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From Mine to Battery: Carbon Footprints, Toxic Waste, and Inequality Behind Indonesia's Nickel Industry

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Abstract

The global energy transition has intensified demand for nickel as a critical mineral for battery technologies, positioning Indonesia as a major supplier within emerging electric vehicle supply chains. This development is frequently presented as evidence of green industrial transformation. However, the environmental costs embedded in nickel production challenge the assumption that critical-mineral extraction is inherently compatible with climate goals. This article examines the ecological footprint of Indonesia's nickel industry by tracing the chain from mining and processing to battery-oriented production. It focuses particularly on carbon emissions, tailings, hazardous waste, water contamination, ecosystem degradation, and potential impacts on community health. Special attention is given to high-pressure acid leaching (HPAL), a processing technology associated with the production of substantial quantities of waste and complex environmental management challenges. The article argues that assessing the sustainability of the battery economy requires moving beyond the emissions profile of electric vehicles and considering the full material and ecological life cycle of their components. From this perspective, the discourse of "critical minerals" can conceal unequal environmental burdens concentrated in producing regions. The study concludes that a genuinely sustainable energy transition must integrate resource justice, stronger waste governance, community participation, and life-cycle accountability across global battery supply chains.

[*Transisi energi global telah meningkatkan permintaan nikel sebagai mineral penting untuk teknologi baterai, memposisikan Indonesia sebagai pemasok utama dalam rantai pasokan kendaraan listrik yang sedang berkembang. Perkembangan ini seringkali disajikan sebagai bukti transformasi industri hijau. Namun, biaya lingkungan yang melekat dalam produksi nikel menantang asumsi bahwa ekstraksi mineral penting secara inheren kompatibel dengan tujuan iklim. Artikel ini mengkaji jejak ekologis industri nikel Indonesia dengan menelusuri rantai dari penambangan dan pengolahan hingga produksi berorientasi baterai. Artikel ini khususnya berfokus pada* *emisi karbon, limbah tambang, limbah berbahaya, kontaminasi air, degradasi ekosistem, dan potensi dampak terhadap kesehatan masyarakat. Perhatian khusus diberikan pada pelindian asam bertekanan tinggi (HPAL), teknologi pengolahan yang terkait dengan produksi limbah dalam jumlah besar dan tantangan pengelolaan lingkungan yang kompleks. Artikel ini berpendapat bahwa menilai keberlanjutan ekonomi baterai membutuhkan pertimbangan lebih dari sekadar profil emisi kendaraan listrik dan mempertimbangkan siklus hidup material dan ekologis komponennya secara keseluruhan. Dari perspektif ini, wacana "mineral penting" dapat menyembunyikan beban lingkungan yang tidak merata yang terkonsentrasi di wilayah penghasil. Studi ini menyimpulkan bahwa transisi energi yang benar-benar berkelanjutan harus mengintegrasikan keadilan sumber daya, tata kelola limbah yang lebih kuat, partisipasi masyarakat, dan akuntabilitas siklus hidup di seluruh rantai pasokan baterai global.*]

Keywords: critical minerals, nickel, HPAL, toxic waste, environmental justice

Introduction

The global transition toward low-carbon energy systems has fundamentally altered the strategic importance of mineral resources. Technologies associated with decarbonization—including electric vehicles (EVs), battery storage, renewable energy infrastructure, and electricity networks—require substantial quantities of minerals whose extraction and processing can generate significant environmental pressures. Nickel occupies an important position within this transition because of its use in several lithium-ion battery chemistries, particularly nickel-manganese-cobalt (NMC) cathodes. Global demand for nickel has consequently expanded alongside the broader growth of energy-related mineral consumption. The International Energy Agency (IEA) reports that nickel demand increased by 6–8 percent in 2024, while energy applications accounted for approximately 85 percent of total demand growth for major battery minerals during the same period (IEA 2025a). Although nickel continues to serve extensive non-energy applications, the rapid expansion of battery-related demand has transformed the mineral into a strategically important component of contemporary energy-transition policies.

Indonesia has emerged as the central geography of this transformation. The country possesses extensive laterite nickel resources and has rapidly expanded both mining and downstream processing capacity. This development has been reinforced by state policies aimed at increasing domestic processing, capturing greater value from mineral resources, and positioning Indonesia within global electric-vehicle and battery supply chains. The result has been a dramatic increase in the country's importance to global nickel markets. In 2024, Indonesia accounted for approximately 60 percent of global mined nickel production, while the concentration of refined nickel supply also increased substantially as Indonesian processing capacity expanded (IEA 2025a). The IEA projects that Indonesia's importance will remain pronounced, with the share of the world's three largest nickel-mining countries expected to rise from 77 percent in 2024 to 84 percent by 2040 (IEA 2025b). Indonesia's nickel strategy is therefore no longer simply a matter of mineral extraction; it has become an integral component of the geopolitical and industrial architecture of the global energy transition.

This transformation is commonly represented through the language of *critical minerals*, *green industrialization*, and *clean technology*. Such terminology emphasizes the role of nickel in enabling technologies that can reduce dependence on fossil fuels and lower operational emissions from transport. Yet this framing risks obscuring the material and ecological conditions under which the energy transition is constructed. The environmental performance of an electric vehicle, for example, cannot be adequately evaluated by examining only emissions generated during vehicle operation. The extraction of ore, production of intermediate materials, refining, electricity consumption, transportation, and manufacturing of battery components all form part of the material system that makes electrification possible. Life-cycle assessment research on nickel has long demonstrated that the environmental impacts of nickel production extend across multiple stages of the production chain rather than being confined to the mine itself (Mistry, Gediga, and Boonzaier 2016). Consequently, the designation of nickel as a critical mineral does not inherently establish the sustainability of the processes through which it is produced.

The Indonesian case is particularly significant because the environmental profile of nickel production is closely connected to the energy and processing systems used for downstream industrialization. Life-cycle research on Indonesian ferronickel production, for instance, identifies coal-fired steam power generation as a major source of environmental pressure and demonstrates substantial differences in climate impacts depending on the energy source used in processing (Wahyono et al. 2024). This finding complicates the idea that minerals become environmentally benign simply because their eventual application is associated with clean technologies. A battery may contribute to the electrification of transport, but the material inputs required to manufacture that battery can embody considerable quantities of energy and associated emissions before the vehicle is ever driven. The environmental question therefore shifts from whether a technology is “clean” at the point of use to whether its entire material supply chain can meet credible standards of ecological sustainability.

The problem extends beyond greenhouse-gas emissions. Indonesia's transition from an export-oriented mining sector toward an integrated downstream industry has encouraged the development of increasingly sophisticated processing technologies, including high-pressure acid leaching (HPAL) for low-grade nickel laterite ores. HPAL is particularly relevant to battery-oriented production because it enables the recovery of nickel and cobalt from ores that are less suitable for conventional pyrometallurgical processing. However, its expansion also introduces complex waste-management requirements. The processing of laterite ores involves substantial quantities of materials, energy, and chemical inputs, while generating residues that require long-term containment and monitoring. Recent assessments of Indonesia's nickel sector emphasize that the growing use of HPAL has intensified environmental and social governance challenges associated with both mining and processing (Gultom and Sianipar 2020). The environmental sustainability of nickel-based battery supply chains must therefore consider not only carbon intensity but also the physical characteristics, scale, and management of industrial waste.

These concerns are inseparable from questions of inequality. The benefits of nickel industrialization are distributed across multiple levels: mining companies generate revenues, the Indonesian state seeks greater industrial value capture, downstream manufacturers obtain access to strategic raw materials, and international markets receive inputs for batteries and other technologies. Environmental risks, however, are geographically concentrated in the territories where extraction and processing occur. Communities living near mining and industrial zones may experience changes in land use, water systems, coastal environments, livelihoods, and exposure to industrial pollution. This uneven distribution has led scholars to identify Indonesia's nickel sector as an important case for examining the justice dimensions of the global energy transition. Astuti, Raman, and Yeremia (2025), for example, argue that the socio-environmental consequences of mineral extraction in the Global South represent a significant blind spot in mainstream approaches to the "just transition," particularly when the environmental burdens of low-carbon technologies are geographically separated from their principal consumers and beneficiaries.

The issue can therefore be understood through the concept of environmental justice. A critical-mineral supply chain is not simply a technical arrangement connecting mines to factories; it is also a system through which environmental risks, economic opportunities, political authority, and social recognition are distributed. From this perspective, the central question is not whether nickel contributes to decarbonization, but under what ecological and social conditions that contribution is achieved. Recent work on critical minerals similarly demonstrates that mineral-intensive energy transitions can intensify water insecurity, disrupt livelihoods, and reproduce environmental inequalities when extraction is concentrated in vulnerable regions (Brown, Zhou, and Sadan 2024). Such concerns are particularly relevant to Indonesia, where the rapid expansion of nickel production has occurred alongside a highly concentrated global market. The IEA estimates that Indonesia has been responsible for the overwhelming majority of recent growth in global nickel supply, making environmental governance within the Indonesian production system consequential not only for domestic communities but also for the sustainability of international battery supply chains (IEA 2025a).

Against this background, this article examines the environmental and social implications of Indonesia's nickel industry by tracing the material pathway from mining and processing toward battery-oriented production. Rather than treating carbon emissions, industrial waste, ecological degradation, and social inequality as separate problems, the article approaches them as interconnected consequences of the same expanding mineral supply chain. It focuses particularly on three dimensions: the carbon footprint associated with nickel production; the waste and ecological risks generated by processing technologies such as HPAL; and the unequal distribution of environmental and economic burdens across producing regions and communities. The analysis draws on academic literature, institutional reports, and secondary evidence to examine the sustainability of nickel production from a life-cycle and environmental-justice perspective.

The central argument is that the sustainability of the battery economy cannot be established by assessing the emissions performance of electric vehicles alone. It must also account for the environmental conditions under which the minerals required for batteries are extracted, processed, and transformed into industrial inputs. Indonesia's nickel sector illustrates this contradiction particularly clearly: the country has become indispensable to the expansion of battery-oriented supply chains while simultaneously confronting the carbon intensity, waste-management challenges, ecological pressures, and social inequalities associated with rapid mineral industrialization. Assessing the energy transition "from mine to battery" therefore reveals a more complex picture than the conventional distinction between fossil-fuel-intensive technologies and clean technologies suggests. A genuinely sustainable transition requires life-cycle accountability and a broader conception of resource justice in which the environmental costs of producing critical minerals are treated as integral to, rather than external to, the global project of decarbonization.

From Mine to Battery: The Carbon Footprint of Indonesia's Nickel Industry

The carbon footprint of Indonesia's nickel industry must be understood as a cumulative outcome of activities that extend across the production chain rather than as a consequence of mining alone. Nickel extraction from laterite deposits involves land clearing, excavation, ore handling, transportation, and subsequent metallurgical processing. As Indonesian production has increasingly shifted toward downstream processing, the energy requirements of the sector have expanded accordingly. This is particularly important because laterite ores generally require intensive processing to convert relatively low-grade mineral resources into commercially valuable nickel products. The environmental significance of Indonesia's nickel industry therefore lies not simply in the quantity of nickel extracted, but in the energy-intensive infrastructure required to transform ore into intermediate and refined products.

The rapid expansion of Indonesian nickel production has occurred alongside an exceptional concentration of global supply. Indonesia's share of mined nickel production increased from 34 percent in 2020 to 52 percent in 2023, while its share of refined production increased from 23 percent to 37 percent over the same period (IEA 2024). By 2024, Indonesia had become responsible for the overwhelming majority of recent growth in global nickel supply, and the IEA projects that the three largest nickel-mining countries could account for approximately 84 percent of global mined supply by 2040 (IEA 2025a). This concentration has important implications for carbon accounting because decisions about energy sources and processing technologies in Indonesia can influence the environmental profile of a substantial proportion of the nickel entering global markets. The carbon intensity of Indonesian nickel is therefore not a geographically isolated issue; it is increasingly embedded within the material foundations of international battery and electric-vehicle supply chains.

One of the most consequential characteristics of the Indonesian nickel-processing model is its reliance on energy-intensive industrial infrastructure. Conventional ferronickel and nickel pig iron production commonly employs rotary kiln-electric furnace (RKEF) technology, which requires substantial quantities of thermal and electrical energy. In Indonesia, this energy demand has frequently been met through coal-fired power generation, particularly within industrial parks where captive power plants support continuous metallurgical operations. This arrangement creates a direct connection between the country's downstreaming strategy and fossil-fuel consumption. Wahyono et al. (2024) identify coal-fired steam power generation as the principal environmental concern in Indonesian ferronickel production. Their life-cycle assessment estimates a climate-change impact of 99,024.7 kg CO_2-equivalent per tonne of ferronickel under a coal-fired steam-power scenario, compared with 60,522.2 kg CO_2-equivalent under a biomass scenario and 3,993.7 kg CO_2-equivalent under a hydropower scenario. The magnitude of these differences demonstrates that the energy source used in nickel processing is not a secondary consideration; it is a major determinant of the industry's carbon intensity.

These findings also reveal an important limitation in interpreting the environmental performance of nickel solely through technological efficiency. A more efficient furnace or refinery does not necessarily produce a low-carbon material if the electricity required to operate it remains highly carbon intensive. In other words, the carbon footprint of nickel is partly determined outside the metallurgical process itself, through the structure of the electricity system that supplies industrial facilities. This creates what may be described as an *energy-system dependency*: improvements in processing technology can be undermined when industrial expansion simultaneously increases reliance on carbon-intensive electricity. The Indonesian case consequently illustrates why mineral decarbonization cannot be separated from power-sector decarbonization. Reducing the emissions intensity of nickel requires not only better extraction and processing practices but also a fundamental transformation of the energy sources supporting those processes.

The relationship becomes more complex when nickel production moves from conventional pyrometallurgical processing toward hydrometallurgical routes intended to produce battery-oriented intermediates. Indonesia's laterite resources contain substantial limonite deposits that can be processed through high-pressure acid leaching (HPAL), producing mixed hydroxide precipitate (MHP), which can subsequently be converted into nickel sulfate for battery applications. A life-cycle assessment by Bartzas and Komnitsas (2024) examined the production of battery-grade nickel sulfate through an Indonesian HPAL route followed by purification in China. Their study demonstrates that environmental impacts are distributed across multiple stages of the supply chain, with operation and purification making particularly important contributions to overall impacts. The study further shows that energy use and the source of that energy are critical variables in determining the environmental performance of battery-grade nickel sulfate.

The importance of this finding lies in the distinction between *battery-oriented nickel* and *low-carbon nickel*. The former refers to the destination and chemical specification of the material, whereas the latter refers to the environmental conditions under which that material is produced. A nickel intermediate can be chemically suitable for an NMC battery while still carrying a substantial carbon footprint. The transition from ore to MHP or nickel sulfate does not eliminate the emissions associated with mining, electricity consumption, heat, chemical production, transportation, and material conversion. Instead, these impacts become incorporated into the embodied environmental burden of the battery material. A recent comparative life-cycle assessment of nickel sulfate production similarly identifies energy consumption in Indonesian nickel processing as a major contributor to global warming potential and estimates that increasing the share of hydropower in the Indonesian scenario could substantially reduce the product's carbon footprint (Valencia et al. 2025).

This distinction is particularly relevant because the global battery industry increasingly depends on geographically concentrated processing networks. Indonesia's contribution is not limited to supplying raw ore. Through the development of smelters, HPAL facilities, MHP production, and other downstream operations, the country is progressively positioned at multiple stages of the nickel value chain. The IEA's analysis indicates that Indonesia's expanding refining capacity is a major reason why global nickel refining is becoming increasingly concentrated. In 2024, the three largest refining countries accounted for 78 percent of global refined nickel production, and the share is projected to increase further by 2030 under the IEA's Stated Policies Scenario (IEA 2025b). This concentration means that the environmental characteristics of Indonesian processing can become structurally embedded in the global battery economy rather than remaining an issue confined to a single national production system.

At the same time, the relationship between nickel and the energy transition should not be treated as technologically fixed. Nickel remains important for high-nickel lithium-ion battery chemistries, particularly those designed to achieve higher energy density. However, the rapid expansion of lithium-iron-phosphate (LFP) batteries has reduced the extent to which future EV growth necessarily translates into equivalent growth in nickel demand. The IEA reports that LFP batteries accounted for nearly half of the global electric-car market in 2024, compared with less than 10 percent in 2020 (IEA 2025a). This development is significant for evaluating Indonesia's nickel strategy because it demonstrates that mineral demand is shaped not only by the number of electric vehicles produced but also by technological choices within the battery industry. The argument that increased nickel extraction is an unavoidable consequence of decarbonization therefore requires qualification. Different battery chemistries can alter the quantity and type of minerals required, while recycling and material-efficiency improvements may further influence future primary demand.

Nevertheless, technological substitution does not resolve the underlying carbon problem within the existing nickel supply chain. As long as nickel remains an important input for particular battery chemistries and other industrial applications, the emissions associated with its production remain relevant to the environmental assessment of those products. Moreover, the existence of alternative battery chemistries should not be used to minimize the current ecological significance of Indonesian nickel production. Rather, it demonstrates the importance of assessing mineral demand dynamically and avoiding technological determinism. A responsible energy-transition strategy should not assume that increasing extraction is inherently necessary; it should evaluate whether demand can be met through lower-carbon production, greater material efficiency, recycling, substitution where technically appropriate, and changes in the energy systems supporting mineral processing.

The concept of *from mine to battery* consequently changes the analytical unit through which the energy transition is evaluated. If the assessment begins only at the point of vehicle use, an electric vehicle appears primarily as a technology for reducing operational emissions. If the assessment begins with mineral extraction, however, the vehicle becomes the final component of a much longer industrial chain involving land disturbance, ore processing, electricity generation, chemical production, transportation, refining, and battery-material manufacturing. Life-cycle assessment is valuable precisely because it makes these upstream relationships visible. Research on battery production has consistently demonstrated that electricity intensity and the carbon intensity of electricity supply can significantly affect manufacturing-related emissions, meaning that cleaner batteries require decarbonization across their material and production networks rather than solely at the point of vehicle operation (Clemente et al. 2025).

For Indonesia, this perspective raises a fundamental tension within the downstreaming model. The policy objective of moving from raw-material exports toward domestic processing can generate greater economic value and industrial capability, but it can also relocate a larger share of energy consumption and associated emissions into the producing country. Downstreaming therefore does not automatically constitute environmental upgrading. Its sustainability depends on the energy sources, technologies, material efficiencies, and environmental standards governing each stage of processing. The critical issue is not whether Indonesia should participate in battery supply chains, but whether the country's participation can be reorganized around substantially lower-carbon production without shifting environmental burdens to other parts of the supply chain.

This tension is especially important when carbon accounting is separated from the broader discourse of "green" industrialization. A nickel product may contribute to a low-carbon technology while being produced through an energy system dominated by fossil fuels. The resulting contradiction does not mean that electric vehicles or battery technologies have no climate value; rather, it demonstrates that their climate benefits cannot be evaluated independently of the material systems that support them. The IEA's assessment that demand for nickel is projected to approximately double by 2040 under its Stated Policies Scenario underscores the continuing importance of improving the environmental performance of primary production even as battery technologies evolve (IEA 2025a).

The carbon footprint of Indonesian nickel should therefore be understood as a question of *life-cycle accountability*. Mining, transportation, electricity generation, smelting, refining, and battery-material production form interconnected stages through which emissions accumulate before nickel becomes part of a battery. The evidence indicates that energy choice is among the most significant determinants of this footprint, particularly where coal supplies the electricity required for energy-intensive processing. Decarbonizing the nickel supply chain consequently requires more than incremental improvements within individual facilities. It requires a transition toward lower-carbon electricity, greater transparency in emissions accounting, systematic life-cycle assessment, and stronger environmental standards across the entire production chain. Only by incorporating these upstream emissions into assessments of battery technologies can the environmental claims associated with the global energy transition be evaluated on a genuinely material basis.

HPAL, Toxic Waste, and Ecological Degradation

The expansion of high-pressure acid leaching (HPAL) represents a significant transformation in Indonesia's nickel industry because it enables the processing of limonite-rich laterite ores that are less suitable for conventional pyrometallurgical routes. HPAL uses sulfuric acid under elevated temperature and pressure to dissolve nickel and cobalt from the ore, after which the dissolved metals can be recovered and converted into mixed hydroxide precipitate (MHP), an intermediate material suitable for subsequent battery-material production. The technological significance of HPAL is therefore closely connected to Indonesia's ambition to move beyond the export of raw minerals and participate in battery-oriented value chains. Yet the same process creates a substantial residue stream that presents a fundamentally different environmental challenge from the carbon emissions discussed above. The environmental question is no longer only how much energy is required to produce nickel, but what happens to the large quantities of material that remain after the economically valuable metals have been extracted.

Recent research indicates the scale of this challenge. A 2025 study on Indonesian HPAL operations estimates that production of approximately 543,000 tonnes of nickel product could generate more than 26 million tonnes of nickel limonite tailings (NLT) (Masudin et al. 2025). The figure illustrates a basic characteristic of hydrometallurgical processing: the recovery of a relatively small quantity of valuable metals can be accompanied by the generation of a much larger mass of residual material. Such residues cannot simply be treated as an incidental by-product. Their volume, physical characteristics, and chemical composition determine the infrastructure required for containment, dewatering, transportation, monitoring, and long-term management. The scale of waste generation therefore has the potential to become a structural constraint on the sustainability of battery-oriented nickel production rather than merely an operational issue for individual processing facilities.

The composition of HPAL residues further complicates their management. Research on lateritic nickel tailings describes HPAL residue as an iron-rich material containing other mineral components that remain after the preferential recovery of nickel and cobalt. A study characterizes the residue generated through HPAL treatment of laterite nickel ore as a massive stream of acidic, iron-rich material and identifies its management as a significant environmental challenge (Luo, et al. 2025). This does not mean that every HPAL residue should automatically be classified as legally "toxic waste." Rather, the environmental concern arises from the combination of very large volumes, residual chemical constituents, potential mobility of contaminants, and the need to maintain stable containment over long periods. The distinction is important because environmental risk should be assessed according to the properties and exposure pathways of the waste rather than solely through categorical labels.

The problem becomes particularly significant when tailings management is considered in relation to Indonesia's physical geography. Many nickel-processing facilities are located in coastal or island environments where industrial infrastructure is situated close to marine ecosystems. This geography creates a potentially direct connection between terrestrial waste storage and coastal waters. Tailings facilities must therefore withstand intense rainfall, drainage pressures, slope instability, and other site-specific conditions while preventing seepage or uncontrolled movement of contaminated material. The International Institute for Sustainable Development (IISD) identifies tailings and waste management as one of the major socio-environmental governance challenges associated with the rapid expansion of Indonesia's nickel industry, particularly as HPAL operations increase in scale (Gultom and Sianpar 2020). The central issue is consequently not simply the existence of waste but the capacity of regulatory institutions and operators to ensure that containment systems remain effective throughout the operating and post-closure periods of industrial projects.

The shift toward filtered or dry-stacked tailings has often been presented as an important technological response to the environmental challenges associated with wet tailings storage. By removing a substantial proportion of water before deposition, dry stacking can reduce the mobility of slurry and alter the physical characteristics of the stored material. However, the technology should not be interpreted as eliminating environmental risk. Tailings remain a large mass of industrial residue that must be physically contained, drained, monitored, and stabilized. The relevant question is therefore whether dry stacking reduces particular pathways of exposure under specific geological and climatic conditions, rather than whether it makes tailings environmentally harmless. This distinction is especially important in Indonesia, where high rainfall, seismic activity, steep terrain, and coastal proximity can create complex conditions for long-term tailings management. The environmental performance of a tailings technology is consequently inseparable from site selection, engineering standards, monitoring capacity, emergency preparedness, and institutional enforcement.

Evidence emerging from Indonesia illustrates why these issues require close scrutiny. A specific study concerning the Halmahera Persada Lygend HPAL project in North Maluku alleged problems involving tailings storage, groundwater pathways, drainage, monitoring, and geotechnical stability, including alleged contamination affecting groundwater resources near Kawasi. These claims were presented as allegations in an assessment by Earthworks and have not, by themselves, established a definitive regulatory finding of causation. Nevertheless, the case is analytically important because it demonstrates how the environmental risks of HPAL tailings extend beyond the industrial facility itself: failures or weaknesses in containment can potentially connect industrial residues to groundwater systems and community water supplies. Such cases reinforce the need for independent monitoring and transparent disclosure of environmental data rather than reliance exclusively on company-generated assessments.

The ecological implications also extend beyond tailings storage. Nickel extraction and processing can alter terrestrial and marine environments through land clearing, sediment movement, wastewater, atmospheric emissions, and the physical expansion of industrial infrastructure. A recent life-cycle assessment of critical-mineral industries in Indonesia found that nickel mining and processing can generate potential environmental and human-health impacts through pollutant releases to soil, water, and air, in addition to the impacts associated with material and energy consumption (Wahyono et al. 2024). This finding is important because it places tailings within a wider environmental pathway. Tailings are one component of a larger industrial system in which extraction changes landscapes, processing changes material and chemical flows, and waste management determines whether residual pollutants remain contained or enter surrounding ecosystems.

The connection between nickel processing and coastal ecosystems is particularly important in Indonesia because major industrial complexes have developed along coastlines. New research examining the Indonesia Morowali Industrial Park (IMIP) used multi-decadal satellite observations and causal inference techniques to identify a deterioration in nearshore water clarity following the rapid expansion of nickel-processing infrastructure, including HPAL facilities (Gulliver, Wibisono, and Louis 2022). The study also identified substantial built-area expansion and concurrent tree-cover loss within the industrial footprint. Reduced water clarity is environmentally significant because increased turbidity can reduce light penetration into the water column and thereby affect photosynthetic organisms, including coral communities. In biologically productive coastal environments, therefore, industrial expansion can generate ecological effects that are not captured by conventional measurements of factory-level emissions or waste volumes alone.

This relationship illustrates an important weakness in narrow approaches to environmental regulation. If pollution is assessed primarily at the point of discharge or within the formal boundaries of an industrial facility, cumulative ecological changes across watersheds and coastal systems may remain inadequately recognized. Nickel industrialization produces multiple environmental pathways simultaneously: mining can increase sediment loads; roads and industrial construction can transform drainage patterns; processing can generate waste and wastewater; and port infrastructure can alter coastal environments. These pressures can interact rather than operate independently. A river receiving increased sedimentation, for example, is not necessarily affected only by one discharge point; its condition may reflect cumulative changes throughout the upstream landscape. Environmental assessment therefore needs to move from a facility-centered model toward a cumulative and ecosystem-based approach.

The scale of waste generated by nickel processing also creates a temporal problem. The economic life of a mine or processing plant is finite, but the environmental management obligations associated with its waste may persist for decades or longer. This creates an asymmetry between the time horizon of industrial investment and the time horizon of ecological risk. A company may evaluate a project according to its expected operational life, while tailings facilities must remain stable beyond the period in which the project generates revenue. The environmental sustainability of HPAL therefore depends not only on whether a facility can safely operate today but also on whether waste containment can remain effective after production ceases. This is why long-term monitoring, financial guarantees, closure plans, and institutional responsibility are central components of waste governance rather than administrative details added after the technological design has been completed.

One possible response is to treat HPAL residues not exclusively as waste but as potential secondary resources. Recent research has explored the recovery of iron, calcium, aluminium, sodium, and silicon from HPAL residues and demonstrated the technical potential for converting components of the residue into useful materials (Luo, et al. 2025). Similarly, research on Indonesian nickel limonite tailings has examined their incorporation into construction materials, including bricks, as a strategy for reducing the quantity of material requiring conventional disposal (Masudin et al. 2025). Such approaches are important because they introduce principles of circularity into a highly material-intensive industry. Nevertheless, waste valorization should not be treated as a substitute for rigorous waste prevention and containment. The commercial feasibility, environmental safety, market demand, and long-term stability of secondary uses must be demonstrated before large-scale reuse can be considered an adequate response to the waste problem.

The environmental challenge of HPAL therefore lies in a paradox at the heart of battery-oriented nickel production. The technology can improve the utilization of laterite resources and produce materials required for high-nickel battery chemistries, yet the process simultaneously creates substantial quantities of residual material whose management can impose long-term ecological obligations. Technological sophistication does not eliminate this contradiction. Indeed, as processing becomes more advanced and production expands, the scale and complexity of associated waste streams can also increase. The question of sustainability must consequently shift from whether HPAL is more technologically advanced than conventional processing to whether its entire material system—including extraction, chemical inputs, residue generation, storage, monitoring, and closure—can be governed within credible ecological limits.

From this perspective, the concept of “toxic waste” should be understood not merely as a description of a particular chemical substance but as part of a broader governance problem. Waste becomes an environmental-justice concern when the risks associated with its storage and management are transferred from producers and consumers to communities and ecosystems located near processing facilities. The global battery supply chain captures the economic value of nickel at multiple stages, but the residual material remains physically tied to the place where extraction and processing occur. This creates a spatial asymmetry: the useful product can move across borders and enter global markets, while the waste remains in the producing territory. The environmental sustainability of the battery economy therefore depends not only on whether valuable minerals can be recovered efficiently, but also on whether the waste left behind can be managed without imposing disproportionate risks on local ecosystems and populations.

The Indonesian experience demonstrates that HPAL should consequently be evaluated through a broader life-cycle framework. Carbon emissions represent only one dimension of the environmental footprint of nickel. The other dimensions include the quantity and characteristics of processing residues, the integrity of tailings storage, water quality, terrestrial disturbance, coastal degradation, and the institutional capacity to manage risks over long periods. A study of Indonesia's nickel sector similarly identifies the interaction between mining, processing, waste management, ecosystem degradation, and social impacts as a cumulative governance challenge rather than a series of isolated environmental problems (Rosada 2025).

The significance of these findings extends beyond Indonesia. As global demand for battery materials grows, the environmental consequences of mineral processing become part of the environmental footprint of the energy transition itself. Treating tailings and industrial residues as externalities allows the battery economy to appear cleaner at the point of consumption than it is across the material chain. Conversely, incorporating waste generation and ecological degradation into life-cycle assessments makes visible the material costs that accompany technological decarbonization. The central issue is therefore not whether nickel can support a low-carbon economy, but whether the production of that nickel can occur without creating new and geographically concentrated forms of ecological risk. Without robust waste governance, transparent monitoring, cumulative environmental assessment, and meaningful accountability for long-term impacts, the transition from mine to battery risks transforming one form of environmental externalization into another.

Nickel, Inequality, and Environmental Justice

The environmental consequences of Indonesia's nickel industry cannot be separated from the question of who benefits from nickel-dependent industrialization and who bears its associated risks. The expansion of mining, smelting, and battery-oriented processing creates economic value at multiple scales, from local employment and regional revenues to national industrial development and participation in global battery supply chains. Yet the environmental burdens generated by these activities are geographically concentrated in the territories where minerals are extracted and processed. This uneven geography creates a central environmental-justice problem: the people who live closest to the material foundations of the energy transition may receive only a fraction of the value generated by the commodities while experiencing a disproportionate share of environmental and social disruption. In this sense, inequality is not an unintended consequence external to the nickel economy; it is produced through the spatial organization of extraction, processing, and value accumulation.

The case of Obi Island provides a particularly important illustration. The expansion of nickel mining and processing around Kawasi has been associated with reported changes in access to land and water, declining fishing and agricultural conditions, and a proposed relocation of residents from the old village to a newly developed settlement. A recent study of the Kawasi relocation process identifies limited community participation, insufficient transparency, and weaknesses in the implementation of livelihood-support programs as important concerns (Sari et al. 2025). These findings are significant because relocation cannot be evaluated merely through the physical quality of replacement houses or infrastructure. For communities whose livelihoods depend on fishing, farming, forests, coastal resources, and social networks, relocation also involves the restructuring of economic practices, cultural relationships, and territorial identities. A settlement can therefore be materially improved while simultaneously producing forms of social displacement if residents lose meaningful control over land, livelihoods, and decisions concerning their future.

This distinction is central to the concept of distributive justice. Conventional assessments of mining benefits frequently emphasize employment, infrastructure, tax revenues, investment, and national value added. Such indicators are important, but they do not reveal how benefits and costs are distributed among different groups. The economic value of nickel can travel through domestic and international supply chains, while the ecological risks of extraction remain tied to specific territories. Fishers cannot relocate the marine ecosystem on which their livelihoods depend, and communities cannot easily transfer the environmental costs of contaminated water or altered landscapes to the consumers of batteries and electric vehicles located elsewhere. The geographical separation between the beneficiaries and burden-bearers of the battery economy consequently creates a form of environmental inequality in which the material costs of decarbonization are disproportionately localized.

The Indonesian legal framework formally recognizes several principles that should constrain this unequal distribution. Law No. 32 of 2009 on Environmental Protection and Management establishes principles including justice, precaution, sustainability, the polluter-pays principle, participation, and recognition of local wisdom (Republic of Indonesia 2009). It also recognizes a right to a good and healthy environment and provides rights to environmental information, participation, and access to justice. Article 65 further recognizes the right of individuals to submit proposals or objections concerning planned activities that may cause environmental impacts. These provisions are important because they establish environmental protection not merely as a matter of administrative compliance but as a rights-based dimension of environmental governance.

However, the existence of these legal rights does not automatically guarantee environmental justice. The more difficult question concerns whether communities possess sufficient information, institutional capacity, bargaining power, and procedural opportunities to exercise those rights in practice. This is particularly relevant in large-scale extractive projects, where decisions concerning land allocation, environmental approval, industrial infrastructure, and relocation may involve multiple state institutions and corporate actors. A formally available consultation process may therefore produce limited justice if affected communities participate only after major decisions have effectively been made. Environmental participation becomes meaningful only when community input can influence the substance of a decision rather than merely document community awareness of a predetermined project.

This concern is reflected in Indonesia's environmental approval framework. Government Regulation No. 22 of 2021 provides for public involvement in the environmental assessment process, including consultation with directly affected communities. The regulation provides that directly affected communities can provide suggestions, opinions, and responses during public consultation and that their participation occurs before the preparation of the terms of reference for an environmental impact assessment (Republic of Indonesia 2021). The regulatory architecture therefore recognizes participation as an element of environmental decision-making rather than an optional corporate-relations activity. The significance of this requirement is considerable for nickel projects because decisions concerning mining boundaries, processing facilities, waste-management systems, water resources, and relocation can generate impacts that extend beyond the physical boundaries of industrial facilities.

The legal framework governing mining similarly contains provisions intended to connect mineral development with community empowerment. Law No. 3 of 2020 amended the Mining Law and strengthened provisions concerning environmental management, reclamation, post-mining obligations, community empowerment, and supervision (Republic of Indonesia 2020). The subsequent Law No. 2 of 2025 further amended the mining framework and expressly requires holders of mining business licenses to establish community development and empowerment programs, including corporate social and environmental responsibility, involvement of local and Indigenous communities in mining activities, and community-based economic partnerships. The preparation of these programs is also required to involve consultation with government and local and/or Indigenous communities (Republic of Indonesia 2025).

These provisions reveal an important tension in the governance of nickel industrialization. On the one hand, Indonesian law increasingly recognizes that mining should generate social benefits and that affected communities should be involved in development and environmental governance. On the other hand, the legal framework remains strongly oriented toward facilitating mineral development and downstream industrialization. The 2025 amendment itself describes downstreaming as an important driver of national economic growth while simultaneously emphasizing the need for sustainable and environmentally oriented mineral management (Republic of Indonesia 2025). This dual orientation creates a governance dilemma: the state is simultaneously a promoter of mineral industrialization, a regulator of environmental impacts, and a guarantor of citizens' environmental rights. The effectiveness of environmental justice therefore depends substantially on whether environmental and community protections can constrain development decisions when ecological or social costs become significant.

The principle of participation is particularly important when examining relocation in Kawasi. Relocation associated with extractive development should not be understood solely as a technical solution to physical proximity between residential areas and mining operations. It involves questions of consent, land rights, livelihood restoration, cultural continuity, and access to decision-making. Recent reporting based on interviews with Kawasi residents describes concerns about limited consultation concerning the EcoVillage, loss of access to customary land, changes in fishing and farming livelihoods, and uncertainty over long-term tenure in the new settlement. These accounts should be treated as evidence of community experience and reported concerns rather than as conclusive judicial findings concerning legal violations. Nevertheless, they raise precisely the procedural questions that environmental law is intended to address: whether affected people receive adequate information, whether participation occurs before decisions are effectively settled, and whether alternatives are genuinely available to them.

The issue can also be analyzed through recognitional justice. Environmental decision-making often treats affected populations as generic “communities” whose interests can be represented through compensation, infrastructure, or employment. Such an approach may fail to recognize the distinct relationships that local and Indigenous communities have with land and marine resources. Recognition requires more than acknowledging that residents live within a project-affected area; it requires recognizing them as political actors with knowledge, territorial relationships, livelihood systems, and legitimate claims concerning how development should occur. The 2025 amendment to the Mining Law is significant in this respect because it expressly refers to the involvement of local and Indigenous communities in mining-related activities (Republic of Indonesia 2025). Yet the practical meaning of such recognition depends on whether participation can influence decisions and whether community interests are treated as substantive considerations rather than merely inputs into a development program.

There is also an important distinction between community development and community participation. Corporate social responsibility programs, employment opportunities, infrastructure, education, and economic assistance can generate tangible benefits. However, these benefits do not necessarily resolve procedural or recognitional injustice. A community may receive new housing while losing access to fishing grounds; receive employment while experiencing declining agricultural production; or obtain public infrastructure while having limited influence over the location and design of industrial development. Community empowerment therefore cannot be reduced to the distribution of development benefits. It must also include the capacity to participate in determining the terms under which development occurs. The distinction is particularly important in the context of Law No. 2 of 2025, which requires both community-development programs and consultation with local and Indigenous communities. The legal framework provides an institutional basis for participation, but its justice implications depend on how consultation is conducted and whether community preferences can materially shape project decisions.

Environmental justice also requires consideration of intergenerational distribution. Mining projects generate benefits over a finite period, whereas environmental risks associated with altered landscapes, contaminated water, industrial waste, and damaged ecosystems may persist beyond the operational life of a project. Indonesian environmental law explicitly incorporates intergenerational justice among the objectives of environmental protection (Republic of Indonesia

2009). This principle has particular relevance to nickel because the material intensity of downstream processing can create environmental liabilities whose duration exceeds the period in which the original economic benefits are realized. The legal obligation to conduct reclamation and post-mining activities, reinforced through the mining regulatory framework, reflects an attempt to address this temporal imbalance (Republic of Indonesia 2020).

Evidence from Obi Island also demonstrates why reclamation should be considered part of environmental justice rather than simply an engineering obligation. A 2025 study evaluating reclamation performance at a nickel mine operated by PT Trimegah Bangun Persada on Obi Island found that reclamation activities should be assessed through land arrangement, soil management, revegetation, and restoration of ecological functions (Kamarullah et al. 2025). The relevance of such findings extends beyond the technical success of vegetation establishment. Effective reclamation determines whether communities inherit functioning landscapes after extraction ends or are left with degraded territories and reduced livelihood opportunities. The distributional question therefore continues after the mine closes: who will bear the cost of restoring the ecological systems that supported local life before industrialization?

The environmental-justice dimension is further strengthened by the legal principle of access to justice. Article 65 of Law No. 32 of 2009 recognizes access to information, participation, and justice as components of the right to a good and healthy environment (Republic of Indonesia 2009). The law also contains protections for individuals who defend environmental rights. Following Constitutional Court Decision No. 119/PUU-XXIII/2025, the protection under Article 66 was clarified so that individuals—including victims, complainants, witnesses, experts, and environmental activists—participating in environmental protection or pursuing legal remedies are protected against retaliatory criminal, civil, or other legal actions, subject to the constitutional court's conditional interpretation (Republic of Indonesia 2009). This development is important because procedural environmental justice depends not only on the existence of consultation mechanisms but also on the ability of affected communities and civil-society actors to raise objections without facing retaliatory consequences.

Nevertheless, legal protection should not be confused with effective enforcement. The regulatory framework can establish environmental rights, participation requirements, reclamation duties, and community-development obligations, but these norms become meaningful only through monitoring, transparency, institutional independence, and accessible remedies. Government Regulation No. 22 of 2021 provides an integrated framework covering environmental approval, water and marine quality, hazardous and non-hazardous waste, environmental restoration guarantees, supervision, and administrative sanctions (Republic of Indonesia 2021). The challenge in resource-intensive regions is therefore partly one of implementation capacity. Where regulatory institutions face information asymmetries relative to large corporations or where affected communities lack resources to independently verify environmental claims, formal legal protections may not be sufficient to prevent unequal environmental outcomes.

The emergence of new environmental standards also demonstrates that the legal framework is evolving in response to environmental risks. Minister of Environment/BPLH Regulation No. 20 of 2025 establishes standard criteria for environmental damage to land caused by mining activities and provides provisions concerning prevention, monitoring, and the responsibilities of operators (Republic of Indonesia 2025b). This development is significant because it potentially strengthens the ability of environmental governance to translate ecological degradation into measurable regulatory criteria. Yet its effectiveness will depend on the quality of baseline data, frequency of monitoring, transparency of results, and willingness of authorities to impose corrective measures where standards are exceeded.

Taken together, these legal developments suggest that the central problem is not the complete absence of environmental or social safeguards. Indonesia possesses a relatively extensive regulatory architecture governing environmental rights, environmental approval, public participation, mining reclamation, post-mining obligations, and community empowerment. The deeper problem is the relationship between these safeguards and an industrial policy that treats nickel downstreaming as a strategic component of national economic transformation. When rapid industrial expansion becomes a policy priority, environmental law must function not merely as an instrument for legitimizing projects but as a mechanism capable of setting meaningful ecological and social limits on development. Environmental justice requires that the costs of those limits not be negotiated away by communities with the least economic and political power.

The Indonesian nickel case therefore illustrates all three dimensions of environmental justice. Distributive justice concerns the unequal allocation of economic benefits and environmental burdens between industrial actors, consumers, the state, and producing communities. Procedural justice concerns whether affected communities have timely information, meaningful participation, and effective access to legal remedies. Recognitional justice concerns whether local and Indigenous communities are treated as legitimate rights-bearing actors whose territorial relationships and knowledge matter in decisions concerning extraction and relocation. Indonesian law contains elements addressing each dimension, but the existence of formal provisions does not guarantee their substantive realization. The gap between legal recognition and lived experience is consequently a central issue for evaluating the sustainability of nickel industrialization.

This gap also changes how the global energy transition should be understood. The conventional narrative treats the transition as a movement from high-carbon technologies toward cleaner technologies, but the Indonesian nickel industry demonstrates that the transition also involves a redistribution of land, materials, environmental risks, and political authority. The battery economy can therefore reproduce an extractive geography in which resource-producing territories absorb the environmental consequences while the resulting technologies circulate through global markets. This does not invalidate the climate rationale for electrification. Instead, it requires the concept of a low-carbon transition to be expanded so that carbon reduction is pursued together with environmental protection, social rights, and equitable distribution.

The question of inequality consequently returns the analysis to the meaning of sustainability itself. If sustainability is defined only in terms of reducing operational emissions from vehicles, the environmental costs of nickel extraction and processing remain largely externalized. If sustainability is instead understood through a life-cycle and environmental-justice framework, the performance of the battery economy must be assessed according to the conditions under which its material inputs are produced. Indonesia's nickel industry demonstrates that a mineral can be “critical” to global decarbonization while simultaneously generating critical questions about land, water, livelihoods, participation, and rights. The challenge is therefore not simply to produce more nickel for the energy transition, but to establish institutional arrangements under which the benefits of mineral development are shared fairly and the ecological risks are neither concentrated in vulnerable communities nor transferred to future generations.

Conclusion

This article has demonstrated that Indonesia’s nickel industry occupies a contradictory position within the global energy transition. Nickel is increasingly important to battery-oriented supply chains, yet the production of this critical mineral remains associated with substantial energy requirements, carbon emissions, industrial residues, and ecological pressures. The analysis from mine to battery shows that the environmental performance of electric-vehicle technologies cannot be separated from the material and industrial systems that make them possible. Indonesia’s position as the dominant source of global nickel supply therefore gives the country particular significance in determining whether the expansion of battery supply chains contributes to a genuinely lower-carbon economy or reproduces carbon-intensive patterns of industrialization. The central implication is that the “clean” character of an energy technology cannot be established at the point of consumption alone; it must be evaluated across the full material life cycle of the technologies on which decarbonization depends. This is increasingly important as Indonesia’s nickel-processing capacity becomes more deeply integrated into global supply chains and as the concentration of global nickel mining and refining remains exceptionally high (IEA 2025a; IEA 2025b).

The analysis also demonstrates that carbon intensity represents only one dimension of the sustainability problem. The expansion of HPAL and other downstream processing technologies creates substantial residual material and long-term environmental management obligations, while the spatial concentration of mining and processing places ecological risks in particular territories and communities. These risks expose a fundamental weakness in approaches to the energy transition that treat critical minerals primarily as inputs into technological modernization. The question is not simply whether nickel is necessary for particular battery chemistries, but whether the extraction and processing of nickel can be governed within credible ecological and social limits. Indonesia's existing legal framework provides important principles and institutional mechanisms for addressing this challenge, including environmental protection, participation, reclamation, community empowerment, and sustainable mineral management. Law No. 2 of 2025, for example, explicitly frames downstream mineral development in terms of sustainability and environmental considerations while strengthening provisions concerning community development and participation (Republic of Indonesia 2025). Yet the existence of regulatory provisions does not by itself resolve the underlying justice problem. Effective sustainability requires enforcement capacity, transparent environmental information, independent monitoring, meaningful community participation, and accountability that extends beyond the operational life of individual projects.

Ultimately, Indonesia's nickel experience suggests that a just energy transition must be understood as a question of resource justice as much as carbon reduction. The benefits of nickel-based industrialization are distributed through national and global markets, whereas many environmental risks remain territorially concentrated in producing regions. This asymmetry requires a broader conception of transition policy in which the environmental and social costs of critical-mineral production are incorporated into the definition of sustainability rather than treated as externalities. Indonesia should therefore strengthen life-cycle carbon accounting for nickel products, accelerate the decarbonization of industrial electricity, establish more rigorous and transparent standards for HPAL residues and tailings, strengthen cumulative ecosystem monitoring, and ensure that affected communities possess meaningful influence over land-use, environmental, and relocation decisions. Such measures would not require abandoning nickel downstreaming, but would require redefining its success: not by the volume of ore processed or the scale of battery-related investment alone, but by whether industrial development generates shared economic value without transferring disproportionate ecological risks to local communities and future generations. In this sense, the sustainability of the global battery economy ultimately depends on whether the transition from mine to battery can also become a transition toward greater ecological accountability and social justice.

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