

## Designing a Model Using a Dynamic Systems Approach in the Utilization of Nickel Slag Waste

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### ABSTRACT

The nickel smelting industry in Indonesia generates substantial volumes of slag waste, which pose significant environmental risks if not managed effectively. Despite various utilization efforts, the accumulation of unmanaged nickel slag continues to increase annually, creating urgent sustainability challenges for the industry and surrounding ecosystems. This study aims to develop a comprehensive utilization model for nickel slag over the 2025–2034 time horizon. The research utilizes secondary data obtained from smelter company reports, relevant literature, and scenario simulations constructed using Powersim software. The dynamic systems model incorporates causal loop diagrams and stock-flow analysis to capture the complex interactions between production growth, slag generation, processing capacity, and utilization rates. The simulation outcomes reveal a progressive increase in slag generation that is disproportionate to the available processing capacity, resulting in the accumulation of unmanaged nickel slag from 23.68 million tons in 2023 to a projected 181.44 million tons by 2034 under current conditions. Scenario-based optimization demonstrates that enhancing processing capacity by approximately 5%–10% annually, combined with diversifying slag utilization pathways in construction materials and other value-added applications, can markedly reduce the volume of unmanaged slag and potentially eliminate accumulation by the end of the projection period. These results underscore the importance of adopting a circular economy framework supported by robust policy interventions, technological innovation, and multi-stakeholder collaboration to support sustainable nickel slag utilization within the smelting industry. The model provides actionable insights for industry practitioners and policymakers to design strategic interventions that balance production growth with environmental stewardship.

**KEYWORDS** *nickel slag, dynamic systems, waste utilization, smelting industry*



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### INTRODUCTION

High-grade nickel ore is needed for the processing industry or smelters in Indonesia. From the nickel ore production process, the nickel smelting industry produces waste in the form of nickel slag with a fairly large volume. Data from the Ministry of Environment's reporting application indicate that the amount of nickel slag waste produced every year is increasing along with rising nickel ore production. The laterite ore smelting process produces a large amount of solid waste in the form of slag. Judging from the upstream-to-downstream nickel ore production process, nickel mining is an important activity in the global economy, but it also has significant environmental impacts (Cerai, 2024; Supriadi et al., 2025; Tela & Yu, 2025; Wang et al., 2022). Nickel mining represents a critical activity in the global economy, particularly with the rising demand for electric vehicle batteries and stainless-steel production; however, it simultaneously generates significant environmental impacts that require systematic management approaches.

With the increasing amount of nickel slag waste produced every year, difficulties arise in implementing nickel slag waste management (Bartzas et al., 2021; Quéheille et al., 2021; Susanto et al., 2020; Zhang et al., 2017). This is evident from existing data showing that much of the nickel slag waste produced remains stored without further utilization. This accumulation

pattern illustrates a critical gap between slag generation rates and available management capacity. Waste that is not managed further will accumulate in quantity, and with large volumes that cannot be processed, it creates substantial environmental, operational, and regulatory challenges for the smelting industry.

Nickel slag waste, which results from the nickel ore processing process, has several impacts on the environment. These impacts include potential soil contamination, groundwater pollution from leachate, land occupation for storage facilities, and loss of opportunities for resource recovery. These conditions reveal a phenomenon indicating systemic problems in waste governance. With the increasing amount of nickel slag waste produced, fulfilling the obligation to manage it correctly in accordance with regulations becomes more difficult (Fatmeriany et al., 2025; Godbole et al., 2025; Keskin et al., 2024; Srivastava et al., 2022). To overcome this phenomenon, an optimal nickel slag waste management system must be created.

Despite growing research on nickel slag utilization in construction materials (Ashad & Gunawan, 2022; Mustika et al., 2021; Nuroji et al., 2022), significant research gaps remain regarding the systemic modeling of slag management under dynamic production conditions. Previous studies have primarily focused on material properties and specific applications, while lacking comprehensive system-level analysis that integrates production trends, processing capacity constraints, regulatory frameworks, and multi-year projections. Furthermore, the application of dynamic systems modeling—a methodology proven effective in complex waste management scenarios (Budiyanto, 2021; Retuerto et al., 2021)—has not been adequately explored in the context of nickel slag utilization in Indonesia.

This study addresses these gaps by employing a dynamic systems approach to analyze and optimize nickel slag waste management over a ten-year projection period. The novelty of this research lies in its integrated modeling framework that captures feedback loops between production growth, slag generation, management capacity, and utilization pathways, enabling scenario-based policy analysis and strategic planning. The purpose of the study is to analyze the optimal nickel slag waste management system by identifying and evaluating the existing nickel slag waste management system and then creating a model of the nickel slag waste management system that can be implemented by the waste-producing industry and the waste management industry while still referring to the provisions in the applicable laws and regulations in Indonesia. Specifically, this research aims to: (1) develop a validated dynamic systems model of nickel slag management; (2) project future slag accumulation patterns under current management scenarios; (3) evaluate alternative policy interventions through scenario simulation; and (4) provide evidence-based recommendations for achieving sustainable slag utilization.

## **METHOD**

This research was conducted using a mixed-methods approach combining qualitative and quantitative techniques. The qualitative approach involved descriptive analysis of current management practices and stakeholder analysis to understand the roles, interests, and capacities of various actors in the nickel slag management system. The quantitative approach focused on secondary data collection and measurement of variables affecting nickel slag waste utilization and their systemic interactions. This study also employed dynamic systems modeling to examine the complexity of interactions between factors in the nickel slag waste utilization

system. Through this modeling, different scenarios were evaluated to maximize slag utilization and assess impacts on the overall system.

### **Data Collection and Validation**

Secondary data for this study were systematically collected from multiple sources to ensure reliability and comprehensiveness. Primary data sources include: (1) annual production and waste management reports from 40 nickel smelter companies registered with the Ministry of Environment's reporting system for the period 2021–2024; (2) regulatory documents including Law No. 11 of 2020 on Job Creation (as amended by Law No. 6 of 2023), Government Regulation No. 22 of 2021, and Ministry of Environment and Forestry Regulation No. 19 of 2021; (3) peer-reviewed academic literature on nickel slag properties, utilization technologies, and waste management systems; and (4) industry technical reports and feasibility studies on slag processing technologies.

Data validation was conducted through triangulation, comparing figures across multiple reports and cross-referencing with official government statistics. Outliers and inconsistencies were identified and resolved through consultation with industry experts and verification against historical trends. Where data gaps existed, conservative estimates were applied based on industry standards and similar facility benchmarks. The validated dataset covers production volumes, slag generation rates (with ratios ranging from 1.8 to 2.2 tons of slag per ton of ferronickel product), current management capacity (utilization and landfill), and unmanaged slag accumulation.

### **Model Development and Assumptions**

Model development using Powersim software. Dynamic systems models are built on the basis of the functional relationships between the identified variables. This model includes mathematical equations that describe the interactions between variables. Powersim is used to build and simulate a dynamic model. A dynamic model is a collection of variables that affect each other over a period of time. Each variable corresponds to a real quantity or a self-made quantity. All of these variables have numerical values and are already part of it. When simulating the model, the variables will be interconnected to create a system that can mimic the actual conditions. In powersim software, a system that describes the relationship between variables is called a flow diagram. These variables will be depicted with several symbols, the main one being the flow symbol which is always connected to the level symbol through a thick arrow for the flow process. The flow of objects that can flow here is goods, money, people, etc., which can be observed, and measured by their addition and subtraction in the level. In level modeling, it represents the main issue that is of concern.

The Powersim model developed in this study is based on several critical assumptions validated through literature review and expert consultation: (1) The production growth rate follows historical trends observed during 2021–2024, with an average annual increase of 25–30% reflecting industry expansion plans and government downstream processing targets; (2) The slag generation ratio of 2:1 (slag to nickel product) represents the average across different smelter technologies (RKEF and blast furnace), acknowledging variations based on ore grade and process efficiency; (3) Current management capacity remains constant at 64% annually unless modified in intervention scenarios, representing the combined capacity of utilization

(50%) and landfill (14%) pathways; (4) The model assumes no catastrophic disruptions (e.g., major policy changes, facility closures, natural disasters) during the projection period; (5) Utilization pathways include construction aggregates, cement additives, road base materials, and emerging applications based on existing research (Bethary et al., 2023; Cosme et al., 2021; Ngii et al., 2020); and (6) Environmental carrying capacity and storage space limitations are implicit in the model through the accumulation dynamics but are not explicitly quantified.

To build a dynamic system model that will be used in this study, some specific data is needed, including:

- a. **Input Variables:** Data regarding the main input variables in the system, such as nickel production volume, volume of slag produced, waste treatment capacity, and waste utilization rate.
- b. **Inter-Variable Linkage:** Information about the functional relationship between variables in the system, such as the relationship between production volume and slag volume, or the relationship between the level of waste utilization and the capacity of waste utilization in accordance with regulatory factors.
- c. **Data for Model Calibration and Validation:** Historical data that can be used to calibrate and validate dynamic system models. This includes data from previous periods that can be compared with the results of the model's simulation to ensure accuracy.

## **RESULT AND DISCUSSION**

The object of this research is the nickel smelter industry in Indonesia which is recorded in the application of the Ministry of Environment and reports nickel slag waste management data for 40 companies. This industry is a company that produces laterite nickel ore processing into semi-finished products in the form of Ferronickel (FeNi) or Nickel Matte which is used as raw materials for the stainless steel industry and electric vehicle batteries. The production process in the nickel smelting industry includes stages: ore pre-treatment, drying, calcining, reduction-smelting, refining and casting. Through the smelting process, in addition to producing nickel products, solid waste in the form of nickel slag is also produced. Slag is a non-metallic residue formed from nickel ore impurities that are separated in the smelting process at high temperatures ( $\pm 1,500^{\circ}\text{C}$ ).

These smelter industries have an average production capacity of 21,113,751.17 tons per year, with a total average of 42,227,502.34 tons of nickel slag generation per year during the 2021-2024 period. Every 1 ton of ferronickel products produced generally produces 1.8 – 2.2 tons of nickel slag waste, depending on the level of Ni in the ore and the type of smelter technology used.

### **Nickel Slag Generation and Management Data**

Existing data on nickel slag management is presented in Table 3.1 below. It can be seen that the generation of nickel slag waste has increased every year, from 7,226,940.88 tons in 2021 to 108,564,284.76 tons in 2024. New nickel slag processing can be carried out at 168,910,009.40 tons, so there is a difference in unmanaged nickel slag of 75,911,347.48 tons during the period of 2021 - 2024.

Table 1. Nickel Slag Waste Generation Data

Year	Production Quantity (Ton)	Amount generated (Ton)	Amount Managed (Ton)	Not Managed (Ton)
2021	4.014.967,15	7.226.940,88	4.038.813,00	3.188.127,88
2022	26.362.642,45	52.725.284,89	26.398.114,58	26.327.170,31
2023	34.684.021,07	76.304.846,35	56.661.041,96	19.643.804,39
2024	49.347.402,16	108.564.284,76	81.812.039,86	26.752.244,90
<b>Total</b>	<b>114.409.032,80</b>	<b>244.821.356,88</b>	<b>168.910.009,40</b>	<b>75.911.347,48</b>

### Slag Generation Trend Chart

Referring to the waste generation data above, it shows a significant trend of increasing nickel slag generation. This increase is in line with an increase in nickel production.

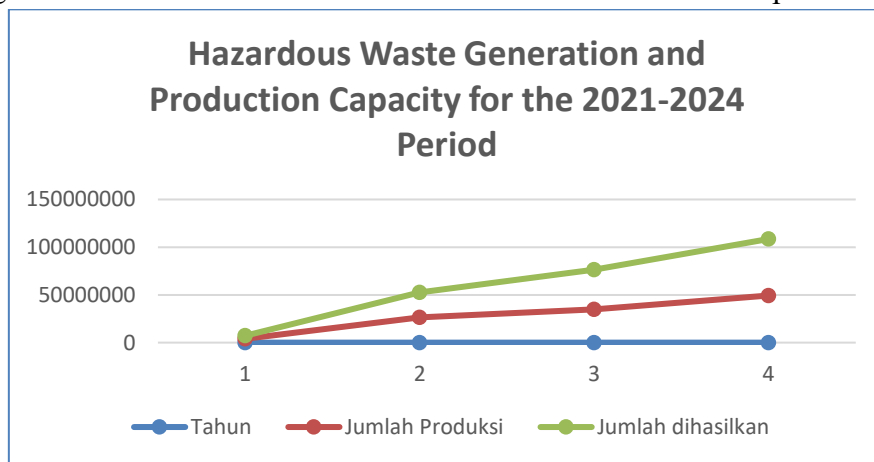


Figure 1. Nickel Slag Waste Generation Trend Chart and Production Capacity

With the increase in nickel slag waste generation, it is not balanced with the optimal capacity of nickel slag management. This condition causes the accumulation of unmanaged nickel slag to continue to increase every year.

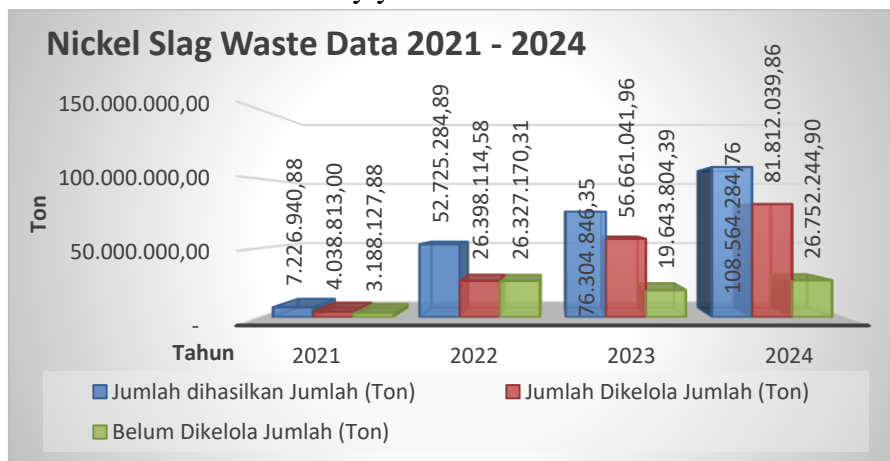


Figure 2. Nickel Slag Waste Generation and Management Trend Chart

The growth of slag generation which is much faster than its management capacity causes slag accumulation to continue to increase. Without strategic intervention, this condition has the potential to cause environmental and technical problems, so optimal management capacity planning is needed through a dynamic system approach.

### Causal Loop Diagram

Before making a nickel slag waste management model, it is necessary to know several factors that affect the occurrence of nickel slag waste deposits. This is necessary for the creation of causal loops. The causal loop is then the basis for thinking in the development of a nickel slag waste management model. This model is made based on two alternative waste management, namely utilization and landfill. From these two activities, if there is not enough capacity for management, there will be a buildup of nickel slag waste that cannot be managed.

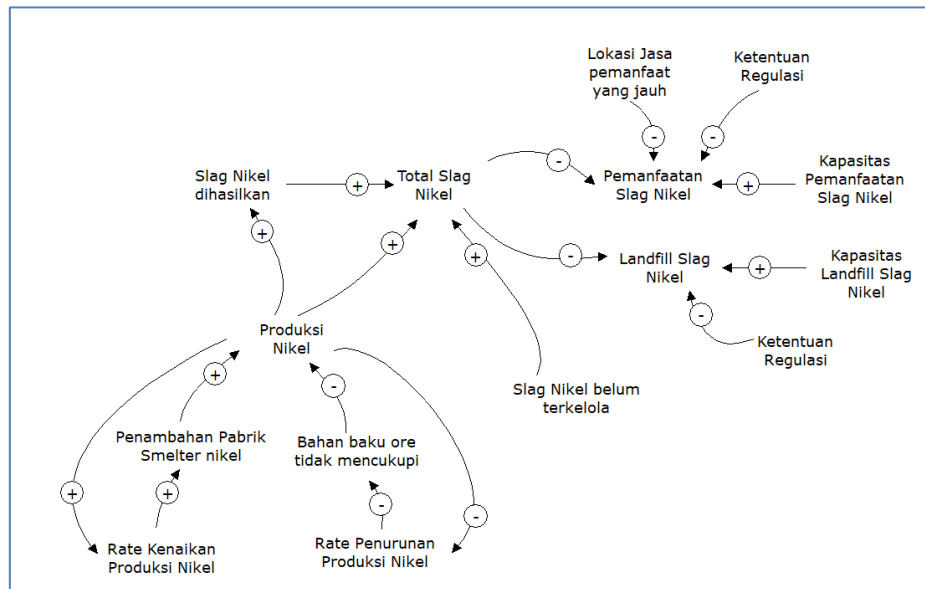


Figure 3. Causal Loop Nickel Slag Waste Management Diagram

### Stock and Flow Diagram

To provide a more comprehensive overview of the structure of the nickel slag waste utilization system, in this sub-chapter a Flow Diagram (Stock and Flow Diagram) is presented used in the preparation of a dynamic system model. This diagram illustrates the relationships between the main components of the system, including stock variables (slag buildup), flow variables (slag production rate and slag management rate), and supporting variables that affect slag volume changes over time.

This model aims to show how the dynamics of nickel slag availability are affected by management capacity, production growth, and efforts to increase utilization. By looking at the relationship structure in the diagram, it is possible to understand the overall behavior of the system and use it as a basis for preparing scenarios and simulations for the next 10-year projection period. The following is a Flow Diagram (Stock and Flow Diagram) which is the basis for the development of a simulation model in this study.

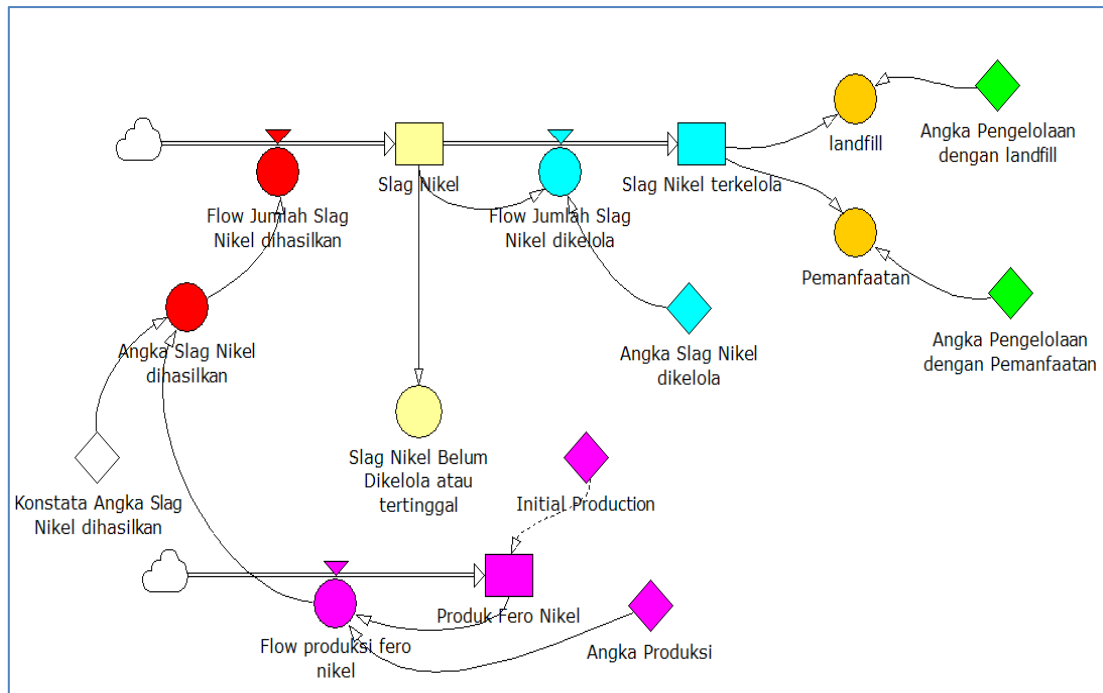


Figure 4. Nickel Slag Waste Management Flow Diagram

The modeling flow diagram is created with consideration of existing data and processes. From the initial production data in 2021 to the last production in 2024. From the ferronickel production figure, the next production flow will be obtained. From this production flow, it will then be possible to calculate the nickel slag waste produced per unit of time. From the available data, the average nickel product and the average nickel slag waste are produced with a ratio of 1 : 2. Furthermore, calculations can be carried out with nickel slag waste management activities carried out by means of utilization and landfill, with a total management of 64% per year. Unmanaged nickel slag waste is 36%.

### Model Formulation and Mathematical Equations

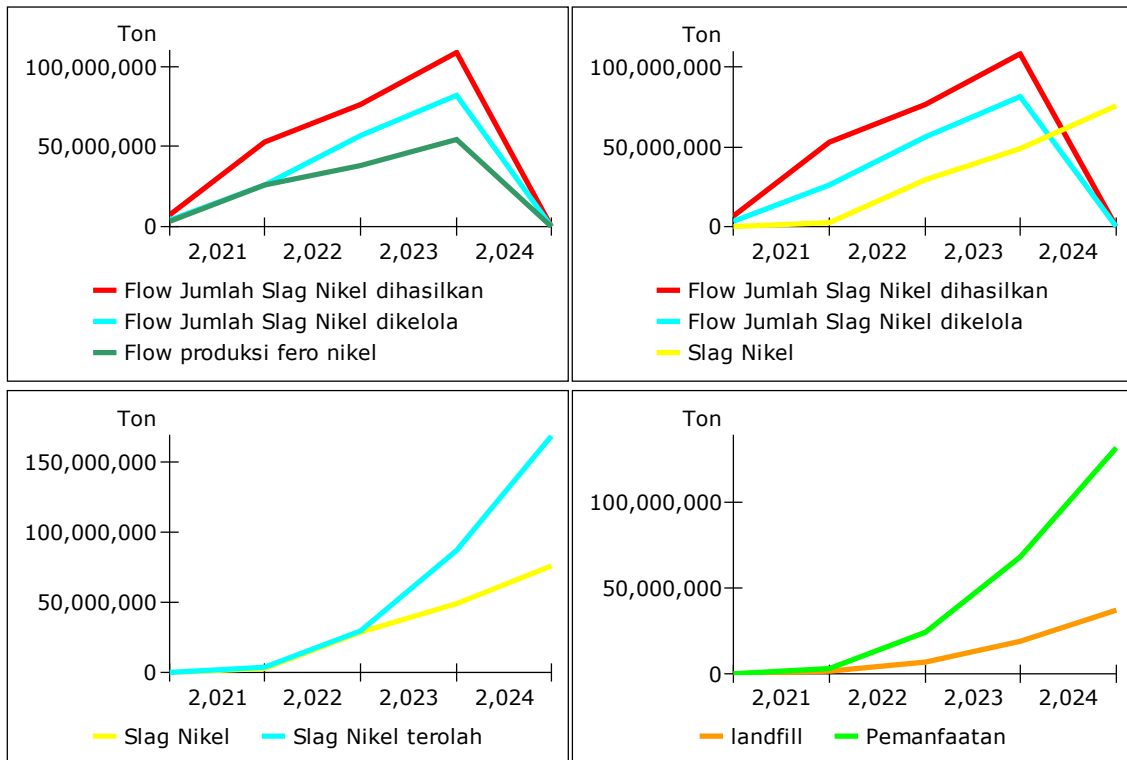
The mathematical equations in the calculations carried out on the powersim application are as follows:

- Iron Nickel Production Flow = Iron Nickel \* Production Growth Rate.
- Nickel Slag Rate generated = Iron nickel production flow \* Nickel Slag Rate Rate Condensation is produced.
- Flow Amount of Nickel Slag produced = Number of Nickel Slag produced
- Nickel Slag = Flow Total Nickel Slag produced - Flow Total Nickel Slag is managed
- Unmanaged or Under-Managed Nickel Slag = Nickel Slag
- Nickel Slag Rate Managed = 64 %/year
- Processed Nickel Slag = accumulated Nickel Slag Numbers managed
- Management Numbers with landfill =  $14/64 * 100 \%$
- Management Numbers with Utilization =  $50/64 * 100 \%$
- Landfill = Managed numbers with landfill \* Nickel slag managed
- Utilization = Management number with Utilization \* Nickel Slag managed

From the model equations made, a model scenario will be made for a period of 10 years from the 2024 nickel slag waste data. The calculation scenario in 2025 to 2034, to find out the amount of ferronickel products, the amount of nickel slag waste, the management capacity of nickel slag waste, and the amount of nickel slag waste that cannot be managed.

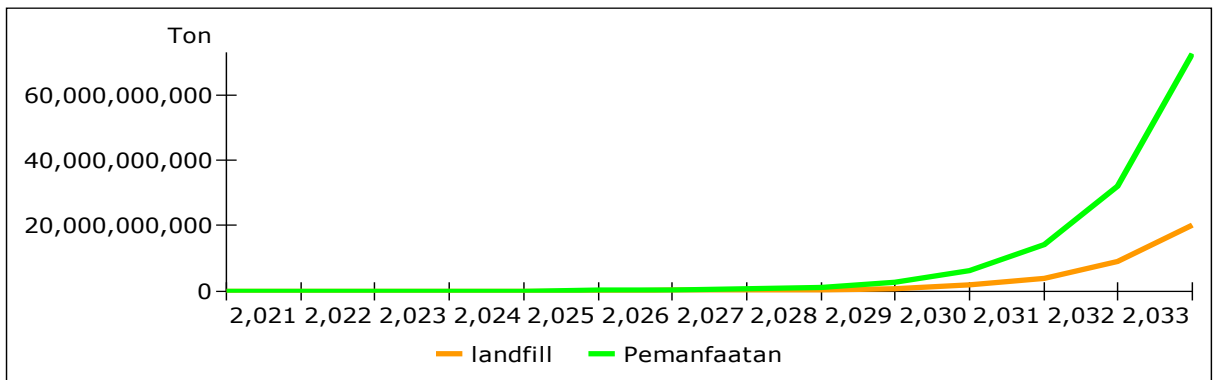
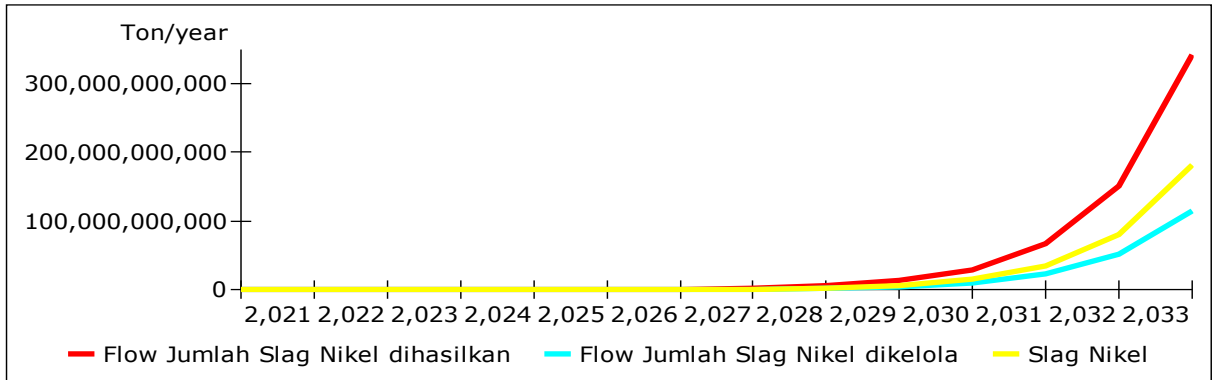
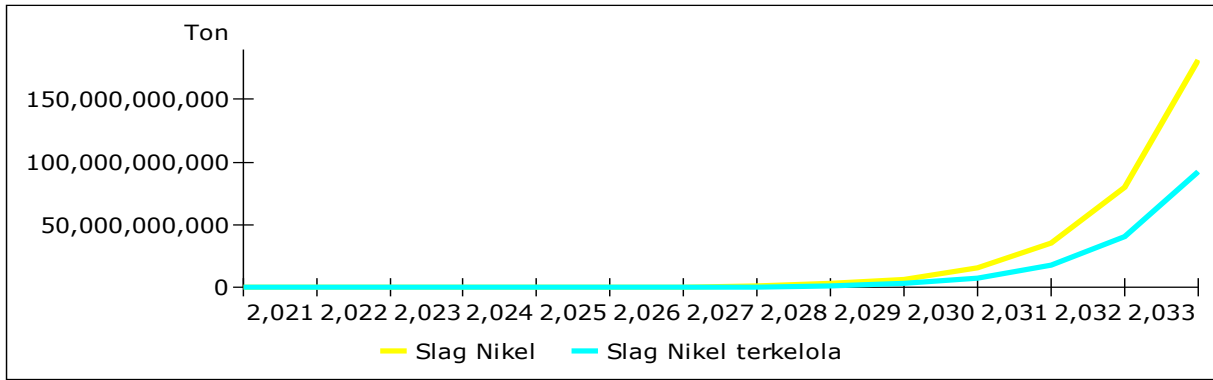
### 1. Model Simulation Results

a. Simulation of the existing conditions of nickel slag waste management for the period 2021 - 2024 is as follows.



(Ton)									
year	Angka Slag Nikel dihasilkan	Angka Slag Nikel dikelola	Slag Nikel	Slag Nikel terolah	Slag Nikel Belum Dikelola atau tertinggal	Flow produksi fero nikel	Fero Nikel	landfill	Pemanfaatan
2,021	7,226,940.88	4,038,813.00	0.00	0.00	0.00	3,613,470.44	0.00	0.00	0.00
2,022	52,725,284.89	26,398,114.58	3,188,127.88	4,038,813.00	3,188,127.88	26,362,642.45	3,613,470.44	883,490.34	3,155,322.66
2,023	76,304,846.35	56,661,041.96	29,515,298.19	30,436,927.58	29,515,298.19	38,152,423.17	29,976,112.89	6,658,077.91	23,778,849.68
2,024	108,564,284.76	81,812,039.86	49,159,102.58	87,097,969.54	49,159,102.58	54,282,142.38	68,128,536.06	19,052,680.84	68,045,288.70
2,025	0.00	0.00	75,911,347.48	168,910,009.40	75,911,347.48	0.00	122,410,678.44	36,949,064.56	131,960,944.84

b. Simulation of nickel slag waste management modeling for the next 10 years for the period 2025 - 2034 is as follows.



year	Angka Slag Nikel dihasilkan (Ton/year)	Angka Slag Nikel dikelola (%/year)	Slag Nikel (Ton)	Slag Nikel terkelola (Ton)	Slag Nikel Belum Dikelola atau tertinggal (Ton)	Flow produksi fero nikel (Ton/year)	Produk Fero Nikel (Ton)	landfill (Ton)	Pemanfaatan (Ton)
2,021	9,033,676.10	64.00	0.00	0.00	0.00	4,516,838.05	3,613,470.44	0.00	0.00
2,022	20,325,771.23	64.00	9,033,676.10	0.00	9,033,676.10	10,162,885.61	8,130,308.49	0.00	0.00
2,023	45,732,985.26	64.00	23,577,894.62	5,781,552.70	23,577,894.62	22,866,492.63	18,293,194.10	1,264,714.65	1,264,714.65
2,024	102,899,216.83	64.00	54,221,027.32	20,871,405.26	54,221,027.32	51,449,608.41	41,159,686.73	4,565,619.90	4,565,619.90
2,025	231,523,237.86	64.00	122,418,786.66	55,572,862.75	122,418,786.66	115,761,618.93	92,609,295.14	12,156,563.73	12,156,563.73
2,026	520,927,285.18	64.00	275,594,001.06	133,920,886.21	275,594,001.06	260,463,642.59	208,370,914.07	29,295,193.86	29,295,193.86
2,027	1,172,086,391.67	64.00	620,141,125.57	310,301,046.89	620,141,125.57	586,043,195.83	468,834,556.67	67,878,354.01	67,878,354.01
2,028	2,637,194,381.25	64.00	1,395,337,196.87	707,191,367.25	1,395,337,196.87	1,318,597,190.62	1,054,877,752.50	154,698,111.59	154,698,111.59
2,029	5,933,687,357.80	64.00	3,139,515,772.12	1,600,207,173.24	3,139,515,772.12	2,966,843,678.90	2,373,474,943.12	350,045,319.15	350,045,319.15
2,030	13,350,796,555.06	64.00	7,063,913,035.77	3,609,497,267.40	7,063,913,035.77	6,675,398,277.53	5,340,318,622.02	789,577,527.24	789,577,527.24
2,031	30,039,292,248.88	64.00	15,893,805,247.94	8,130,401,610.29	15,893,805,247.94	15,019,646,124.44	12,015,716,899.55	1,778,525,352.25	1,778,525,352.25
2,032	67,588,407,559.99	64.00	35,761,062,138.14	18,302,436,968.97	35,761,062,138.14	33,794,203,780.00	27,035,363,024.00	4,003,658,086.96	4,003,658,086.96
2,033	152,073,917,009.98	64.00	80,462,389,929.72	41,189,516,737.38	80,462,389,929.72	76,036,958,504.99	60,829,566,803.99	9,010,206,786.30	9,010,206,786.30
2,034	342,166,313,272.45	64.00	181,040,377,384.68	92,685,446,292.40	181,040,377,384.68	171,083,156,636.23	136,866,525,308.98	20,274,941,376.46	20,274,941,376.46

### Simulation Scenario Analysis

Based on the results of the simulation of the nickel slag management scenario over the next 10-year period (2025–2034), it can be seen that the amount of slag produced shows a very significant increase from year to year. At the beginning of the 2021 simulation, the slag produced was 9,363,676.10 tons and continued to increase sharply until it reached 342,185,313,272.45 tons in 2034. This increase is the impact of the exponentially increasing

growth of smelter production capacity. Meanwhile, the management ability of nickel slag is very limited, which is only 64% per year and has not increased in the simulation period. This condition causes a huge difference between the amount of nickel slag produced and the amount of nickel slag that can be managed. As a result, there is an increase in slag accumulation that has not been handled every year.

The accumulation of unmanaged nickel slag began to increase to 23,677,964.52 tons in 2023, 153,212,859.95 tons in 2029 and reached 181,440,377,384.29 tons by the end of 2034. This value describes the burden of slag accumulation that is getting larger over time and has the potential to cause storage space limitations, environmental risks, and large investment needs if management intervention is not carried out. The simulation results show that with the current management capacity, the nickel slag management system is not able to keep up with the growth of nickel slag production, so the slag buildup will continue to increase drastically. This emphasizes that the strategy of increasing slag processing capacity or diversifying its use as a construction material is very important to avoid wider environmental and operational impacts in the future.

The following is an analysis table that creates a risk in the future if no policy is taken for the further management of nickel slag waste.

Table 2. Simulation scenario analysis

Indicator	Value
Early slag production (2021)	9.03 million tons
Simulation final slag production (2034)	342.16 million tons
Management capacity	64 %/year (fixed)
Unmanaged slag accumulation 2034	181.04 million tons
Production trends	Very sharp (exponential) increase
Risks	Build-up in the environment increases dramatically

## 2. Results of Nickel Slag Simulation for the Year 2021–2034

The following is the calculation (tons) for each year in the 2021–2034 period based on the Powersim model of the production value. The results of the calculation of additional capacity needs (tons/year). The total additional capacity needed during the 2021-2034 period (the sum of all additional nickel slag per year) is 221.68 billion tons.

Table 3. Nickel slag management capacity required during the period 2021–2034

Year	Produced Nickel Slag (Ton)	Nickel slag managed by 64% (tons)	Unmanaged (Tons)
2021	9.033.676,10	5.781.552,70	3.252.123,40
2022	20.325.771,23	13.008.493,59	7.317.277,64
2023	45.732.985,26	29.269.110,57	16.463.874,69
2024	102.899.216,83	65.855.498,77	37.043.718,06
2025	231.523.237,86	148.174.872,23	83.348.365,63
2026	520.927.285,18	333.393.462,52	187.533.822,66
2027	1.172.086.391,57	750.135.290,60	421.951.100,97
2028	2.537.194.381,25	1.623.804.404,00	913.389.977,25
2029	5.933.687.357,80	3.797.559.908,99	2.136.127.448,81
2030	13.350.796.555,06	8.544.509.795,24	4.806.286.759,82
2031	30.039.292.248,88	19.225.146.239,28	10.814.146.009,60
2032	67.588.407.559,99	43.256.981.638,39	24.331.425.921,60

Year	Produced Nickel Slag (Ton)	Nickel slag managed by 64% (tons)	Unmanaged (Tons)
2023	152.073.917.009,98	97.327.106.086,39	54.746.810.923,59
2034	342.165.313.272,45	218.986.801.495,37	123.178.511.777,08
<b>Quantity</b>	<b>615.791.136.949,44</b>	<b>394.107.527.848,64</b>	<b>221.683.609.100,80</b>

### Discussion

The results of the nickel slag management simulation during the 2021–2034 period show a very significant slag growth pattern from year to year, with management capacity not increasing. This causes an accumulation of untreated slag that continues to increase over time. In 2021 there has been no accumulation, but in 2023 the accumulation of unmanaged slag has reached 23.57 million tons and increased drastically to reach 181.04 million tons in 2034.

The findings of this simulation provide technical implications that slag management capacity must be significantly increased to be able to keep pace with the growth of slag production. The calculations show that the additional capacity required continues to increase every year and cumulatively reaches 615.89 billion tons over 14 years. This condition emphasizes that the strategy of increasing processing capacity must be carried out gradually and planned, for example by investing in new slag processing facilities, applying advanced processing technology (slag processing for reuse), and diversifying the use of slag into value-added commercial products. From a policy perspective, this result provides the basis for the need for regulations and incentives to encourage the use of nickel slag as a resource that can be reused with the implementation of the Circular Economy. The government can encourage cooperation between the smelter industry, construction companies, and universities to accelerate the commercialization of nickel slag-based products.

### CONCLUSION

This study concludes that a dynamic systems model effectively captures the unsustainable trajectory of nickel slag waste management in Indonesia's smelting industry, projecting a dramatic increase in unmanaged slag from 23.68 million tons in 2023 to 181.44 million tons by 2034 under current conditions. The model reveals that the significant gap between exponential slag generation and static processing capacity (64% annually) necessitates urgent strategic intervention. Scenario analysis demonstrates that a combined strategy of systematically increasing processing capacity by 5–10% annually and diversifying utilization pathways—particularly into construction materials—can substantially mitigate accumulation and align the system with circular economy principles. Future research should focus on validating the model with primary, real-time operational data from smelters, integrating economic and lifecycle assessment (LCA) variables to evaluate the cost-effectiveness and environmental benefits of specific utilization technologies, and expanding the system boundaries to include social acceptance, regulatory enforcement mechanisms, and cross-sectoral supply chain dynamics to support holistic policy formulation and industry adoption.

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