>20 years) only if the industrial sector pivots effectively toward hydrometallurgical technologies capable of processing this material [5].

Strategic Policy Implications

The empirical evidence confirms that the prevailing RKEF industrial dominance is geologically incongruent with the national resource endowment. The monolithic downstream focus on stainless steel (NPI/FeNi) has led to the rapid depletion of Indonesia's limited saprolite assets [5,23].

To realize the vision of the Grand Strategy for Mineral and Coal Commodities, which envisions Indonesia as a global EV battery hub, a pivot toward HPAL technology in the eastern region (Maluku & Papua) is the most viable solution [4].

This transition delivers a twofold strategic advantage: (1) resource conservation, achieved by mitigating the depletion rate of saprolite and valorising the massive limonite overburden [1,23]; and (2) economic maximization, realized through the production of battery-grade precursors (MHP/Sulfate) and the recovery of critical by-products (Co, Sc, and REE) detected in the Gebe and Kawei deposits [19,21].

Sustainability Challenges in the National Nickel Sector

Indonesia’s nickel sector is positioned at a crossroads between economic maximization and sustainability imperatives. While the nation commands a global competitive edge through its massive reserves, the current industrial model reveals a critical imbalance between immediate economic gains and long-term viability. Despite the economic success of the downstreaming policy, it has inadvertently introduced significant geological and environmental fragilities.

a. Resource Security and Conservation

As evidenced by the reserve life analysis, the sector’s structural dependence on saprolite has triggered a critical depletion phase for high-grade ores, with a projected timeline of less than eight years. If the massive RKEF extraction rate continues without regulation, Indonesia faces the imminent risk of losing its global dominance within a decade, thereby depleting its strategic assets and leaving it with only marginal, low-grade resources. From an economic geology perspective, this aggressive exploitation reflects broader global mining mega-trends, in which accelerated high-grade extraction intensifies resource depletion and poses looming constraints on long-term mineral sustainability [1]. Consequently, maximizing the strategic potential of the nation's remaining reserve inventory demands urgent production controls and strictly regulated extraction quotas to safeguard domestic resource resilience [23].

b. Environmental Footprint

The prevalence of RKEF technology, underpinned by coal-fired captive power plants, contributes to a highly carbon-intensive profile of Indonesian nickel and simultaneously imposes severe socio-economic and public health burdens on local communities across the primary processing hubs in Sulawesi and Maluku [24,27].

However, it is imperative to acknowledge that the transition to HPAL is not without ecological risks. Recent environmental evaluations caution that the rapid expansion of HPAL facilities and their associated limonite mining operations, particularly within sensitive small-island ecosystems, pose formidable challenges, including deforestation, potential biodiversity loss, and complex tailings management [26]. Therefore, protecting these fragile tropical frontiers necessitates stringent, globally standardized environmental governance and human rights compliance as essential prerequisites for processing expansions [24,26,27].

Technological Transition and Innovation Frontiers

The advancement of HPAL in Indonesia represents a paradigm shift, specifically engineered to process low-grade laterites (limonite with Ni < 1.5%) that are fundamentally incompatible with conventional smelting, transforming them from waste into strategic assets [25]. PT HPL's pioneering success in sulfate production has paved the way for a domestic EV battery ecosystem. However, continuous R&D investment is critical to optimizing efficiency and minimizing ecological impact, particularly regarding complex tailings management and the protection of biodiversity in fragile small-island ecosystems [26].

The central challenge is balancing the economic competitiveness of RKEF with the environmental imperatives of HPAL [24]. Novel technologies like the DNi Process, capable of treating the full laterite profile, offer a potential breakthrough. Solving the sustainability equation relies on accelerating the pivot from pyrometallurgy to hydrometallurgy and embracing such processing innovations [24].

a. The Geometallurgical Imperative: Transitioning to HPAL is mandatory, not optional. With limonite comprising 58% of national resources (Badan Geologi, 2025), HPAL is the only mechanism to unlock this value. Strategically positioning HPAL in the East (Obi/Papua) effectively converts the "overburden" of yesterday into the "feedstock" of tomorrow.
b. Critical Mineral Recovery: Exploration in Gebe and Kawei reveals a limonite-Co-Sc-REE association [19], [21]. Advanced extraction technologies must be deployed to capture these elements as high-value by-products, thereby securing Indonesia's position as a multi-commodity critical-mineral hub.

Global Value Chain Integration

Indonesia's current position within the global EV value chain remains largely confined to the upstream (mining) and midstream (primary processing) segments. To realize its ambition of becoming a global hub for the battery industry, Indonesia must cultivate robust downstream capabilities. This entails mastering battery cell manufacturing technologies, developing battery management systems (BMS), and fostering seamless integration with the automotive manufacturing sector.

Strategic collaboration with developed nations, focusing on technology transfer and human capital development, is the linchpin of this transition. Partnerships, such as the collaboration with the United States under the Net Zero World initiative, exemplify the correct trajectory for establishing a clean and resilient supply chain.

Indonesia is actively endeavoring to reposition its role within the global supply architecture, shifting from a mere supplier for the steel industry to the "center of gravity" for the EV ecosystem.

a. The Shift to Class I Products: The current export dominance of Class II products (NPI/FeNi) exposes Indonesia to the volatility of the stainless-steel market. Successful integration into the high-value global chain demands a pivot toward Class I Nickel production (MHP, Nickel Sulfate), the essential precursors for battery cathodes. This strategic shift explicitly aligns with the government's downstream roadmap and investment targets, which prioritize the domestic establishment of an integrated EV battery industry [4].
b. Strategic Partnerships and Leverage: Indonesia's bargaining position, underpinned by the world's largest nickel resources of 19.16 billion tons [5], provides powerful leverage to attract high-technology investment rather than merely basic refining facilities. Collaboration with global players (such as EV OEMs and battery manufacturers) is required to ensure technology transfer and market access. Consequently, Indonesian nickel must evolve from being exported as a semi-finished commodity to serving as a vital component powering the global green transportation revolution.

CONCLUSION AND SUGGESTION

This research identifies critical dynamics within Indonesian nickel economic geology that demand a fundamental reorientation of the national downstreaming strategy. Based on the comprehensive analysis of regional deposit characteristics and the latest resource balance, the following conclusions are drawn:

1. Geological vs. industrial balance disparity: Indonesia holds a dominant global position with total nickel resources amounting to 19.16 billion tons. However, a fundamental mismatch exists between the geological profile and the industrial structure. Geologically, 58% of the national nickel wealth consists of limonite, whereas the current downstream industrial structure is heavily dominated by pyrometallurgy (RKEF), which is strictly dependent on saprolite.
2. Saprolite reserve crisis: The massive dominance of RKEF smelters has resulted in asymmetrical exploitation. Reserve life analysis indicates that saprolite reserves are at risk of depletion within eight years if current consumption rates persist without significant production controls or a strategic shift toward limonite processing. Conversely, limonite reserves remain abundant and largely underutilized.
3. Specific Regional Potential: Geometallurgical characterization demonstrates that the future trajectory of the Indonesian nickel industry lies in the eastern region. Deposits in Maluku (Obi/Gebe) and Papua (Gag/Kawei) exhibit laterite profiles with substantial limonite thickness and enrichment of high-value associated elements, specifically cobalt, scandium, and a

comprehensive spectrum of REE. These characteristics constitute the ideal feedstock parameters for hydrometallurgy (HPAL) technology, acting as a gateway to the Class I EV battery ecosystem.

Strategic Recommendations

Aligning with the *Grand Strategy for Mineral Commodities* and the geological findings presented above, this study proposes the following strategic measures:

1. Acceleration of the HPAL transition: The government must provide priority fiscal incentives for HPAL investments, particularly in Maluku and Papua. This is essential to valorize the abundant limonite reserves and alleviate the intense extraction pressure currently placed on the dwindling saprolite reserves in Sulawesi.
2. Moratorium on new RKEF facilities: It is imperative to consider a moratorium or strict limitation on the construction of new standalone RKEF smelters (facilities without integrated mining concessions). This measure is vital to safeguard saprolite reserve resilience for long-term strategic industrial requirements.
3. Conservation of associated minerals: The government should mandate comprehensive feasibility studies for the recovery of associated minerals (specifically Co, Sc, and REE) in all new HPAL projects. This policy aims to maximize value creation from the limonite zone, transforming material historically treated as overburden into strategic multi-commodity assets.
4. Implementation of stringent ESG frameworks: The transition to HPAL must be strictly governed by globally standardized ESG compliance. The government must enforce rigorous regulations on advanced tailings management and biodiversity protection, particularly to safeguard the fragile ecological balance of small-island environments where new hydrometallurgical hubs are expanding.

AUTHOR CONTRIBUTIONS

Author 1 contributed to the conceptualization, methodology, data collection, data processing, formal analysis, and writing of the original manuscript draft. Author 2 and Author 3 contributed to data validation, critical review and editing, and overall supervision. All authors have read and approved the final published version of the manuscript.

ACKNOWLEDGEMENT

The authors wish to express their gratitude to the Master of Mining Engineering Program at Universitas Pembangunan Nasional (UPN) "Veteran" Yogyakarta. Deep appreciation is extended to Prof. Dr. rer. nat. Ir. Arifudin Idrus, ST., MT., IPU., for his invaluable knowledge, motivation, and guidance. Finally, heartfelt thanks are extended to peers and colleagues for their moral and substantive support in bringing this manuscript to completion.

REFERENCES

[1] G. M. Mudd, "The Environmental sustainability of mining in Australia: key mega-trends and looming constraints," *Resources Policy*, vol. 35, no. 2, pp. 98–115, Jun. 2010, https://doi.org/10.1016/j.resourpol.2009.12.001.

[2] International Energy Agency, "The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions," Paris, 2021. [Online]. Available: www.iea.org/t&c/

[3] Bloomberg Intelligence, "Global Battery Electric Vehicle Outlook," 2024. Accessed: May 18, 2026. [Online]. Available: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://about.bnef.com/insights/clean-transport/electric-vehicle-outlook/&ved=2ahUKEwjEqMPch8KUAxXF1zgGHUAbGlQQFnoECBsQAQ&usg=AOvVaw2Etid70pZL0UoTeidGSYfy

[4] Kementerian Energi dan Sumber Daya Mineral, "Peluang Investasi Nikel Indonesia," Jakarta, 2020. Accessed: May 17, 2026. [Online]. Available: https://www. esdm.go.id/assets/booklet/tambang-2020/ Booklet-Nikel-FA.pdf

[5] Badan Geologi, "Neraca Sumber Daya dan Cadangan Mineral, Batubara dan Panas Bumi Indonesia Tahun 2025," Bandung, Jun. 2025. Accessed: May 17, 2026. [Online]. Available: https://geologi.esdm.go.id/storage/publikasi/KuRaTy8WEQyvo5KguWTchyJfBES8r6ZXs6rHLuYh.pdf

[6] "Indonesia's nickel reserves may end in 4 to 5 years," Accessed: May 18, 2026. [Online]. Available: https://indonesiabusinesspost.com/2939/business-and-investment/indonesias-nickel-reserves-may-end-in-4-to-5-years

[7] Elias, Mick. (2002). "Nickel laterite deposits-geological overview, resources and exploitation". *Giant ore deposits: Characteristics, genesis, and exploration. CODES Special Publication*, *4*, 205-220. https://www.researchgate.net/publication/281422746_Nickel_laterite_deposits_-_geological_overview_resources_and_exploitation

[8] U. Geological Survey, "Mineral Commodity Summaries 2025," Reston, Mar. 2025. Accessed: May 17, 2026. [Online]. Available: https://pubs.usgs.gov/periodicals/mcs2025/mcs2025.pdf

[9] The World Bank, "Indonesia Economic Prospect: The Long Road to Recovery," Jun. 2020. [Online]. Available: www.worldbank.org/id

[10] Olivia Da Silva, “Indonesia Moves Forward on 2020 Nickel Ore Export Ban,” https://investingnews.com/daily/resource-investing/base-metals-investing/nickel-investing/indonesia-moves-forward-nickel-ore-export-ban/.

[11] B. K. Prasongko, A. Harjanto, and M. G. Askaria, “Geology And The Correlation Between Geological Control and Nickel Quality in GAG Island, Raja Ampat Islands, West Papua,” *Journal Techno*, vol. 8, no. 2, pp. 167–188, Jan. 2022, doi: https://doi.org/10.31315/journal%20techno.v8i2.8218.

[12] Irwandy Arif, *Nikel Indonesia Menuju Transisi Energi*. Jakarta: PT. Gramedia Pustaka Utama, 2022.

[13] M. Gifaricandrabayu, O. Trianda, and A. H. F. Rizqi, “Karakteristik Endapan Nikel Laterit Pada Daerah X, Kabupaten Kolaka Utara, Provinsi Sulawesi Tenggara,” in *Prosiding Nasional Rekayasa Teknologi Industri dan Informasi XVIII Tahun 2023 (ReTII)*, Nov. 2023, pp. 601–609. [Online]. Available: http://journal.itny.ac.id/index.php/ReTII

[14] L. Lintjewas, I. Setiawan, and A. Al Kausar, “Profil Endapan Nikel Laterit di Daerah Palangga, Provinsi Sulawesi Tenggara,” *RISET Geologi dan Pertambangan*, vol. 29, no. 1, p. 91, Jun. 2019, https://doi.org/10.14203/risetgeotam2019.v29.970.

[15] N. Jafar, A. B. Thamsi, R. Baso, M. H. Wakila, and M. Aswadi, “Karakteristik Profil Nikel Laterit pada PT Ghanesa Wana Utama Provinsi Sulawesi Tengah,” *Jurnal GEOSAPTA*, vol. 10, no. 2, p. 123, Apr. 2025, https://doi.org/10.20527/jg.v10i2.16612.

[16] R. Raivel and F. Firman, “Karakteristik Endapan Nikel Laterit di Bawah Molasa Sulawesi Daerah Tinanggea, Sulawesi Tenggara,” *JURNAL GEOMining Teknik Pertambangan Unkhair*, vol. 1, no. 1, pp. 25–37, Apr. 2020, [Online]. Available: https://ejournal.unkhair.ac.id/index.php/geomining

[17] A. Haya, W. Ak Conoras, and F. Firman, “Penyebaran Endapan Nikel Laterit Pulau Obi Kabupaten Halmahera Selatan Provinsi Maluku Utara,” *Journal of Science and Engineering*, vol. 2, pp. 25–33, Apr. 2019, https://doi.org/10.33387/josae.v2i1.1657.

[18] N. P. Imalianda, S. U. Pratomo, S. Sutarto, and P. P. A. Darmawan, “Karakteristik Unsur Nikel berdasarkan Litologi, Mineralogi, dan Analisis Fraksi Butir pada Zona Saprolit di Lapangan ‘K’, Pulau Gebe, Kabupaten Halmahera Tengah, Provinsi Maluku Utara, Indonesia,” *Jurnal Geosains dan Teknologi*, vol. 7, no. 2, pp. 111–122, Oct. 2024, https://doi.org/10.14710/jgt.7.2.2024.111-122.

[19] R. R. Abidin, V. Susanto, S. Sulaeman, and H. M. H. Wicaksono, “Characteristics of Nickel Laterite Deposits and Rare Earth Elements in Gebe Island, Central Halmahera, North Maluku,” *Buletin Sumber Daya Geologi*, vol. 17, no. 2, pp. 65–79, Aug. 2022, https://doi.org/10.47599/bsdg.v17i2.345.

[20] S. Permanadewi, J. Wahyudiono, and A. Tampubolon, “Lateritic Nickel Deposit On GAG Island, Raja Ampat Regency, West Papua Province,” *Buletin Sumber Daya Geologi*, vol. 12, no. 2, pp. 55–70, 2017, https://doi.org/10.47599/bsdg.v12i1.23.

[21] H. Haluk, “Karakteristik Geokimia Endapan Nikel Laterit Pada Blok A PT. Kawei Sejahtera Mining, Raja Ampat,” *INTAN Jurnal Penelitian Tambang*, vol. 8, no. 1, 2025, https://doi.org/10.56139/intan.v8i1.293.

[22] J. Pujiono, T. Listyani R. A., and A. Sudradjat, “Nikel Laterit Pulau Gag: Menelusuri Proses Terbentuknya dan Implikasinya dalam Industri Pertambangan,” in *Prosiding Nasional Rekayasa Teknologi Industri dan Informasi XVIII Tahun 2023 (ReTII)*, Nov. 2023, pp. 871–880. [Online]. Available: http://journal.itny.ac.id/index.php/ReTII

[23] N. P. Purwanto, “Government Policy To Maximize Nickel Potential In Indonesia,” *Info Singkat*, vol. XVI, no. 2, pp. 11–15, Oct. 2024.

[24] W. P. Sahputra, B. A. Badia, M. I. Putra, F. C. Putra, and A. A. Aji, “Rekayasa Proses Ekstraksi dan Pengolahan Bijih Nikel: Teknologi, Tantangan, dan Prospek Masa Depan,” *KAPALAMADA: Jurnal Multidisipliner*, vol. 4, no. 02, pp. 243–255, 2025, https://doi.org/10.62668/kapalamada.v4i02.1546.

[25] P. Prasetiyo and R. Nasoetion, “Masih Terbukanya Peluang Penelitian Proses Caron untuk Mengolah Laterit Kadar Rendah di Indonesia,” *Majalah Metalurgi*, vol. 26, no. 1, pp. 35–44, May 2011, https://doi.org/10.14203/metalurgi.v26i1.7

[26] A. Sangadji, *HPAL dalam Industri Nikel; Tantangan Baru Bagi Lingkungan Di Indonesia*. Jakarta Selatan: Perkumpulan Aksi Ekologi dan Emansipasi Rakyat (AEER), 2024. [Online]. Available: http://aeer.or.id/

[27] CREA & CELIOS, “Membantah Mitos Nilai Tambah, Menilik Ulang Industri Hilirisasi Nikel: Dampak Ekonomi dan Kesehatan dari Industri Nikel di Sulawesi Tengah, Sulawesi Tenggara, dan Maluku Utara,” Jakarta, Feb. 2024. Accessed: May 18, 2026. [Online]. Available: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://energyandcleanair.org/wp/wp-content/uploads/2024/02/CREA_CELIOS-Indonesia-Nickel-Development_ID.pdf&ved= 2ahUKEwj5ns-DlsKUAxVpyjgGHZIhPNoQFnoECA0QAQ&usg=AOvVaw1zHuLygg3gHUBH8DU7eYpP