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Environmental externalities of the nickel industry: A case study of Morowali and Halmahera, Indonesia

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ABSTRACT

Indonesia's rapid expansion of nickel mining and downstream processing has positioned the country as a key supplier for the global energy transition, yet it has also generated significant environmental externalities. This study examines how nickel industrialization produces cumulative environmental impacts through interconnected transmission pathways and how these impacts affect ecosystems, human health, and biodiversity. Using a qualitative, pathway-based analytical framework, the research synthesizes peer-reviewed literature indexed in Scopus, policy and regulatory documents, environmental reports, and spatial evidence, with a focus on major nickel-producing regions such as Morowali, Halmahera, and Raja Ampat. The findings demonstrate that environmental externalities in the nickel sector are systemic rather than isolated. Air pathways transmit particulate matter and gaseous emissions that degrade terrestrial ecosystems and increase health risks. Water pathways convey heavy metals and sediments into riverine and coastal systems, undermining aquatic ecosystem functions, food security, and public health. Land pathways drive deforestation, soil degradation, and habitat fragmentation, resulting in long-term losses of ecosystem services and biodiversity. These impacts interact across pathways, producing cumulative and spatially dispersed effects that disproportionately burden local communities. By integrating multiple environmental pathways and receptors, this study addresses a critical gap in existing literature that has largely relied on sectoral or single-impact analyses. The results underscore the need for integrated, pathway-aware governance approaches to internalize environmental costs and support sustainable nickel-led development.

INTRODUCTION

Nickel has become a critical mineral in the global energy transition due to its central role in lithium-ion battery technologies used for electric vehicles (EVs) and renewable energy storage systems. High-nickel cathode chemistries are increasingly adopted because they enhance energy density, extend driving range, and improve battery efficiency, making nickel a key input for global decarbonization strategies (International Energy Agency, 2021; Ravi et al., 2024). As governments and industries accelerate commitments toward net-zero emissions, global demand for battery-grade nickel has increased sharply, reshaping mineral supply chains and intensifying extractive activities in resource-rich regions (Hund et al., 2020). While the energy transition is often framed as

environmentally beneficial at the global scale, it simultaneously generates localized environmental pressures, revealing a structural tension between climate-oriented technological solutions and the ecological costs embedded in mineral-intensive production systems (Lèbre et al., 2020).

Indonesia occupies a dominant position in the global nickel industry, supported by extensive lateritic nickel reserves and an assertive industrial policy framework. Over the past decade, the country has emerged as the world's largest nickel producer, with annual output reaching approximately 2.2 million metric tons in 2024, accounting for more than 50% of total global nickel production (USGS, 2024). This rapid growth has been driven not only by expanded mining capacity but also by a strategic shift toward domestic

downstream processing. Since the implementation of the raw nickel ore export ban in 2020, Indonesia has pursued a resource-based industrialization strategy aimed at increasing domestic value addition, attracting foreign direct investment, and strengthening integration into global value chains for stainless steel and electric vehicle batteries (Warburton, 2024). This policy has accelerated the construction of smelters and refining facilities, particularly within large-scale industrial estates. Strategic nickel hubs in Morowali and Halmahera have emerged as flagship centers of this transformation, concentrating mining, processing, energy supply, and logistics infrastructure while simultaneously amplifying environmental and social pressures associated with large-scale mineral development (Lahadalia et al., 2024; Soamole & Mokodompit, 2025).

Resource-based industrialization frequently generates significant environmental externalities, uncompensated costs imposed on ecosystems and communities that are not reflected in market prices or private investment decisions (Stiglitz & Rosengard, 2015). In the nickel industry, these externalities include large-scale deforestation and land degradation, contamination of surface and groundwater by heavy metals, biodiversity loss in terrestrial and coastal ecosystems, and heightened health risks for populations living near mining and processing sites (Mudd, 2010; Sonter et al., 2018). Such impacts are rarely isolated or short-term. Instead, environmental externalities tend to be cumulative, spatially diffuse, and temporally persistent, propagating through hydrological systems and ecological networks and often extending beyond the operational lifespan of mining projects (Lèbre et al., 2020). These characteristics complicate environmental governance and challenge conventional regulatory approaches that emphasize site-specific mitigation rather than systemic impact management.

Existing scholarship on nickel mining and processing has documented a wide range of environmental and social impacts, including land-use change, freshwater and marine pollution, biodiversity loss, and livelihood disruption in mining-affected regions (Bridge, 2004; Sonter et al., 2018). However, much of the literature remains fragmented, with studies typically focusing on isolated environmental indicators or narrowly

defined economic outcomes. While these studies provide valuable insights, they rarely integrate ecological impacts with social consequences and institutional dynamics within a single analytical framework. Moreover, relatively few studies explicitly link observed environmental degradation to governance arrangements, regulatory enforcement, and political-economic processes underlying nickel industrialization (Arsel et al., 2025). This sectoral separation limits understanding of how environmental externalities are produced, distributed, and perpetuated over time. Consequently, there remains a clear research gap for interdisciplinary approaches that holistically connect environmental, social, and governance dimensions of nickel-led development.

This study seeks to address these gaps by examining the environmental externalities of Indonesia's nickel industry through a comparative case study of Morowali and Halmahera. The research has three primary objectives: (1) to identify and characterize the major environmental externalities associated with large-scale nickel mining and downstream processing; (2) to analyze how these externalities are shaped by governance structures and regulatory practices; and (3) to assess the implications of these dynamics for sustainable resource-based development. Theoretically, the study contributes to debates on environmental externalities by situating ecological degradation within broader institutional and governance contexts (Rosada, 2025). Methodologically, it advances an integrated analytical approach that combines environmental assessment, spatial analysis, and qualitative institutional analysis (Brander et al., 2024). From a policy perspective, the study provides evidence-based insights to inform more sustainable and accountable governance of nickel downstreaming, emphasizing the need to internalize environmental costs within industrial development strategies.

MATERIALS AND METHODS

This study adopts a qualitative case study research design to examine the environmental externalities associated with large-scale nickel mining and downstream processing in Indonesia. A case study approach is particularly suitable for investigating complex socio-environmental phenomena embedded within specific institutional,

spatial, and governance contexts, where causal mechanisms cannot be isolated through purely quantitative methods (Yin, 2018). By focusing on the nickel industry, this research seeks to capture the multidimensional and cumulative nature of environmental externalities that arise from extractive-led industrialization.

The study employs a comparative case study strategy, enabling analytical generalization rather than statistical inference. This approach allows for the identification of common patterns and divergences across cases, strengthening the explanatory power of the findings (George & Bennett, 2005).

The cases of Morowali and Halmahera were selected using a purposive sampling strategy based on their strategic importance within Indonesia's nickel industrialization agenda. These regions host some of the country's largest integrated nickel mining and smelting operations and have experienced rapid industrial expansion following the implementation of the nickel ore export ban in 2020.

Morowali represents a highly concentrated nickel industrial cluster characterized by large-scale smelting complexes, captive coal-fired power plants, and extensive supporting infrastructure. Halmahera, by contrast, reflects a geographically dispersed mining landscape where extraction and processing activities intersect with ecologically sensitive coastal and island environments. The selection of these two cases enables a comparative assessment of how environmental externalities manifest across different spatial configurations, ecological settings, and governance arrangements within Indonesia's nickel sector.

This research relies primarily on secondary data, complemented by spatial and documentary evidence. The main data sources include a peer-reviewed academic literature indexed in Scopus, focusing on nickel mining, environmental externalities, extractive industrialization, and governance issues. Journal articles published between 2015 and 2025 were systematically identified using the Scopus database, employing structured keyword combinations such as "nickel mining," "environmental externalities," "downstream industrialization," "resource-based development," and "environmental governance." Only articles published in reputable international

journals were included to ensure data reliability and academic rigor. An environmental and industry reports produced by international organizations, research institutes, and civil society groups that document land-use change, pollution pathways, ecosystem degradation, and social impacts associated with large-scale nickel extraction and smelting.

The use of multiple data sources enables data triangulation, enhancing the credibility and robustness of the analysis by cross-validating findings across independent forms of evidence and reducing the risk of single-source bias (Denzin & Lincoln, 2013; Flick, 2018).

The analysis is guided by an environmental externalities framework, which conceptualizes environmental damage as costs generated by economic activities that are not internalized by producers or reflected in market prices (Stiglitz & Rosengard, 2015). To operationalize this framework, the study adopts a straightforward integrative approach that examines: (1) the main environmental pressures arising from nickel mining and processing activities, (2) the observable environmental impacts on land, water, ecosystems, and human well-being, and (3) the role of regulatory and institutional arrangements in shaping the occurrence and persistence of these impacts. Rather than applying complex modeling or monetary valuation, the analysis focuses on systematically identifying patterns of environmental degradation and linking them to industrial practices and governance conditions. This simplified approach allows for a clear assessment of how environmental costs are generated, distributed, and left unaccounted for within Indonesia's nickel industrialization process, while remaining transparent, replicable, and appropriate for a qualitative case study design.

Data analysis was conducted through qualitative content analysis and thematic synthesis. Academic articles, policy documents, and environmental reports were systematically reviewed and coded to identify recurring themes related to land-use change, water and marine pollution, biodiversity loss, health risks, and governance failures. Coding followed an iterative process, allowing analytical categories to be refined as new patterns emerged (Saldana, 2011).

The final stage involved cross-case comparison, synthesizing findings from Morowali and Halmahera to identify shared mechanisms and context-specific differences in the generation and governance of environmental externalities.

To enhance analytical validity, the study employs triangulation across data types and sources and grounds interpretations in established theoretical frameworks (Hussein & Hussein, 2009). Nevertheless, several limitations should be acknowledged. The reliance on secondary data may constrain the precision of impact attribution, particularly where environmental monitoring data are incomplete or inconsistent. In addition, the qualitative nature of the analysis limits the ability to quantify externalities in monetary terms. Despite these constraints, the integrated methodological approach provides a robust basis for examining the structural drivers and consequences of environmental externalities in Indonesia's nickel industry.

RESULTS AND DISCUSSION

Why Nickel Matters: Strategic Importance and Distribution of Benefits

Nickel has become a strategically important commodity for multiple stakeholders due to its central role in contemporary development agendas at global, national, and local levels. For the national government, nickel represents a cornerstone of industrial policy aimed at accelerating economic growth, strengthening fiscal revenues, and enhancing Indonesia's position within global value chains for battery materials and low-carbon technologies. Empirical studies highlight that downstream-oriented mineral policies are increasingly adopted by resource-rich countries to escape dependence on raw material exports and to capture higher domestic value through processing and manufacturing activities (Havranek et al., 2016; Warburton, 2024). In this context, nickel is not merely a mineral commodity but a strategic instrument for industrial upgrading and geopolitical positioning in the global energy transition.

At the subnational level, provincial and local governments view nickel development as a driver of regional economic transformation. The expansion of mining and smelting activities is commonly associated with increased local revenues, employment opportunities, infrastructure

development, and the stimulation of supporting industries. Studies on extractive-led regional development indicate that large-scale mining projects can generate short- to medium-term economic benefits for local governments through fiscal transfers, local procurement, and labor absorption (Aragón & Rud, 2012; Aspinall & Berenschot, 2019; Cust & Poelhekke, 2015). These anticipated benefits underpin strong political and administrative support for nickel projects at the regional level, particularly in previously underdeveloped areas.

For international firms and investors, nickel has gained heightened importance as a critical input for the global energy transition. The rapid expansion of electric vehicle manufacturing and renewable energy storage technologies has intensified competition for secure and long-term nickel supplies, particularly for battery-grade materials. As a result, Indonesia has emerged as a pivotal node in global production networks, attracting multinational mining companies, battery manufacturers, and downstream industrial investors seeking supply security and cost advantages (Church & Crawford, 2018; Lèbre et al., 2020; Shen et al., 2022; Sovacool et al., 2020; Sun et al., 2024). This convergence of national development objectives, regional growth expectations, community interests, and global industrial demand makes nickel a strategically significant yet highly contested resource, warranting careful examination of its economic benefits alongside its environmental and governance implications.

For local communities, nickel industrialization presents a more ambivalent set of outcomes. On the one hand, mining and processing activities can create new sources of income, wage employment, and access to infrastructure and public services. On the other hand, a substantial body of literature documents that communities living in proximity to extractive activities frequently bear disproportionate environmental and social costs, including land dispossession, environmental pollution, declining agricultural and fisheries productivity, and heightened health risks (Bebbington et al., 2018; Conde & Le Billon, 2017; Hilson, 2012; Storey, 2010). These contrasting outcomes highlight the importance of examining nickel not only as an economic asset but also as a source of environmental externalities and social trade-offs.

However, the results of this study indicate that the benefits of nickel development are accompanied by direct and indirect externalities that vary across stakeholder groups. While economic gains are largely captured at national and corporate levels, environmental degradation, health risks, and livelihood disruption are disproportionately borne by local communities and ecosystems. These findings reinforce the analytical relevance of environmental externalities, as many social and ecological costs remain insufficiently internalized within existing governance and market mechanisms. The following sections present empirical evidence on how these trade-offs materialize in Morowali and Halmahera, highlighting the uneven distribution of benefits and burdens across scales and actors.

Using the methodological approach outlined in this study, namely a systematic review of Scopus-indexed literature, analysis of policy and regulatory documents, examination of environmental and industry reports, and interpretation of geospatial data. This section analyzes how the perceived benefits of nickel development coexist with, and are often offset by, significant environmental externalities. By synthesizing evidence across these data sources, the Results and Discussion section traces how economic gains for governments and investors are accompanied by cumulative environmental degradation and unevenly distributed social impacts at the local level. This integrated analysis allows for a nuanced understanding of nickel industrialization as a development pathway that simultaneously generates economic opportunities and entrenches environmental and governance challenges.

Analytical Lens for Identifying Environmental Externalities

This study conceptualizes environmental externalities as social and ecological costs arising from nickel mining and processing activities that are not internalized by producers and are absent from market pricing, resulting in the transfer of environmental burdens to ecosystems and surrounding communities. In extractive industries, such externalities typically emerge when private economic benefits coexist with public environmental losses, reflecting persistent forms of environmental market failure under resource-based industrialization (Feng et al., 2025; Lameck et al., 2025).

Analytically, externalities are identified using a pathway-based qualitative framework that links industrial activities mining, ore processing, and smelting to three primary environmental transmission routes: air, water, and land. These pathways function as conduits through which pollutants, waste materials, and physical disturbances propagate beyond production sites. Air pathways contribute to atmospheric pollution and ecosystem stress; water pathways transmit heavy metals and sediments into riverine and coastal systems; and land pathways drive deforestation, soil degradation, and habitat fragmentation. These processes ultimately affect key receptors, ecosystems, and human populations, resulting in outcomes such as ecosystem degradation, biodiversity loss, and health and livelihood risks (Mabey et al., 2020; Odoh et al., 2024).

Rather than treating environmental impacts as discrete or short-term, this study interprets externalities as cumulative and spatially interconnected phenomena, where multiple pathways often operate simultaneously and reinforce one another. Such cumulative dynamics disproportionately affect environmentally and socially vulnerable communities and are increasingly recognized as characteristic of large-scale mineral extraction in developing economies, particularly where industrial expansion outpaces governance and regulatory capacity (Kafu-Quvane & Mlaba, 2024; Leonard, 2024; Teku, 2025).

Methodologically, the identification of externalities is derived from qualitative thematic analysis of peer-reviewed literature, supported by policy documents and environmental reports. Recurring patterns of land degradation, water and marine pollution, biodiversity disruption, and social risk were systematically coded and grouped into major categories of environmental externalities. Geospatial and remote sensing data were employed as a supporting analytical layer to visualize the spatial extent, persistence, and overlap of mining-related disturbances. Rather than serving as a primary measurement tool, spatial evidence provides contextual validation, illustrating how localized industrial activities translate into broader environmental transformations across landscapes and coastal systems (Frantz, 2019; Tang & Werner, 2023).

Through this analytical lens, environmental externalities are understood not merely as unintended by-products of nickel production, but as structurally embedded outcomes of resource-based

industrialization, shaped by the interaction between industrial practices, environmental pathways, and governance arrangements (Adranyi et al., 2024; Leonard, 2024).

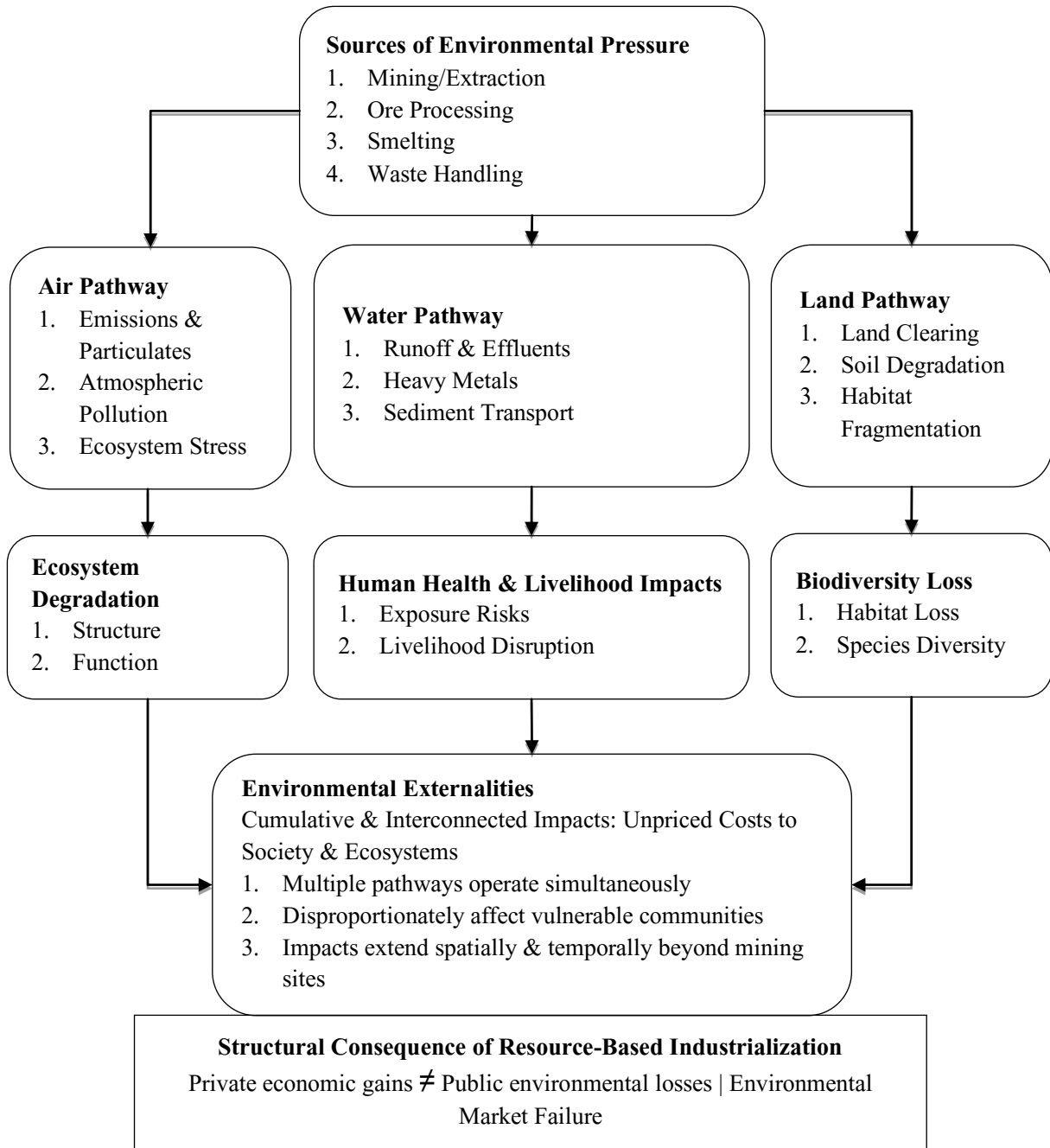


Figure 1: Environmental Externalities Framework: Nickel Mining and Processing

Source of Environmental Externalities

Environmental pressure in nickel mining arises from three core industrial activities: extraction, processing, and waste management, each of which generates emissions, effluents, and physical landscape alterations that collectively produce cumulative environmental stress (Gartsyanova et

al., 2025). In Indonesia, nickel mining operations generate diverse waste streams throughout the production cycle, including solid wastes such as waste rock, dust, and sludge; liquid wastes in the form of wastewater and process effluents; and gaseous emissions released during smelting and refining activities (Matinde et al., 2018). Major

nickel-producing regions, including Central Sulawesi (Morowali), Southeast Sulawesi (Kolaka and Kendari), North Maluku (Weda Bay and Obi Island), and Papua, have experienced rapid industrial expansion, intensifying environmental pressure across terrestrial and coastal systems. Empirical evidence indicates that heavy metal concentrations in soils surrounding mining areas frequently reach 2.5–3.5 times regulatory threshold values, confirming sustained contamination at the source level (Alborov, Tedeeva, et al., 2019).

These pressures are transmitted through interconnected air, water, and land pathways. Airborne pressure originates from quarrying, ore handling, and smelting operations, which emit particulate matter and sulfur compounds that degrade regional air quality. Studies demonstrate that mining-related emissions can disperse up to 20 km from extraction sites, with certain pollutants detected more than 100 km downwind (Horb et al., 2022). In Central Sulawesi and North Maluku, smelter operations have been associated with elevated particulate and SO₂ concentrations affecting surrounding settlements. Water pathways represent a critical mechanism through which environmental pressure propagates, as mining runoff and industrial effluents containing heavy metals and suspended solids contaminate rivers, estuaries, and marine ecosystems (Lao et al., 2024). In eastern Indonesia, including the Banda Sea, Morowali, and waters surrounding Obi Island, nickel-related discharges have been linked to riverine and coastal pollution, with case studies from Kendari documenting contamination concentrated in river mouths and nearshore zones (Rakuasa, Rifai, & Wutres, 2025). Land pathways reflect direct land-use change driven by mine development and infrastructure expansion, as well as secondary contamination through atmospheric deposition. Metal-bearing particulates released from mining activities have been shown to disperse 50–70 km, generating secondary soil contamination that affects agricultural systems and terrestrial ecosystems beyond concession boundaries (Zanetta-Colombo et al., 2024).

The magnitude and persistence of environmental pressure from nickel mining are well documented. Mining operations generate substantial dust emissions, estimated at 1.61–5.04 tonnes per

operational phase, reinforcing the role of mining sites as continuous sources of environmental stress (Zari et al., 2023). The spatial distribution of these pressures is uneven, with industrial clustering amplifying localized impacts and creating persistent contamination hotspots. Such conditions demonstrate that mining sites function not as temporary disturbances but as long-term sources of environmental degradation (Alborov, Burdzieva, et al., 2019).

The persistence of these pressures reflects a structural market failure inherent in extractive industries. While nickel mining generates significant private economic benefits, the environmental costs associated with pollution, ecosystem degradation, and health risks are not fully internalized by producers and are instead borne by surrounding communities and ecosystems (Akhtar et al., 2021). This misalignment between private gains and public environmental costs explains why environmental pressure continues to intensify in Indonesia's nickel-producing regions, despite the economic rationale of resource-based industrialization. The accumulation of these unpriced social and ecological costs underscores the need for integrated governance and mitigation approaches capable of addressing multiple environmental pathways simultaneously rather than isolated emission sources.

Externalities Impacts

Environmental externalities arising from the nickel industry are examined through a pathway-based analytical framework that identifies how industrial pressures are transmitted via air, water, and land systems. This approach responds directly to a key gap in existing literature, which has often treated environmental impacts as isolated sectoral outcomes rather than as interconnected processes operating across multiple environmental media. By tracing transmission pathways, this study demonstrates how pressures originating from mining and smelting activities propagate toward multiple receptors, including ecosystems, human health, and biodiversity. Importantly, these externalities are cumulative, transboundary, and long-term, with impacts intensifying over time and extending far beyond the immediate sites of extraction. In Indonesia, particularly in nickel mining and smelting regions such as Central Sulawesi, Halmahera, and Raja Ampat, this pattern

is clearly observable, as intensive industrial activity produces complex environmental footprints that are difficult to reverse (Hyldmo et al., 2025). This pathway-based framing, therefore, directly addresses the research question concerning how nickel industrialization generates systemic environmental externalities rather than discrete environmental disturbances.

Air-pathway externalities represent one of the most immediate manifestations of these pressures. Emissions of particulate matter and gaseous pollutants from quarrying, ore processing, and smelting induce physiological stress on vegetation and soils, reducing terrestrial ecosystem productivity. These effects are amplified by local climatic conditions, such as rainfall and topography, which shape pollutant dispersion and deposition patterns. Empirical evidence from Indonesia shows that sulfur dioxide and particulate emissions from nickel smelters in Morowali have contributed to measurable declines in vegetation quality and soil productivity in surrounding areas (Natsir et al., 2024). From a human health perspective, inhalation exposure to PM, SO₂, and heavy metals significantly increases the risk of respiratory and cardiovascular diseases among communities living near mining and smelting facilities. The uneven distribution of exposure where local residents face substantially higher risks than industrial actors highlights a core externality problem in which environmental and health costs are displaced onto vulnerable populations (Gultom et al., 2023). Comparable dynamics have been documented in Halmahera, where chronic illnesses linked to heavy metal exposure remain inadequately addressed by local health systems (Congge & Gohwong, 2023). Biodiversity impacts along the air pathway are similarly pronounced, as pollutant deposition degrades habitat quality and disproportionately affects pollution-sensitive species. Rapid mining expansion in Weda Tengah, Halmahera, where mining areas increased more than tenfold between 2016 and 2024, has coincided with a marked reduction in vegetated areas, signaling extensive habitat loss and ecological stress (Farrokhpay et al., 2019; Rakuasa, Rifai, Latulanit, et al., 2025).

Water-pathway externalities further illustrate the interconnected nature of nickel-related environmental pressures. Heavy metal

contamination and sediment discharge from mining and processing operations degrade water quality in rivers, estuaries, and coastal ecosystems, undermining critical ecological functions such as nursery habitats and nutrient cycling. In Morowali and Weda Bay, sedimentation linked to nickel mining and processing has been identified as a major threat to coral reef systems and to the livelihoods of fishing communities that depend on healthy coastal ecosystems. Recent regulatory reforms in Indonesia have explicitly recognized sedimentation and declining water quality as central governance challenges for small island regions (Zahar & Rosyid, 2025), underscoring the policy relevance of these findings. Human health risks emerge through contaminated drinking water and food chains, particularly via bioaccumulation in fish and seafood. Empirical studies in Central Halmahera document arsenic and mercury concentrations exceeding safety thresholds in both water and fish samples, highlighting chronic exposure risks and food security concerns for local communities (Oetomo et al., 2025). Aquatic biodiversity is also adversely affected, with pollution-sensitive species declining and pollution-tolerant species becoming dominant, leading to disrupted community structures and reduced ecosystem resilience (Nur et al., 2020).

Land-pathway externalities add a further layer of cumulative impact. Deforestation, soil degradation, and landscape fragmentation associated with nickel mining infrastructure directly reduce terrestrial ecosystem services, including carbon storage and water regulation, with implications for both local and global climate processes. In eastern Indonesia, large-scale nickel industrial expansion has resulted in the loss of thousands of hectares of high-value tropical forest, significantly diminishing ecosystem integrity and increasing long-term environmental vulnerability (Wibisono, 2024). Soil contamination from mining residues contributes to indirect human exposure through agricultural systems, reducing land productivity and household incomes while intensifying land-use conflicts. Studies indicate that farmers and fishers in mining regions frequently lose access to productive land and resources, while economic benefits from nickel industrialization are unevenly distributed (Adiansyah et al., 2023). Biodiversity impacts are particularly severe in

ecologically sensitive regions such as Raja Ampat, where mining expansion threatens globally significant terrestrial and marine species assemblages, compounding pressures from climate change and urban development (Amalia et al., 2025).

A critical contribution of this study lies in demonstrating how externalities operate across pathways simultaneously, producing reinforcing and cumulative impacts. Airborne pollutants can deposit onto land and water surfaces, linking atmospheric emissions to soil and aquatic contamination and creating complex pollution chains. In Morowali, emissions from nickel smelters not only degrade air quality but also accumulate in agricultural land and water sources, illustrating the multi-pathway transmission of environmental pressure (Herawati et al., 2025). Over time, these interacting pressures generate deep environmental injustice, as vulnerable communities and sensitive ecosystems disproportionately absorb the costs of nickel extraction. Empirical evidence from Sulawesi shows that downstream communities far removed from mine sites experience water pollution transmitted through regional river systems, highlighting the transboundary nature of these impacts (Amalia et al., 2025).

In synthesis, the environmental externalities associated with Indonesia's nickel industry reveal a structural imbalance between economic gains and environmental and social costs. While nickel industrialization contributes to national economic growth and global energy transition objectives, the associated environmental degradation and social displacement are borne primarily by local communities and ecosystems (Setiawan et al., 2025). Weak governance, limited public participation, and asymmetries in information and power exacerbate these outcomes, as documented in Morowali and Raja Ampat, where consultation processes are often procedural rather than substantive (Ananda, 2025). By integrating pathway-based environmental analysis with empirical case evidence, this study fills a critical gap in the literature and provides a more comprehensive understanding of how nickel-led development generates systemic externalities. Addressing these challenges requires regulatory reform, inclusive governance, and mechanisms to internalize environmental costs, ensuring that

economic development does not undermine environmental sustainability and intergenerational equity (Hapsari et al., 2025).

CONCLUSION

This study analyzed the environmental externalities of nickel mining and downstream processing in Indonesia using a pathway-based framework that traces how industrial pressures are transmitted through air, water, and land systems to ecosystems, human health, and biodiversity. Drawing on empirical evidence from major nickel-producing regions such as Morowali, Halmahera, and Raja Ampat, the findings show that nickel industrialization generates systemic, cumulative, and spatially dispersed environmental impacts rather than isolated disturbances.

Airborne emissions from mining and smelting degrade terrestrial ecosystems, increase health risks for surrounding communities, and disrupt biodiversity. Water-based pathways transmit heavy metals and sediments into riverine and coastal ecosystems, undermining aquatic functions, food security, and public health through bioaccumulation. Land-based impacts drive deforestation, soil degradation, and habitat fragmentation, resulting in long-term losses of ecosystem services. These impacts interact across pathways, producing cumulative effects that intensify environmental degradation and deepen environmental injustice.

By integrating multiple pathways and receptors, this study addresses a key gap in existing literature that has often examined environmental impacts in isolation. The findings demonstrate that environmental externalities extend well beyond mining sites, affecting downstream communities and ecologically sensitive regions, particularly small islands and coastal zones. From a governance perspective, the persistence of these externalities reflects a structural imbalance between private economic benefits and public environmental costs, exacerbated by weak enforcement and limited community participation.

Overall, the study highlights the need for integrated, pathway-aware governance approaches that internalize environmental costs, strengthen cumulative impact assessment, and promote inclusive decision-making. Such measures are essential to ensure that Indonesia's nickel-led

development supports economic objectives without compromising environmental sustainability and intergenerational equity.

This study recommends several priority actions to address the environmental externalities associated with nickel mining and downstream processing in Indonesia. First, environmental governance should adopt an integrated, pathway-aware approach that accounts for cumulative and cross-boundary impacts across air, water, and land systems. Environmental impact assessments must move beyond site-specific evaluations to incorporate spatial and temporal dimensions of environmental pressure.

Second, the internalization of environmental externalities should be strengthened through economic and regulatory instruments, including pollution-based fees, stricter liability provisions, and mandatory environmental restoration bonds. These mechanisms are essential to align private industrial incentives with public environmental costs, particularly in ecologically sensitive regions.

Third, environmental monitoring and enforcement need to be enhanced through continuous air and water quality monitoring, supported by remote sensing and transparent data platforms. Improved transparency can reduce information asymmetries and strengthen accountability among industrial actors and regulators.

Fourth, meaningful community participation and equitable benefit-sharing should be embedded in nickel development policies. Early and substantive involvement of local and Indigenous communities, combined with livelihood restoration and local economic inclusion, is critical to reducing environmental injustice.

Finally, Indonesia's nickel industrial strategy should be aligned with long-term sustainability objectives, ensuring that its role in the global energy transition does not come at the expense of domestic environmental integrity. Cleaner production technologies and stricter environmental standards are key to achieving this balance.

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