

Evaluating Environmental Sustainability Performance through Green Industry Standards in Indonesian Ammonia Production

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Abstract

The fertilizer industry is a strategic sector that supports global food security. However, the production processes associated with this industry are characterized by high energy consumption and significant greenhouse gas emissions. The present study assesses environmental management and corporate performance within an integrated ammonia and urea production system based on Green Industry Standard (GIS) indicators. A quantitative descriptive approach was employed; whereby corporate performance was measured through the use of key performance indicators (KPIs), trend analysis, and benchmarking against national GIS technical requirements. Secondary data from operational records, annual reports, and sustainability reports covering the period of 2021–2024 were analysed. The outcomes demonstrate that economic growth is concomitant with alterations in environmental and economic performance. Ammonia and urea production increased by 13% and 11.5%, respectively, while natural gas consumption intensity remained relatively stable, with only a 0.15% increase compared with the baseline period. Nevertheless, greenhouse gas emission intensity exhibited a 35.8% increase compared to the 2021 baseline level, signifying that the effective management of emissions continues to pose a substantial challenge to the pursuit of sustainable industrial performance. From an economic vantage point, the augmentation in production capacity was accompanied by a 19.1% diminution in net profit margin, underscoring the necessity of achieving a balance between operational efficiency and environmental objectives. The findings indicate that Green Industry Standards offer a quantifiable framework for evaluating sustainability outcomes in energy-intensive fertilizer industries. To this end, there is an imperative for ongoing enhancement in emission reduction strategies, energy efficiency, and operational reliability. Such enhancements are crucial for fortifying environmental management practices and underpinning long-term corporate sustainability.

Keywords

Green Industry Standard, Corporate Sustainability, Environmental Performance, Fertilizer Industry, Energy Intensity, Greenhouse Gas Emission

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1. INTRODUCTION

The fertilizer industry plays a critical role in supporting global food production and agricultural sustainability. Among diverse categories of fertilizer products, urea stands as a preeminent nitrogen fertilizer, a distinction attributable to its substantial nitrogen content, rendering it indispensable for augmenting agricultural productivity. The production of urea is contingent upon ammonia, which serves as the pivotal intermediate product. This underscores the pivotal role of the ammonia industry within the broader context of the global fertilizer supply chain (Food and Agriculture Organization of the United Nations, 2019). The Haber–Bosch

process is the predominant method of ammonia production. It requires hydrogen, which is obtained from natural gas-based steam methane reforming. This process is recognized as one of the most energy-intensive activities in the chemical industry due to its high demand for thermal energy and feedstock resources (Amhamed et al., 2022; Erfani et al., 2024). According to the International Energy Agency (IEA), the production of ammonia contributes approximately 2% of global energy consumption and around 1.8% of global carbon dioxide emissions (International Energy Agency, 2021). Consequently, enhancing energy efficiency and reducing emissions have emerged as pivotal

strategies for achieving sustainable fertilizer production.

In the face of mounting environmental pressure and growing commitments to sustainability, industrial sectors have been compelled to shift their focus from conventional production objectives toward more balanced approaches that integrate economic performance with environmental protection and social responsibility. Corporate sustainability frameworks emphasize that long-term industrial competitiveness requires the integration of these three dimensions through measurable performance indicators (Dyllick and Muff, 2016; Lozano, 2015). A significant strategy for the promotion of sustainable industrial development is the concept of green industry. The green industry framework emphasises efficient resource utilisation, environmentally responsible production processes, and continuous improvement in industrial performance (Kusumastuti, 2023). This concept is closely aligned with the broader sustainability paradigm represented by the triple bottom line, which integrates environmental, economic, and social dimensions into corporate performance evaluation (Elkington, 1997; Książak and Fischbach, 2018).

In order to support the implementation of corporate sustainability, a number of internationally recognised assessment frameworks have been developed, each of which serves a complementary purpose. The Global Reporting Initiative (GRI) provides a comprehensive reporting framework that standardises the disclosure of environmental, economic, and social performance (Adams et al., 2022). Environmental, Social, and Governance (ESG) frameworks are utilised to evaluate sustainability from an investment and governance perspective (Padilla-Rivera et al., 2025). Conversely, ISO 14001 establishes an Environmental Management System (EMS) that is oriented towards continual improvement through systematic planning and monitoring (Hasanah et al., 2022). Life Cycle Assessment (LCA) provides a comprehensive evaluation of environmental impacts throughout the product life cycle (D'Eusanio et al., 2025). Despite the substantial advancement these frameworks have brought to industrial sustainability, it is important to note that each was developed for different overarching objectives. Consequently, there is an absence of explicit integration of sector-specific operational performance indicators with stringent regulatory compliance requirements for routine, plant-level sustainability evaluation in energy-intensive manufacturing industries. This creates a critical research gap in the operationalisation of sustainability assessments that directly align with national technical targets. The Green Industry Standard (GIS) addresses this gap by combining measurable operational indicators with sector-specific regulatory thresholds, making it a uniquely suitable framework for evaluating annual operational performance, socio-economic resilience, and environmental compliance in Indonesian ammonia manufacturing.

Within this context, the Green Industry Standard (GIS) issued by the Indonesian Ministry of Industry represents a regulatory-based sustainability assessment framework specif-

ically designed to improve industrial resource efficiency and environmental performance. Unlike internationally recognized sustainability reporting or management frameworks, GIS establishes sector-specific technical requirements covering resource utilization, energy efficiency, production processes, environmental management, and performance evaluation through measurable operational indicators. Therefore, GIS functions not only as an environmental management instrument but also as a regulatory benchmark for assessing industrial operational sustainability at the plant level while supporting Indonesia's low-carbon industrial development strategy (Kementerian Perindustrian Republik Indonesia, 2023; Kementerian PPN/Bappenas, 2024; Kusumastuti, 2023; Styawati et al., 2023). The fertilizer industry provides a significant context for evaluating corporate performance based on GIS due to its substantial consumption of energy and natural resources. In the context of ammonia and urea manufacturing, natural gas fulfils dual roles: it serves as both an energy source and the primary feedstock. Consequently, enhancements in energy efficiency, resource, and process reliability can substantially impact environmental performance and greenhouse gas emissions (International Renewable Energy Agency and Ammonia Energy Association, 2022).

A number of studies have emphasized the importance of energy efficiency and emission-reduction strategies in ammonia production systems. Process optimization, technological improvements, and energy integration strategies have been identified as key approaches for reducing energy consumption and improving environmental performance in fertilizer manufacturing (Lee et al., 2022; Liu et al., 2020). Recent studies have also explored emerging pathways for low-carbon ammonia and sustainable fertilizer production, including renewable hydrogen and process intensification technologies (Mao et al., 2024). Moreover, the evolution of sustainability performance measurement systems has empowered organizations to methodically assess environmental and social performance through the use of quantifiable indicators. These frameworks enable companies to assess the efficacy of sustainability initiatives and align operational practices with overarching sustainability objectives (Adams et al., 2022; Searcy, 2012).

Despite the growing body of literature on sustainable ammonia production, previous studies have predominantly focused on technological innovations, energy efficiency improvement, emission reduction strategies, and life-cycle environmental assessments (Lee et al., 2022; Liu et al., 2020; Mao et al., 2024). Comparatively limited attention has been devoted to evaluating how regulatory sustainability frameworks influence operational performance in energy-intensive fertilizer industries. Furthermore, environmental, economic, and social sustainability indicators are commonly assessed independently, while few studies integrate sector-specific technical operational indicators with broader sustainability dimensions within a regulatory assessment framework.

Table 1. Data Categories, Variables Collected, Units, Sources, and Analytical Uses

Data Category	Variables Collected	Unit	Source	Analytical Use
Production data	Ammonia production; Urea production	Ton	Annual Report 2021–2024	Calculation of gas, electricity, and emission intensity
Financial data	Business revenue; Cost of goods sold; Net profit	IDR	Annual Report 2021–2024	Calculation of profitability and cost efficiency
Technical /environmental data	Gas feedstock consumption; Electricity consumption; GHG emissions	MMBTU; kWh; Ton CO ₂ e	Sustainability Report 2021–2024	Calculation of energy and emission intensity
Social data	CSR fund realization; Employee training hours	IDR; Hours	Sustainability Report 2021–2024	Evaluation of social contribution and human-capital development

Consequently, the practical application of policy-driven sustainability standards for evaluating industrial sustainability remains insufficiently explored. The evaluation of environmental indicators, such as energy intensity and greenhouse gas emissions, is frequently conducted in isolation from economic efficiency and social performance indicators. Consequently, an integrated evaluation framework that combines Green Industry Standards with measurable sustainability indicators is required to provide a more comprehensive assessment of corporate sustainability.

The novelty of this study lies in the operationalization of the Indonesian Green Industry Standard (GIS) into an integrated sustainability assessment framework for ammonia and urea production. Unlike previous studies that primarily emphasize technological improvements or life-cycle environmental assessments, this study combines sector-specific regulatory indicators with environmental, economic, and social key performance indicators within a unified benchmarking framework. By integrating technical operational performance with broader sustainability dimensions, the proposed framework provides a practical approach for evaluating plant-level performance while supporting continuous improvement and regulatory compliance in energy-intensive fertilizer industries.

The objective of this study is to evaluate the environmental management and corporate performance of an integrated ammonia and urea production system based on Green Industry Standard indicators. The study integrates environmental efficiency indicators, greenhouse gas emission intensity, operational-economic performance, and social sustainability indicators through a key performance indicator (KPI) framework. The selection of Key Performance Indicators (KPIs) was not based on subjective judgement but followed a structured procedure. First, technical indicators specified in the Indonesian Green Industry Standard (GIS) for ammonia production were identified as the primary assessment criteria. Second, these indicators were cross-referenced with sustainability indicators commonly reported in the literature

and internationally recognized sustainability frameworks to ensure consistency with environmental, economic, and social sustainability dimensions. Finally, the selected indicators were evaluated for their relevance to ammonia production processes, considering the industry’s high energy intensity, dependence on natural gas, and environmental impacts. The results of this study provide empirical evidence regarding sustainability outcomes trends and benchmarking outcomes, which support continuous improvement strategies in energy-intensive fertilizer industries.

2. EXPERIMENTAL SECTION

2.1 Materials

This study was conducted at PT Pupuk Iskandar Muda (PT PIM), located in Krueng Geukueh, North Aceh Regency, Aceh Province. Established in 1982, PT PIM operates as a subsidiary of PT Pupuk Indonesia (Persero), the state-owned holding company for Indonesia’s fertilizer industry. The company operates two integrated production facilities: an ammonia plant with a capacity of approximately 1,000 tons per day and a urea plant with a capacity of approximately 1,725 tons per day, with ammonia serving as the primary feedstock for urea production. The primary materials analyzed in this study consist of secondary operational, environmental, and financial datasets obtained from publicly available annual reports and sustainability reports covering the period 2021–2024 as summarized in Table 1. Corporate sustainability reports have increasingly become a reliable source for evaluating environmental and social performance because they contain audited operational and financial information aligned with international reporting standards (Adams et al., 2022; Searcy, 2012). The compiled dataset includes specific parameters required by the Indonesian Green Industry Standard (GIS) framework issued by the Ministry of Industry (Kementerian Perindustrian Republik Indonesia, 2018). These parameters encompass production output (ammonia and urea volumes), natural gas consumption (used as both feedstock and fuel), electricity consumption, green-

Table 2. Chronology of Green Industry Standard Implementation Strategy at PT PIM

Year	Phase	Main Strategic Focus	Key Distinction
2021	Initiation	Operations driven by maximum production targets; manual energy monitoring; CSR limited to philanthropic donation	No full integration between production targets and strict energy efficiency
2022	Transition	ISO 50001:2018 energy-management certification; steam-trap and pipe-insulation improvement; integration of CSR with the Creating Shared Value (CSV) concept	Initial investment in energy-efficiency technology and stronger operational control systems
2023	Implementation	Adoption of specific gas-intensity targets; revitalization of catalysts and key equipment; focus on process-plant reliability	Focus on maintaining reliability despite ongoing operational-stability challenges
2024	Consolidation	Post-disruption operational stabilization; large-scale employee training; periodic internal GIS audits	Focus on maintaining consistent efficiency and full compliance with Minister of Industry Regulation No. 11 of 2023

house gas emissions (calculated as CO₂ equivalent), and financial performance indicators (revenue and net profit).

A systematic selection process was conducted to isolate indicators technically relevant to the thermochemical characteristics of ammonia production (Ghavam et al., 2021; International Energy Agency, 2021). Only quantitatively derived parameters from audited corporate documentation were included to ensure transparency, reliability, and reproducibility (Searcy, 2012). These selected indicators represent the three fundamental pillars of corporate sustainability: environmental metrics (energy and emission efficiency), economic metrics (profitability and cost ratios), and social metrics (CSR expenditure and training intensity).

2.2 Methods

This study adopts a quantitative descriptive research design utilizing a performance evaluation method based on regulatory and national standards (Kementerian Perindustrian Republik Indonesia, 2023). Quantitative descriptive analysis is widely applied in industrial sustainability assessments to evaluate operational performance trends and identify improvements in resource efficiency and environmental management (Dyllick and Muff, 2016; Lozano, 2015). To analyze the impact of green industry implementation, the observation period was divided into four strategic execution phases: initiation, transition, implementation and Consolidation. As see in Table 2 summarizes the chronological development of PT PIM’s GIS implementation strategy across the four years observed, enabling a longitudinal evaluation of operational shifts over time (Adams et al., 2022).

To evaluate performance across these phases, several quantitative intensity-based and financial indicators were calculated. Intensity-based metrics are utilized to facilitate comparisons independent of production scale (International Energy Agency, 2021; Liu et al., 2020). Energy intensity,

representing the efficiency of natural gas including both feedstock and fuel consumption, was calculated using Equation (1).

$$EI_{\text{gas}} = \frac{G}{P_{\text{NH}_3}}$$

(1)

Where EI_{gas} represents natural gas intensity MMBTU/ton ammonia, G denotes the total natural gas consumption (MMBTU) and P_{NH₃} refers ammonia production (ton). The natural gas intensity calculated in this study includes both feedstock consumption used for hydrogen production and fuel consumption required for process heating in the reforming section (Ghavam et al., 2021).

To assess the environmental performance of the production process, emission intensity is used as a key indicator. This metric measures the amount of greenhouse gas emissions generated per unit of total production output, allowing for the evaluation of environmental efficiency alongside operational performance. The emission intensity is calculated using Equation (2).

$$EI_{\text{emission}} = \frac{CO_2e}{P_{\text{total}}}$$

(2)

Where EI_{emission} represents emission intensity (ton CO₂e/ton product), CO₂e denotes total greenhouse gas emissions (ton CO₂e) and P_{total} refers to total production of ammonia and urea (ton). The use of CO₂ equivalent (CO₂e) allows for the aggregation of various greenhouse gases into a single standardized metric, facilitating a more comprehensive evaluation of environmental impact. By relating emissions to total production output, this indicator provides insight into how effectively the plant minimizes environmental impact while maintaining production performance (International Energy Agency, 2021). Economic performance was evaluated using financial indicators such as Net Profit Margin and

Table 3. Mapping of GIS Requirements into Sustainability Indicators

GIS Requirement	KPI	Sustainability Dimension	Rationale
Energy efficiency	Natural gas intensity	Environmental	Measures energy utilisation efficiency
Energy efficiency	Electricity intensity	Environmental	Measures electrical energy efficiency
Emission control	GHG emission intensity	Environmental	Measures climate impact
Production efficiency	Ammonia production	Economic	Represents operational productivity
Economic sustainability	Net Profit Margin	Economic	Reflects financial performance
Human resource development	Employee training	Social	Employee competency
Social responsibility	CSR expenditure	Social	Community contribution

cost efficiency ratios, which are commonly used in corporate performance evaluation (Adams et al., 2022). This study evaluates using profitability and cost efficiency indicators. Net Profit Margin (NPM) was calculated in Equation (3).

$$NPM = \frac{\text{Net Profit}}{\text{Revenue}}$$

(3)

Cost efficiency was evaluated using the ratio of production costs to total revenue. Social performance was monitored through the descriptive evaluation of CSR expenditure ratios, employee training intensity, and occupational safety records (Dyllick and Muff, 2016; Lozano, 2015). The Green Industry Standard framework provides a comprehensive set of performance indicators intended to evaluate industrial sustainability across multiple dimensions, including resource efficiency, environmental management, economic performance, and social responsibility (Kementerian Perindustrian Republik Indonesia, 2018). However, not all indicators within the Green Industry Standard framework are directly applicable to every industrial sector. Therefore, a systematic selection process was conducted to identify indicators that are technically relevant to ammonia and urea manufacturing operations.

First, the indicators were evaluated based on their relevance to the technological characteristics of ammonia production. The technological characteristics of ammonia production justify the selection of energy and emissions indicators, as ammonia plants are highly energy-intensive industrial systems. Because of this process configuration, ammonia production is widely recognized as one of the most energy-intensive operations within the chemical industry (Ghavam et al., 2021; International Energy Agency, 2021). Energy consumption, particularly natural gas use, accounts for a substantial share of both production costs and environmental emissions in ammonia manufacturing facilities. Based on these process characteristics, indicators related to energy consumption intensity and greenhouse gas emissions were identified as the most critical environmental performance metrics. Natural gas intensity directly reflects the thermodynamic efficiency of reforming and synthesis processes,

whereas emission intensity reflects the environmental impact associated with fuel combustion and process-related carbon dioxide emissions.

Second, the selection of indicators took into account the availability and reliability of operational data. Only indicators that could be quantitatively derived from audited corporate reports and sustainability reports were included in the analysis. This approach ensures transparency and reproducibility of the results while maintaining consistency with widely accepted sustainability reporting practices (Searcy, 2012).

The resulting mapping of GIS requirements into the sustainability dimensions adopted in this study is presented in Table 3. to represent the three fundamental pillars of corporate sustainability: environmental, economic, and social performance. Environmental indicators focus on energy and emission efficiency within the production system. Economic indicators capture the financial implications of operational performance through profitability and cost efficiency metrics. Social indicators reflect the organization’s commitment to employee development and community engagement. Through this selection process, a subset of Green Industry Standard indicators was identified as the most appropriate for evaluating sustainability performance in ammonia and urea production facilities.

Because the resulting KPIs differ in scale and unit, a benchmark-index approach was applied to enable an integrated comparison across the three pillars. The year 2021 was set as the performance baseline, and each subsequent year’s KPI value was indexed relative to this baseline. The year 2021 was selected as the baseline because it represents the earliest year with complete and consistently reported sustainability and operational data following the implementation of the company’s sustainability reporting practices. Using a common baseline enables normalized year-to-year comparisons while minimizing inconsistencies arising from changes in reporting scope or indicator definitions. The purpose of the baseline year is to provide a consistent internal reference for benchmarking trends rather than to estimate statistical sensitivity. Since the study evaluates longitudinal

operational performance within a single company using consistent reporting practices, changing the baseline year would alter only the relative benchmark values without affecting the observed performance trends, because mathematically, rebasing a ratio index applies a constant scalar to the entire series, thereby perfectly preserving the relative period-to-period percentage changes.

The baseline is intended as a reference for internal benchmarking rather than as an absolute industry benchmark. Indicators were classified into benefit indicators where a higher value reflects better sustainability outcomes (e.g., net profit margin, training intensity, CSR intensity) calculated using Equation 4, and cost indicators where a lower value reflects better performance (e.g., gas intensity, electricity intensity, emission intensity, cost efficiency ratio) calculated using Equation 5.

$$\text{Benefit Indicator Index} = \left(\frac{X_i}{X_{\text{baseline}}} \right) \times 100 \quad (4)$$

$$\text{Cost Indicator Index} = \left(\frac{X_{\text{baseline}}}{X_i} \right) \times 100 \quad (5)$$

Where X_i denotes the KPI value in the observation year and X_{baseline} denotes the KPI value in the baseline year (2021). An index value above 100 confirms improved performance relative to the baseline, whereas a value below 100 indicates a decline. To improve methodological transparency and ensure reproducibility, the following sample calculations illustrate how the key performance indicators and benchmark indices were derived using the operational data:

Sample Calculation 1: Natural Gas Consumption Intensity (Equation 1)

In the baseline year of 2021, the facility recorded an ammonia production volume (PNH_3) of 257,688 tons. Based on an aggregated total natural gas consumption (G) of approximately 15,182,977 MMBTU (comprising both feedstock and fuel requirements), the energy intensity is calculated as follows:

$$EI_{\text{gas}} = \frac{15,182,977 \text{ MMBTU}}{257,688 \text{ tons}} = 58.92 \text{ MMBTU/ton NH}_3$$

Calculation 2: Benefit Indicator Index for Benchmarking (Equation 4)

Conversely, for indicators where higher values denote improved performance (such as employee training intensity under the social pillar), the benefit indicator formula is applied. In 2021 (baseline), training intensity was 19 hours/employee, and in 2024, it increased to 20.7 hours/employee. The index for 2024 is calculated as:

$$\text{Benefit Indicator Index} = \left(\frac{20.7}{19} \right) \times 100 = 108.95$$

Sample Calculation 3: Cost Indicator Index for Benchmarking (Equation 5)

To normalize the performance for integrated benchmarking, the 2021 baseline value is set as the reference point. For the natural gas intensity in 2024 (where the actual calculated intensity was 59.01 MMBTU/ton NH_3), the calculation employs the cost indicator formula, as a lower intensity value signifies better environmental performance:

$$\text{Cost Indicator Index} = \left(\frac{58.92}{59.01} \right) \times 100 = 99.84$$

This normalized index value is subsequently aggregated with other environmental metrics to establish the integrated corporate sustainability benchmark index presented in the Results section. Additionally, in all subsequent figures, data points represent single annual aggregated values derived from corporate reports rather than repeated experimental measurements; therefore, statistical variability bands such as error bars or confidence intervals are not applicable. To construct the integrated corporate sustainability benchmark index for each pillar, the individual KPI indices within that pillar were aggregated using a simple arithmetic mean. This approach applies an equal-weighting assumption to all indicators within a pillar, providing a straightforward evaluation of overall performance trends without assigning subjective weighting.

The final analytical stage involved a benchmarking and gap analysis, comparing the company's actual intensity values—particularly for the most recent observation year—against the technical thresholds specified in the Appendix of Minister of Industry Regulation No. 11 of 2023. Actual values below the regulatory threshold indicate compliant and efficient performance, whereas values exceeding the threshold indicate the need for further performance improvement. The results of these three analytical stages were synthesized to evaluate the overall effectiveness of GIS implementation in improving PT PIM's corporate performance. It is important to note that the statistical evaluation in this study relies on aggregated annual data covering a four-year observation period. Due to the limited sample size inherent in annual corporate sustainability reporting, inferential statistical significance tests (e.g., p-values from regression analysis) lack adequate statistical power. Therefore, this study employs the Pearson correlation coefficient (r) strictly as a descriptive statistical measure to quantitatively observe the strength and direction of the relationships between operational variables and sustainability indicators, rather than to establish absolute causal inferences.

3. RESULTS AND DISCUSSION

3.1 Production Performance Trend

Production performance serves as a foundational indicator of plant operational stability. In integrated ammonia and urea manufacturing, output volumes are strictly governed

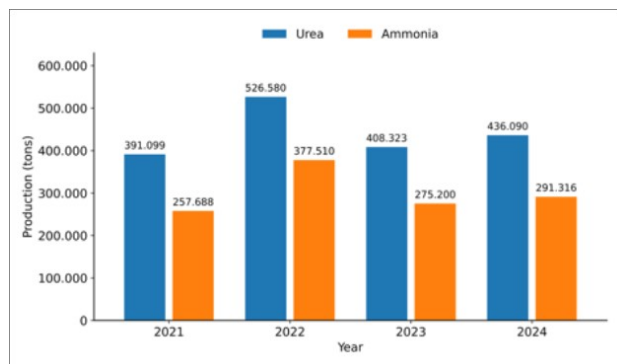


Figure 1. Trend of Ammonia and Urea Production (2021–2024)

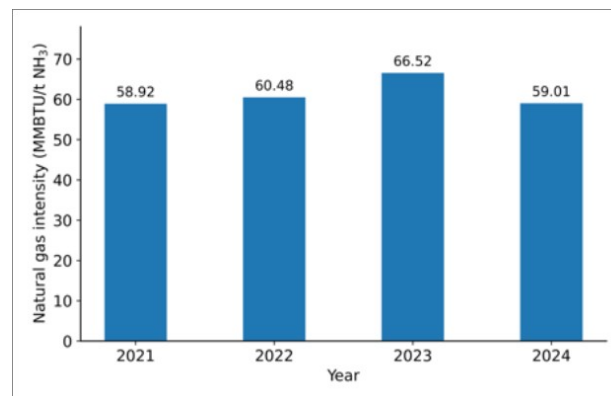


Figure 2. Natural Gas Consumption Intensity

by equipment availability and the continuous steady-state reliability of upstream thermochemical processes. During the 2021–2024 observation period in Figure 1, ammonia production exhibited fluctuating trends before peaking in 2024, signalling a recovery from prior operational constraints. Urea production followed an identical trajectory, as ammonia serves as its primary chemical intermediate.

This operational recovery in 2024 highlights the continuous nature of the Haber-Bosch synthesis loop, where minimizing minor disturbances such as catalyst degradation or reformer instability is critical to preventing massive output drops. Over the entire longitudinal timeline, ammonia production expanded by approximately 13%, while urea production grew by 11.5%. This confirms a net positive production growth trend driven by enhanced plant capacity.

3.2 Environmental Performance

Energy consumption represents the most critical operational factor in ammonia production systems. The Haber-Bosch process requires significant thermal and electrical energy to support hydrogen generation through steam methane reforming, nitrogen separation, and ammonia synthesis under high pressure conditions (Amhamed et al., 2022). Despite its technological maturity, ammonia production remains highly energy intensive and contributes significantly to global energy consumption and greenhouse gas emissions (Smith and Torrente-Murciano, 2024).

As an energy-intensive sector, environmental performance under the Green Industry Standard (GIS) framework is benchmarked through resource intensity and carbon efficiency metrics. The plant's primary ecological footprints involve natural gas intensity, electricity intensity, and greenhouse gas emission intensity. The longitudinal evaluation of natural gas in Figure 2 illustrates a gradual efficiency recovery, with gas intensity reaching 59.01 MMBTU per ton of ammonia in 2024, reflecting optimized thermal control in the primary reformer furnace.

Greenhouse gas emissions from ammonia production

primarily result from natural gas combustion and carbon dioxide generation during steam methane reforming. As hydrogen is produced from methane, carbon dioxide is inevitably generated as a by-product of the reforming reaction. Emission intensity, therefore, closely follows energy consumption patterns. Improvements in energy efficiency generally result in lower greenhouse gas emissions per unit of production (Smith and Torrente-Murciano, 2024). Concurrently, electricity consumption efficiency was maintained relative to total fertilizer product. Conversely, greenhouse gas emission trends presented a significant ecological gap. As shown in Figure 3, although emission intensity decreased toward the end of the observation period due to improved process control, the 2024 emission levels remained 35.8% higher than the 2021 baseline. Descriptive statistical analysis indicates an inverse relationship between ammonia production volume and specific greenhouse gas emission intensity ($r = -0.53$). Given the constraints of using aggregated annual data, production volume is the primary factor that could be quantitatively isolated. A full quantitative decomposition of the 35.8% emission increase into other discrete operational causes (such as specific equipment degradation or flaring events) requires highly granular plant-level operational logs and remains beyond the scope of this annual assessment. For instance, the drop in production in 2023 strongly correlated with the peak in emission intensity (1.05 Ton CO₂e/ton product), mathematically illustrating how fixed baseload emissions are penalized when distributed over lower output volumes. Under such conditions, fixed energy demand and process-related carbon dioxide generation from steam methane reforming are distributed over lower production output, resulting in higher specific emissions. Similar observations have been reported in previous studies on ammonia production (Ghavam et al., 2021; Smith and Torrente-Murciano, 2024). Although this study does not establish a causal relationship, these operational characteristics may have contributed to the temporary increase in emission intensity.

The environmental performance trends observed in this

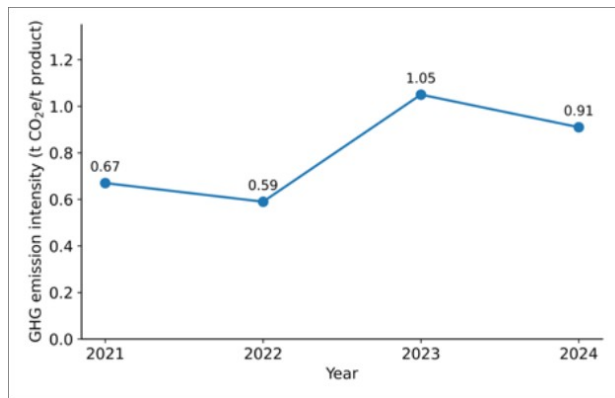


Figure 3. Greenhouse Gas Emission Intensity Trend

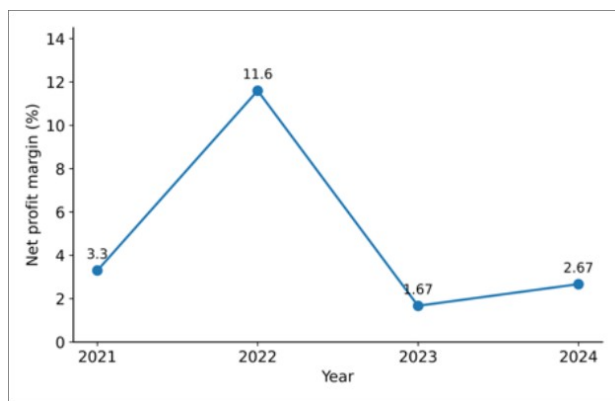


Figure 4. Net Profit Margin Trend (2021–2024)

study are generally consistent with previous studies on ammonia production, which report that improvements in process integration, catalyst performance, and energy management contribute to lower specific energy consumption and greenhouse gas emissions (Lee et al., 2022; Liu et al., 2020). Likewise, recent studies on sustainable ammonia production emphasize that operational stability is a prerequisite for maintaining resource efficiency and reducing carbon intensity in large-scale ammonia plants (Mao et al., 2024). These findings indicate that the improvements observed at PT PIM are consistent with broader developments reported in the ammonia and fertilizer industry.

3.3 Economic Performance

Economic sustainability requires an optimal balance between production scale and cost structures. Financial performance was assessed using total revenue, Net Profit Margin (NPM), and production cost efficiency ratios (Searcy, 2012). Statistical analysis reveals a very strong positive correlation between urea production volume and Net Profit Margin ($r = +0.94$), confirming that plant capacity dictates financial viability. The facility recorded its highest gross revenue in 2024, directly correlated with the 13% expansion in ammonia output. Even so, NPM analysis in Figure 4 revealed a deep

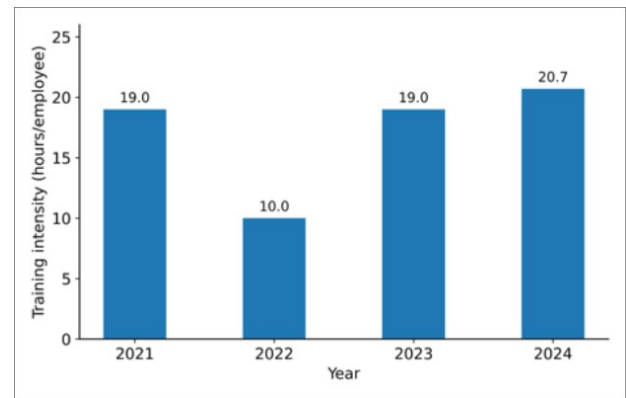


Figure 5. Employee Training Intensity Trend (2021–2024)

financial paradox: despite significant revenue acceleration, the overall NPM experienced a net decline of 19.1% across the study period.

This profitability squeeze is a direct reflection of structural cost pressures. In large-scale fertilizer manufacturing, natural gas represents the dominant component of operational expenditure due to its dual application as both chemical feedstock and primary combustion fuel (International Energy Agency, 2021; Lee et al., 2022). Suboptimal plant and external energy price volatility in the transitional years (2022–2023) led to higher unit production costs because fixed operating expenses were spread over lower output volumes, demonstrating that volume growth without stringent cost-containment cannot guarantee economic viability. Similar relationships between operational efficiency and economic performance have also been reported in previous studies, which demonstrate that improvements in energy efficiency contribute to lower production costs, although profitability remains sensitive to external market conditions and feedstock prices (Cohen and Tubb, 2018; Lee et al., 2022). While this study focuses on a single facility, contextualizing these results with existing literature provides a useful benchmark. Previous studies indicate that conventional steam methane reforming ammonia plants typically exhibit energy intensities ranging from 35 to 45 MMBTU/ton and emission intensities between 1.6- and 2.0-ton CO₂e/ton NH₃, heavily dependent on technology vintage (International Energy Agency, 2021; Liu et al., 2020). PT PIM's 2024 performance (59.01 MMBTU/ton NH₃ and 0.91-ton CO₂e/ton product) highlights that while overall product emissions are relatively controlled due to integrated urea conversion, natural gas efficiency remains structurally higher than global best practices, emphasizing the need for targeted process.

3.4 Social Performance

To fulfil the comprehensive criteria of the Triple Bottom Line (TBL) framework, corporate sustainability must account for human capital development and community equity (Elkington, 1997). The facility's social performance was

evaluated primarily through corporate social responsibility (CSR) expenditure and employee training intensity. Over the 2021–2024 timeline at Figure 5, the company systematically escalated its investment in workforce training programs, focusing heavily on advanced process safety management and green manufacturing protocols.

This human capital development directly correlates with the operational stabilization observed in 2024, as enhanced technical competencies mitigate the risks of unplanned plant shutdowns. Furthermore, the company expanded its community-based CSR allocations, funding localized environmental programs, educational infrastructure, and public health initiatives. This dual focus on workforce capability and community engagement strengthens the firm's socio-economic legitimacy and secures its long-term social license to operate within complex regional ecosystems. Previous sustainability studies similarly recognize employee competency development and stakeholder engagement as important supporting factors for maintaining long-term operational resilience (Schaltegger and Burritt, 2018).

The index was calculated by normalizing each KPI against the 2021 baseline value, where a value above 100 indicates improvement. An index value above 100 shows improved performance relative to the 2021 baseline, while a value below 100 demonstrates a relative decline. The three pillars exhibit distinct development patterns.

The economic index rose sharply in 2022 (351.52) owing to high profitability during a period of favorable global fertilizer commodity prices, before correcting in 2023 and partially recovering in 2024, though it remained below the exceptional level achieved in 2022. The environmental index followed a fluctuating but relatively stable pattern, reaching its lowest point in 2023 (88.58) due to elevated gas and emission intensity caused by operational disruption, before recovering to 97.42 in 2024 as the company restored energy efficiency and operational stability. The social index showed the most consistent upward trend, rising to 108.95 in 2024, reflecting strengthened investment in human-resource development, occupational safety, and corporate social commitment.

Overall, the integrated benchmark index suggests that sustainability improvements observed during the GIS implementation period were reflected across the environmental, economic, and social dimensions. Energy efficiency and operational stability were associated with improved environmental performance, while enhanced workforce competence through training and safety culture coincided with sustained plant operational stability. To evaluate the company's conformity with national green-industry technical standards, a gap analysis comparing actual performance with regulatory thresholds was conducted, as summarized in Table 4.

The gap analysis presented in Table 4. indicates that while PT PIM successfully restored its internal gas efficiency in 2024 following the operational deterioration in 2023, the actual performance (59.01 MMBTU/Ton NH₃) remains

structurally higher than the ideal steady-state GIS threshold (≤ 9.8 MMBTU/Ton Urea). This variance is primarily because the aggregated operational data includes start-up, shutdown, and flaring inefficiencies. Furthermore, the emission intensity in 2024 (0.91 Ton CO₂e) remained 35.8% higher than the 2021 baseline and substantially exceeded the GIS direct emission threshold (≤ 0.48 Ton CO₂e). This indicates that future improvement efforts must prioritize consistent operational stability to reduce process emissions and approach absolute green-industry technical standards. Although several sustainability indicators improved during the period of GIS implementation, these improvements should not be attributed solely to the implementation of GIS. External factors, including fluctuations in natural gas prices, global fertilizer market conditions, scheduled maintenance activities, and temporary operational disruptions, have also heavily influenced annual environmental and economic performance. Therefore, the observed sustainability trends should be interpreted as reflecting the combined effects of GIS implementation and broader macroeconomic conditions rather than an isolated causal relationship.

The findings suggest three main conclusions. First, energy efficiency and operational stability emerged as the most prominent factors associated with PT PIM's corporate sustainability, exhibiting a multiplier effect across all pillars. Natural gas feedstock efficiency dictates both economic and environmental outcomes, as it constitutes the largest component of the cost of goods sold and the principal source of carbon emissions in the Steam Methane Reforming process. Second, the findings suggest a strong interaction between GIS implementation and the three sustainability dimensions. From an environmental and economic perspective, reductions in energy and emission intensity coincided with lower cost ratios and improved profitability, mathematically supporting the concept of eco-efficiency. From a managerial perspective, increased workforce competence through GIS-related training coincided with improved operational stability, illustrating the complementary role of social sustainability in safeguarding environmental performance. Third, the quantitative evaluation highlights measurable KPI improvement following the intensification of GIS implementation in the consolidation phase (2024) relative to the initiation phase (2021): the company recorded its highest human-capital investment, with training intensity reaching 20.7 hours per employee, alongside the recovery of gas efficiency, while a 13% increase in ammonia production supported the company's highest-ever revenue amid commodity-price normalization.

These findings indicate that GIS implementation is not a linear process but a continuous structural-improvement mechanism. To progress toward absolute GIS compliance, strategic targets for 2027 were identified for each pillar. For the environmental pillar, the immediate target is maintaining emission intensity below 0.60 Ton CO₂e per ton of product through predictive, digitally supported main-

Table 4. Benchmarking Results for the Corporate Sustainability Pillars

Sustainability Indicator	GIS Regulatory Threshold	Actual Performance Range (2021–2024)	Evaluation and Gap Analysis
Natural Gas Intensity	≤ 9.8 MMBTU / Ton Urea	58.92–66.52 MMBTU / Ton NH ₃	Needs Improvement. Actual intensity is evaluated based on total aggregated gas relative to ammonia production, including start-up/shutdown losses, temporary idling, and steady-state area benchmarks.
GHG Emission (Direct)	≤ 0.48 Ton CO ₂ e / Ton Product	0.59–1.05 Ton CO ₂ e / Ton Product	Needs Improvement. Consistently above the highest gap observed in 2023 due to operational disruptions and sub-optimal capacity.
GHG Emission (Indirect)	≤ 0.10 Ton CO ₂ e / Ton Product	Not isolated in reports**	Not Evaluated Separately. Corporate sustainability reports aggregate direct and indirect emissions into a single total emission metric.
Social & Management	Management System Requirement	10.0–20.7 Training Hours / Employee	Compliant. Successfully fulfills the GIS requirements for continuous human resource development and operational evaluation.

* The natural gas intensity in this study evaluates the total aggregated gas consumption relative to ammonia intermediate production, including start-up, shutdown, and flaring inefficiencies, whereas the GIS regulatory threshold is specifically targeted at steady-state-area urea final production.

** Corporate sustainability reports do not separately isolate direct and indirect emissions; thus, the total emission intensity is used as the environmental gap assessment.

tenance. Achieving the ultimate regulatory threshold (≤ 0.48 Ton CO₂e) will likely require capital-intensive technological shifts beyond routine operational tweaking, such as accelerated development of carbon-capture-based blue ammonia infrastructure. For the economic pillar, the strategy involves sustaining a cost efficiency ratio below 78% and a double-digit net profit margin through optimized electricity consumption and diversified gas-supply sources. Finally, for the social pillar, the focus must shift from conventional philanthropy toward Creating Shared Value (CSV), integrated with community-based circular-economy waste management to secure long-term operational legitimacy.

3.5 Environmental Performance and Energy Efficiency under GIS Framework

The thermochemical synthesis of ammonia via steam methane reforming (SMR) and the Haber–Bosch process represents one of the most energy-intensive configurations in the global chemical sector (Amhamed et al., 2022; Ghavam et al., 2021). This study demonstrates that improvements in thermodynamic performance were observed within the GIS implementation framework. The achievement of 59.01 MMBTU per ton of ammonia in 2024 reflects successful heat recovery from reformer flue gases and enhanced catalyst performance within the synthesis loop.

In contrast, the continuous nature of large-scale fertilizer production creates a strict dependence on operational stability. Unplanned shutdown cycles or capacity under drastically inflate specific energy intensity because auxiliary units must maintain fixed baseload operations (Hameed and Khan, 2014). This thermodynamic reality explains the energy inefficiencies recorded during the transitional years. More importantly, the persistent 35.8% emission gap above the baseline confirms that optimizing fuel combustion alone cannot resolve the inherent carbon footprint of

SMR processes, where carbon dioxide is generated as an inevitable chemical by-product of methane-to-hydrogen conversion (Smith and Torrente-Murciano, 2024). Consequently, achieving the upper limits of green industry performance requires a strategic transition toward process intensification or low-carbon hydrogen feedstocks.

3.6 Economic Sustainability and Eco-efficiency

The concept of eco-efficiency dictates that a sustainable industrial enterprise must maximize economic value creation while simultaneously minimizing ecological degradation (Majid et al., 2023). This relationship is frequently evaluated through the lens of the Porter Hypothesis, which asserts that well-designed environmental regulations can catalysed operational innovations that offset compliance costs and enhance corporate competitiveness (Muryani, 2017; Wahab, 2025). The financial and operational data analysed in this study offer a nuanced validation of this hypothesis.

The convergence of optimized natural gas intensity and gross revenue growth in 2024 suggests that green manufacturing practices can actively support economic scaling. By lowering the specific energy cost per unit of product, the GIS framework provides a structural pathway to buffer the corporation against market shocks. Although, the net 19.1% decline in NPM across the broader timeline signals a partial decoupling effect. This illustrates that compliance-driven eco-efficiency can be financially constrained when rising structural costs outpace localized technical efficiency gains (Cohen and Tubb, 2018). Therefore, environmental policy instruments must be paired with rigorous internal cost-control mechanisms and long-term asset to prevent sustainability initiatives from eroding corporate profitability.

3.7 Social Dimension and Corporate Sustainability

Modern corporate sustainability metrics emphasize that the long-term survival of capital-intensive industries depends heavily on maintaining social equity and stakeholder trust. The expansion of employee training intensity and community CSR expenditure observed under the GIS framework confirms that environmental management initiatives often act as a catalyst for broader organizational changes. In technologically complex manufacturing, human capital is not merely an operational input but a critical risk-mitigation asset. On an external level, transparent community development programs effectively manage the local socio-ecological risks associated with chemical manufacturing. By aligning corporate objectives with regional education and environmental safety, the facility actively mitigates community-corporate friction, secures its institutional legitimacy, and builds stakeholder trust, indicating that social performance is structurally intertwined with operational resilience (Carroll, 2015; Schaltegger and Burritt, 2018).

3.8 Implications for Sustainable Fertilizer Manufacturing

The integrated evaluation of this large-scale production facility demonstrates that structured regulatory frameworks, such as the Indonesian Green Industry Standard, offer a viable blueprint for operationalizing the Triple Bottom Line within energy-intensive manufacturing sectors. The core implication for policymakers and corporate strategists is that green industrial transitions cannot be evaluated through isolated indicators; they require a balanced systemic approach that integrates technical engineering performance with economic and social resilience.

For the fertilizer sector, the GIS framework transitions from a basic regulatory compliance checklist into a core strategic management tool. While the plant successfully achieved structural improvements in energy efficiency, resource productivity, and human capital capability, the remaining emission gaps highlight the boundary conditions of current process configurations. Long-term sustainable industrial development requires manufacturing firms to utilize GIS benchmarks as a baseline from which to launch deeper technological innovations, such as green ammonia pathways and advanced carbon capture systems, ensuring corporate competitiveness in an increasingly carbon-constrained global market.

From a managerial perspective, the results indicate several priority areas for continuous improvement. Firstly, it is imperative to prioritize energy efficiency through optimisation of natural gas utilisation, implementation of preventive maintenance measures, and enhancement of process reliability. This is due to the fact that natural gas constitutes the most substantial component of production costs and is the primary source of greenhouse gas emissions. Secondly, enhancing operational stability is imperative to minimize production interruptions that increase specific energy con-

sumption and emission intensity. Thirdly, the strategic imperative of sustained investment in employee competency development and operational safety is paramount, as workforce capability is instrumental in ensuring reliable plant operation and the consistent implementation of GIS requirements.

Beyond the scope of operational improvements, the findings also underscore prospective long-term pathways for the sustainable manufacturing of fertilizers. Conventional steam methane reforming inherently generates process-related carbon dioxide; therefore, further reductions in emission intensity are likely to require technological innovations beyond incremental efficiency improvements. This perspective suggests that future industrial development may benefit from considering complementary approaches, such as carbon capture, utilisation and storage (CCUS), blue ammonia production, or renewable hydrogen-based green ammonia, in alignment with current decarbonization strategies documented in recent ammonia literature (Mao et al., 2024; Smith and Torrente-Murciano, 2024). Nevertheless, the present study does not evaluate the technical or economic feasibility of these technologies.

The findings of this study should be interpreted within the context of several methodological considerations. First, the analysis relied exclusively on secondary data obtained from audited annual reports and sustainability reports. These reports provide standardized and publicly accessible information that supports transparency and consistency in longitudinal sustainability assessment (Adams et al., 2022; Searcy, 2012). Nevertheless, because the data were originally prepared for corporate reporting rather than research purposes, variations in reporting scope, data aggregation, and disclosure practices may introduce reporting bias that cannot be independently verified. Second, this study intentionally focused on a single integrated ammonia and urea production facility to enable a longitudinal evaluation of GIS implementation under a consistent operational and regulatory context. Although this approach enabled an in-depth assessment of operational sustainability over time, the findings should not be directly generalized to other fertilizer manufacturers or industrial sectors with different technological characteristics, operational scales, or regulatory environments. Third, the sustainability assessment was limited to indicators that were consistently disclosed throughout the 2021–2024 observation period and aligned with the technical requirements of GIS. Consequently, several complementary sustainability indicators, such as detailed water consumption, wastewater generation, solid waste management, air pollutant emissions (e.g., NO_x, SO_x), and biodiversity impacts, could not be incorporated because comparable longitudinal data were unavailable. In addition, minor variations arising from annual data aggregation and reporting practices may influence the magnitude of individual KPI values, although they are unlikely to alter the overall longitudinal performance trends observed in this study.

Finally, formal uncertainty analysis and statistical confidence intervals were not performed because the study relied on aggregated annual corporate data rather than repeated operational measurements. Therefore, the benchmark index developed in this study is intended to support longitudinal performance comparison and managerial evaluation rather than statistical inference. Furthermore, empirical validation of the proposed GIS-based benchmark index against established assessment frameworks, such as correlating the index with a GRI or ESG score for the same facility, was outside the scope and resources of the present study and is proposed as a valuable avenue for future research.

4. CONCLUSIONS

The present study evaluated the sustainability outcomes of an integrated ammonia and urea production system using the Indonesian Green Industry Standard (GIS) as an operational assessment framework. The findings demonstrate that while production capacity and resource efficiency improved during the 2021-2024 period, greenhouse gas emission intensity and profit margins fluctuated. This indicates that environmental improvements alone do not automatically translate into proportional financial gains. The primary contribution of this study lies in its integration of technical engineering performance with economic and social resilience, thereby substantiating that operational stability and natural gas efficiency are the predominant drivers of sustainability in fertilizer manufacturing. The present study operationalizes the GIS, thereby providing a quantifiable and practical blueprint for energy-intensive industries to balance operational targets with regulatory environmental compliance. Achieving long-term sustainability and absolute emission reductions will ultimately require moving beyond incremental efficiency improvements toward capital-intensive technological shifts, such as the adoption of carbon capture, utilization, and storage (CCUS) or green ammonia pathways.

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