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Regional Case Study

Do Green Industry Standard Scores Reflect Life-Cycle Environmental Performance? An Uncertainty-Based Assessment of Cement Production in Indonesia

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Abstract

The cement industry is a major greenhouse gas contributor, emphasizing the need for effective decarbonization strategies and reliable environmental performance assessment tools. In Indonesia, the Green Industry Standard (GIS) evaluates industrial sustainability, yet its capacity to accurately reflect environmental impacts remains under-examined. This study assesses GIS indicators in capturing the environmental performance of Portland Composite Cement production at PT Semen Padang by combining GIS assessment with a gate-to-gate Life Cycle Assessment (LCA) using the ReCiPe 2016 Midpoint methodology, focusing on Climate Change and Water Consumption from 2021 to 2025. Climate Change, expressed as Scope 1 GHG intensity (GNR net CO_2), showed a modest reduction from 656 to 631 kg CO_2-eq/t cement (–3.8%) that lies within the data uncertainty (86% of Monte Carlo iterations, below the 95% threshold); this result was robust to the inclusion of biogenic CO_2 and of Scope 2 grid. Water Consumption rose from 0.079 m^3 water-eq/t in 2021 to 0.181 in 2022 before declining to 0.114 by 2025, staying above the baseline. While PT Semen Padang achieved GIS Level 5, the GIS score tracked changes in water performance but not in Climate Change, suggesting integrating uncertainty-aware indicators could enhance GIS's support for industrial decarbonization.

Keywords: Cement Industry, decarbonization, greenhouse gas emissions, industrial ecology, monte carlo simulation

1. Introduction

The cement industry plays a critical role in infrastructure development but is also recognized as one of the most carbon-intensive industrial sectors worldwide. Recent studies estimate that cement production contributes approximately 7–8% of global carbon dioxide (CO_2) emissions, primarily due to limestone calcination and the extensive use of fossil fuels in clinker production processes (Ige and Kabeya, 2025; Wu et al., 2024). In addition to greenhouse gas (GHG) emissions, cement manufacturing requires substantial energy and water resources, generating multiple environmental burdens throughout the production system (Candraningtyas et al., 2024; Su et al., 2025). Consequently, improving the

environmental performance of the cement industry has become a strategic component of global decarbonization efforts and national climate commitments (IEA and GCCA, 2024; Scott, 2025).

In Indonesia, industrial decarbonization is supported through the implementation of Green Industry Standards (GIS), which are designed to encourage efficient resource utilization, cleaner production practices, and reduced environmental impacts. The GIS framework evaluates industrial performance using technical and managerial indicators, including energy efficiency, resource conservation, environmental management, and the adoption of environmentally friendly technologies. For the cement sector, key performance indicators include specific thermal energy consumption (STEC), thermal substitution rate (TSR), and clinker-to-cement ratio, all of which are directly associated with energy efficiency and carbon reduction strategies (BSKJI, 2021; Ministry of Industry of the Republic of Indonesia, 2018). The importance of these indicators is consistent with international decarbonization roadmaps, which identify thermal energy efficiency improvement, alternative fuel utilization, and clinker substitution as the most effective short- and medium-term strategies for reducing emissions from cement production (IEA and GCCA, 2024). Moreover, Ige and Kabeya (2025) demonstrated that reducing clinker content significantly decreases the carbon footprint of cement manufacturing, while Scott (2025) emphasized the importance of alternative fuels, and Su et al. (2025) noted that optimizing kiln performance maintains both product quality and operational efficiency.

Life Cycle Assessment (LCA) has become one of the most widely accepted approaches for quantifying environmental impacts in energy-intensive industries. By systematically evaluating material and energy flows throughout a product system, LCA provides a comprehensive understanding of environmental burdens and identifies major impact hotspots within industrial processes (Rihner et al., 2025; Su et al., 2025). In the cement industry, LCA has been extensively applied to assess climate change impacts, resource consumption, alternative fuel scenarios, and low-carbon production pathways (Candraningtyas et al., 2024; Ige and Kabeya, 2025; Mend et al., 2026). Despite the growing body of literature on cement decarbonization and environmental impact assessment, most previous studies have focused either on evaluating environmental performance using LCA or on assessing compliance with environmental policies and industrial sustainability standards. Research examining the relationship between regulatory assessment systems and actual environmental performance remains limited. In particular, there is insufficient empirical evidence regarding whether indicators used in Green Industry Standards accurately reflect environmental outcomes measured through life cycle-based methodologies. Consequently, industries may achieve high compliance scores, while environmental improvements remain uncertain or only partially represented by the assessment framework (Dwiprigitaningtias et al., 2025). This discrepancy primarily occurs because policy-based standards often rely on composite scoring systems that allow for compensatory mechanisms, where high scores in administrative pillars can mask stagnant technical performance. Conversely, LCA provides a non-negotiable, quantitative environmental footprint. A critical synthesis of the current literature reveals that without integrating continuous LCA metrics, statutory green standards risk becoming administrative compliance exercises rather than drivers of absolute industrial decarbonization (Ige and Kabeya, 2025; Su et al., 2025).

This limitation highlights an important research gap (Miller, 2021). Existing studies rarely integrate Green Industry Standard evaluation with Life Cycle Assessment to verify whether improvements in regulatory performance indicators correspond to measurable reductions in environmental impacts (Candraningtyas et al., 2024). Furthermore, longitudinal analyses that compare policy-based performance indicators and actual environmental performance over multiple years remain scarce in the cement industry literature (Georgiades et al., 2023). The novelty of this study lies in the integration of Green Industry Standard evaluation and Life Cycle Assessment to assess the effectiveness of GIS indicators in representing actual environmental performance within the cement industry through robust quantitative frameworks. Rather than relying solely on descriptive or visual correlations (Heijungs and Kleijn, 2001), this research employs a robust methodological suite, including Monte Carlo-based uncertainty analysis, sensitivity scenarios, statistical trend evaluation, and a quantitative consistency matrix. Unlike previous

studies relying on descriptive or visual correlations, this approach provides substantial evidence of whether regulatory compliance directly equates to environmental improvement (Muller et al., 2016). Unlike previous studies that focus solely on environmental impacts or policy compliance, this research directly compares GIS achievement indicators, including STEC, TSR, clinker-to-cement ratio, and GIS performance level, with environmental impacts quantified through the ReCiPe 2016 Life Cycle Assessment method over a five-year period. This integrated approach provides a more comprehensive evaluation of whether regulatory compliance is aligned with environmental improvement and industrial decarbonization outcomes.

Therefore, this study aimed to evaluate the effectiveness of the Green Industry Standard indicators in representing the environmental performance of Portland cement production at PT Semen Padang using a gate-to-gate Life Cycle Assessment approach. The assessment focuses on the climate change and water consumption impact categories and examines the consistency between GIS performance indicators and actual environmental outcomes during the 2021–2025 period.

2. Methods

2.1 Study Area and Research Design

This study was conducted at the Indarung VI production unit of PT Semen Padang, Indonesia, which represents one of the most modern dry-process cement manufacturing facilities in the country, with an annual production capacity of approximately 1.5 million tons of cement. The research employed an integrated assessment approach combining the Green Industry Standard (GIS) evaluation and Life Cycle Assessment (LCA) to examine the effectiveness of regulatory performance indicators in representing actual environmental performance (BSKJI, 2021; Ministry of Industry of the Republic of Indonesia, 2018). The overall integrated methodological framework is illustrated in **Figure 1**. A gate-to-gate system boundary was adopted, covering all production stages within the cement manufacturing facility, including raw material preparation (raw mill), clinker production (kiln system), cement grinding (cement mill), and internal transportation processes (as depicted in **Figure 2**). Upstream activities such as limestone mining and downstream activities, including product distribution, were excluded to ensure consistency with the operational scope of the Green Industry Standard assessment (Su et al., 2025). The climate change result therefore represents direct (Scope 1) GHG intensity, reported as GNR net CO_2, and should be interpreted as a lower bound of the cradle-to-gate footprint. Indirect emissions from purchased grid electricity (Scope 2) are excluded from the base case and are quantified in sensitivity scenario S4. Consequently, the environmental impact values reported in this gate-to-gate study are inherently lower than those derived from comprehensive cradle-to-gate assessments (e.g., Mend et al., 2026), which incorporate upstream burdens such as limestone extraction, fuel production, and external transportation. Therefore, any direct numerical comparison with such literature must account for these boundary differences, positioning our results specifically as a baseline of direct manufacturing performance rather than a full product footprint. The functional unit used in this study was 1 ton of packed finished Portland composite cement (PCC) leaving the factory gate, allowing the comparison of environmental performance over the 2021–2025 assessment period (Candraningtyas et al., 2024; Huijbregts et al., 2017; Mend et al., 2026).

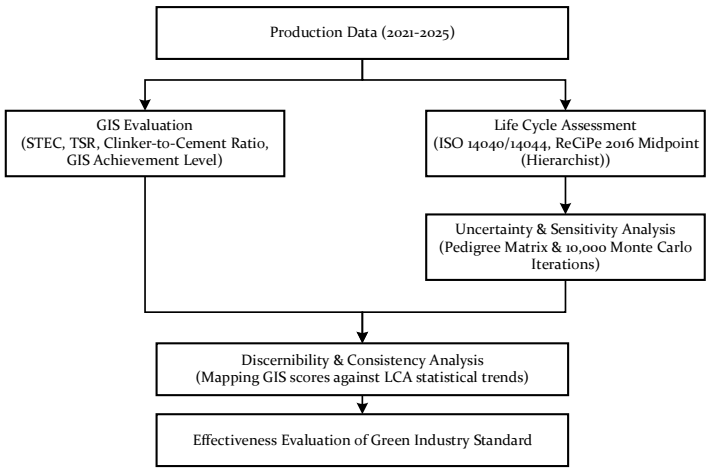


Figure 1. Research flowchart of the integrated GIS and LCA evaluation

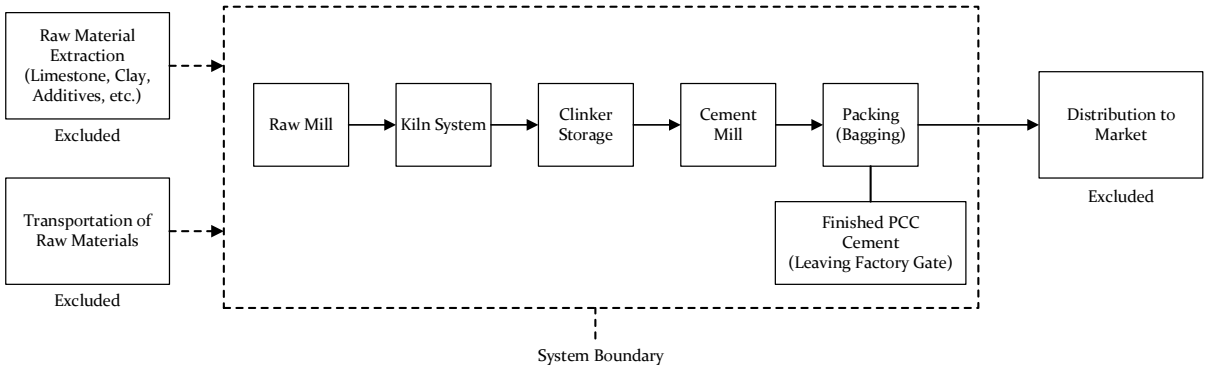


Figure 2. Gate-to-Gate system boundary

2.2 Data Collection

Primary data were obtained from PT Semen Padang environmental and production records, including annual cement production, clinker ratio, thermal energy consumption, electricity consumption, alternative fuel utilization, water consumption, and greenhouse gas emissions for the period 2021–2025. This specific five-year timeframe was selected as it corresponds perfectly to one complete certification cycle of the Green Industry Standard (GIS). We acknowledge that relying on five annual observations presents a statistical limitation in capturing high-frequency operational fluctuations. However, monthly or quarterly data could not be utilized in this comparative framework because the GIS compliance evaluation and scoring are inherently conducted on a strictly annual basis. Therefore, using annual life cycle inventory data was methodologically necessary to ensure a valid, one-to-one consistency analysis against the annual GIS achievement levels. Additional qualitative information regarding Green Industry Standard implementation and decarbonization strategies was collected through in-depth interviews using a purposive sampling approach. Eight key managerial informants were selected based on their direct responsibility for operational control and environmental compliance. These informants represented four specific units: Production Planning and Control, Energy and Process Evaluation, Alternative Fuel and Raw Materials (AFR), and Safety, Health, and Environment (SHE). The interviews were conducted to verify the quantitative data and triangulate the mathematical findings. The discussions focused on two main aspects: technical operational barriers, specifically identifying field constraints related to thermal efficiency and emission reductions; and managerial barriers, particularly the challenges in synchronizing audit document compliance targets with the actual operational limits of the facility's technological capabilities. Secondary data consisted of characterization factors from the ReCiPe 2016

Midpoint (Hierarchist) method, greenhouse gas emission factors, industrial sustainability reports, and scientific literature related to environmental assessment in the cement industry (Huijbregts et al., 2017; IEA and GCCA, 2024; Su et al., 2025).

2.3 Life Cycle Assessment

The LCA was conducted following the framework established by ISO 14040:2006 and ISO 14044:2006, which consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The inventory analysis quantified all material, energy, water, and emission flows associated with cement production. Inventory inputs included raw materials, thermal energy from fossil and alternative fuels, electricity consumption, and freshwater use. Inventory outputs included greenhouse gas emissions and water consumption associated with production activities (Ktori et al., 2025). Electricity use from the PLN grid (88.6–105.6 kWh/t cement) was inventoried, but its emissions were not included in the base-case Climate Change result, consistent with the Scope 1 GNR reporting used by the plant; they are evaluated in scenario S4.

Environmental impacts were assessed using the ReCiPe 2016 Midpoint (Hierarchist) methodology. Life cycle inventory modeling and impact calculations were performed analytically using spreadsheet models (e.g., Microsoft Excel). Two impact categories were selected based on their relevance to cement decarbonization strategies and Green Industry Standard indicators: climate change and water consumption (Huijbregts et al., 2017; Su et al., 2025). Other impact categories, such as acidification and human toxicity, were excluded from this study. The scientific rationale for this exclusion is that those categories do not have direct equivalent parameters within the current GIS assessment framework for the cement industry. Limiting the scope to climate change and water consumption ensures a focused, one-to-one comparative analysis between the LCA results and the GIS regulatory scoring. Climate change impacts were expressed in kilograms of carbon dioxide equivalent (kg CO2-eq), representing the global warming potential of greenhouse gas emissions over a 100-year time horizon. Water consumption impacts were expressed in cubic meters of water equivalent (m3 water-eq), representing the potential environmental burden associated with freshwater use throughout the production system (Candraningtyas et al., 2024; Huijbregts et al., 2017).

The interpretation phase was conducted through hotspot and contribution analyses to identify the dominant processes contributing to environmental impacts. The contributions of limestone calcination and fuel combustion to climate change and of the gas conditioning tower (GCT), cement mill, and CCR cooling water to water consumption were evaluated in scenario S4 to determine key environmental hotspots and support the interpretation of Green Industry Standard performance indicators (Mend et al., 2026; Su et al., 2025).

The system produces a single product, PCC, negating the need for co-product allocation; kiln burdens were ascribed to cement via the clinker-to-cement ratio. Waste-derived alternative fuels and raw materials (e.g., fly ash, bottom ash, copper slag, and drilling cuttings) were modeled using a cut-off approach, entering the system without upstream burdens, with only emissions from combustion or processing considered, and without credits for avoided waste treatment. CO_2 emissions from biomass fuels (such as palm fiber, rice husk, sawdust, and corn cobs) were deemed climate-neutral in alignment with ReCiPe 2016 and IPCC (2006)due to the absence of land-use change, while non-CO_2 greenhouse gas emissions from biomass combustion were considered negligible. A sensitivity analysis, including biogenic CO_2 and alternative fossil fuel CO_2, was performed due to the reporting framework of Climate Change results based on WBCSD/GNR, which reports net CO_2 while excluding emissions from alternative fossil fuels. The key modelling choices are summarized in Table 1 and tested in Section 2.4.

Table 1. Key modelling assumptions and accounting choices

Aspect	Choice in this study	Justification
System boundary	Gate-to-gate: raw mill, kiln system, cement mill and internal transport	Matches the operational scope of the GIS audit
Functional unit	1 t Portland Composite Cement (PCC)	Same basis as GIS indicators
Co-product allocation	Not required (single product); kiln burdens attributed to cement via the clinker-to-cement ratio	ISO 14044: allocation avoided where possible
Electricity	Excluded from base case (Scope 1 GHG intensity)	Consistent with WBCSD/GCCA GNR Scope 1 reporting; Scope 2 tested in scenario S4 with the Sumatera grid emission factor (0.89 t CO_2/MWh)
Alternative fuels (waste-derived)	Cut-off: burden-free input; only in-plant combustion emissions counted; no avoided-treatment credits	Consistent with gate-to-gate boundary
Alternative raw materials	Cut-off: fly ash, bottom ash, copper slag, drilling cuttings enter burden-free	By-products of other systems
Biogenic CO_2	Climate-neutral (CF = 0) for palm fiber, rice husk, sawdust, corn cobs	ReCiPe 2016; IPCC (2006); residues without land-use change
CO_2 from alternative fossil fuels	Excluded in GNR net CO_2; tested in sensitivity analysis	WBCSD/GCCA Cement CO_2 Protocol
Climate Change data	WBCSD/GNR net CO_2 reported by the plant (CF CO_2 = 1)	Verified company reporting
Impact method	ReCiPe 2016 Midpoint (H): Climate Change (GWP100), Water Consumption	Relevance to GIS indicators

2.4 Uncertainty and Sensitivity Analysis

Parameter uncertainty was quantified using the pedigree matrix approach from the ecoinvent database (Weidema et al., 2013). Each inventory parameter was evaluated against five data-quality indicators: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation (pedigree scores, uncertainty factors, and justifications are detailed in Tables S1 and S2, with main assumptions outlined in Table S3.). The resulting uncertainty factors were amalgamated with a baseline uncertainty factor of 1.05 to derive the standard deviation of a lognormal distribution centered on the deterministic value (Muller et al., 2016; Weidema et al., 2013). This uncertainty was propagated through a Monte Carlo simulation, employing 10,000 iterations. Given that the same emission factors were utilized across all reporting years, emission-factor uncertainty was sampled once per iteration and uniformly applied to each year, while activity-data uncertainty was sampled independently for each year. Differences across years were assessed through discernibility analysis (Heijungs and Kleijn, 2001), deeming a change discernible if it manifested in at least 95% of the iterations. Additionally, temporal trends were examined using linear regression and the Mann–Kendall test. Owing to the limited availability of only five annual observations, the statistical power of these analyses is inherently low. Consequently, the findings should be interpreted as suggestive of the direction of change rather than serving as definitive statistical evidence of an established trend. Such probabilistic comparisons are increasingly advocated in the context of cement life cycle assessment (LCA), as reliance

solely on mean values may exaggerate the certainty of mitigation outcomes (Georgiades et al., 2023; Miller, 2021).

The sensitivity of climate change outcomes to various carbon accounting methodologies was evaluated through five scenarios: (S0) the base case employing GNR net CO_2, where biogenic CO_2 is regarded as climate-neutral; (S1) the inclusion of biogenic CO_2; (S2) the incorporation of CO_2 from alternative fossil fuels, defined as gross CO_2; (S_3) the inclusion of both components; and (S_4) the base case plus indirect CO_2 from PLN grid electricity (Scope 2). In S4, Scope 2 emissions were calculated as grid electricity use (kWh/t cement) multiplied by the Sumatera grid emission factor of 0.89 t CO_2/MWh published by the Government of Indonesia (JCM, 2021); the uncertainties of electricity use and of the grid factor were assigned pedigree scores (Table S2) and propagated in the Monte Carlo simulation.

Under the Cement CO_2 and Energy Protocol, gross CO_2 excludes biomass CO_2, while net CO_2 further deducts CO_2 emissions from alternative fossil fuels (World Business Council for Sustainable, 2011). Estimates for biogenic and alternative fossil CO_2 emissions were derived from annual fuel energy inputs, utilizing IPCC (2006) default emission factors of 100–112 kg CO_2/GJ for solid biomass (including other primary solid biomass and wood/wood waste) and 73.3–143 kg CO_2/GJ for waste-derived fossil fuels (such as waste oils and industrial waste), which were subsequently converted to a per-tone-cement basis informed by the annual clinker-to-cement ratio.

2.5 Green Industry Standard Evaluation

The effectiveness of the Green Industry Standard implementation was evaluated using three technical indicators specified in Regulation of the Minister of Industry No. 26 of 2018: specific thermal energy consumption (STEC), thermal substitution rate (TSR), and clinker-to-cement ratio (Ministry of Industry of the Republic of Indonesia, 2018).

Specific Thermal Energy Consumption (STEC) was used to measure the amount of thermal energy required to produce one kilogram of clinker and was expressed in kcal kg^{-1} clinker. The calculation was performed using Equation (1):

$$STEC = \frac{Total\ Thermal\ Energy\ Consumption\ (kcal)}{Clinker\ Production\ (kg)} \quad (1)$$

Where:

STEC = Specific Thermal Energy Consumption (kcal kg-1 clinker)

Total Thermal Energy Consumption = total thermal energy used in clinker production

Clinker Production = annual clinker production

The TSR represented the proportion of thermal energy supplied by alternative fuels relative to the total thermal energy demand. The TSR was calculated using Equation (2):

$$TSR(\%) = \frac{Thermal\ Energy\ from\ Alternative\ Fuels}{Total\ Thermal\ Energy\ Consumption} \times 100 \quad (2)$$

Where:

TSR = Thermal Substitution Rate (%)

Thermal Energy from Alternative Fuels = energy supplied by biomass/alternative fuels

Total Thermal Energy Consumption = total thermal energy demand

The clinker-to-cement ratio was used to evaluate the material efficiency and potential reduction of process-related emissions associated with clinker production (IEA and GCCA, 2024; Ige and Kabeya, 2025). The ratio is determined using Equation (3).

$$Clinker\ to\ Cement\ Ratio(\%) = \frac{Mass\ of\ Clinker}{Mass\ of\ Cement} \times 100 \quad (3)$$

Where:

Mass of Clinker = clinker production

Mass of Cement = finished Portland Composite Cement (PCC)

The overall GIS score was calculated as the weighted sum of three pillars: production process (70%), waste and emission management performance (20%), and company management (10%), following BSKJI Regulation No. 146 of 2021, and a core above 90% corresponds to Level 5 "Very Green" (BSKJI, 2021). Over five years, the waste and emission management pillar and the company management pillar consistently received maximum scores of 20 and 10 points, respectively. Consequently, variations in the overall GIS score were solely linked to the production-process pillar, scoring between 62.3 and 68.6 out of 70 points. This pillar includes essential criteria related to energy consumption, material utilization (clinker-to-cement ratio), and water usage. The environmental impacts of these criteria are reflected in the Climate Change and Water Consumption categories, making their comparison with the overall GIS score particularly significant. In addition, the annual GIS achievement level obtained by PT Semen Padang was documented and compared with environmental performance results generated from the LCA analysis.

2.6 Effectiveness Analysis

The effectiveness of the Green Industry Standard indicators was analyzed by comparing annual changes in STEC, TSR, clinker ratio, and GIS achievement level with changes in Climate Change and Water Consumption impacts from 2021 to 2025. A gap analysis approach was employed to evaluate the consistency between regulatory performance indicators and actual environmental outcomes. Improvement trends were assessed relative to the 2021 baseline to determine whether higher GIS performance corresponded with measurable environmental improvements (Candraningtyas et al., 2024). For each annual transition, changes in Life Cycle Assessment (LCA) impact categories were classified as improved or worsened if the change occurred in at least 95% of Monte Carlo iterations (a discernable change); otherwise, they were classified as no discernible change. The Green Industry Standards (GIS) direction was improved with an overall score increase and worsened with a decrease. Consistency was rated as high when both LCA categories aligned with the GIS score, partial when only one did, and low when neither agreed with the GIS direction. This integrated evaluation framework enabled the identification of potential discrepancies between regulatory compliance and actual environmental performance within the cement manufacturing process (Dwiprigitaningtias et al., 2025; Su et al., 2025). The consistency assessment was restricted to the environmental dimensions of the two LCA categories, excluding GIS criteria, such as management systems and reporting, that lack LCA counterparts from evaluation.

3. Result and Discussion

3.1 Environmental Performance Based on Life Cycle Assessment

The Life Cycle Assessment (LCA) results revealed the environmental performance of Portland Composite Cement (PCC) production at PT Semen Padang during the 2021–2025 period. The examination of Scope 1 greenhouse gas intensity indicates a modest reduction from 656 kg CO2-equivalent per ton of cement in 2021 to 631 kg in 2025, reflecting a 3.8% decrease that aligns with the range of data uncertainty. This finding is consistent with the company's decarbonization efforts, although it does not conclusively demonstrate their effectiveness. Conversely, water consumption increased from 0.079 m^3 water-equivalent per ton in 2021 to 0.181 m^3 in 2022, before declining to 0.114 m^3 in 2025, remaining above 2021 levels, suggesting improved resource efficiency and water management practices (Huijbregts et al., 2017; Su et al., 2025).

Table 2. Environmental impact assessment results for Portland cement production at PT Semen Padang during 2021–2025

Year	Climate Change (kg CO_2-eq/t cement)	Water Consumption (m^3 water-eq/t cement)
2021	656	0.079

Year	Climate Change (kg CO_2-eq/t cement)	Water Consumption (m^3 water-eq/t cement)
2022	651	0.181
2023	656	0.135
2024	640	0.127
2025	631	0.114

The direction of the modest reduction in climate change impacts is consistent with global studies indicating that improvements in thermal efficiency, increased use of alternative fuels, and clinker substitution contribute substantially to reducing cement-sector greenhouse gas emissions (IEA and GCCA, 2024; Ige and Kabeya, 2025). Direct comparison with cradle-to-gate studies requires caution. Mend et al. (2026) reported carbon dioxide emissions ranging from 995 to 1010 kg CO_2-eq/t of clinker in a cradle-to-gate framework, with calcination and fuel combustion contributing 73% and 27%, respectively. This indicates that direct kiln emissions dominate the cradle-to-gate footprint. The 2025 findings, approximately 980 kg CO_2-eq ton^{-1}, align closely with these figures, suggesting minimal impact from excluding upstream stages on climate change metrics (Mend et al., 2026). However, the gate-to-gate boundary may overstate the benefits of decarbonization efforts, as upstream burdens related to biomass collection, transportation, and drying increase with higher TSR and are not accounted for, nor are emissions from purchased electricity. The incorporation of purchased electricity, which was not included in the base case analysis, would contribute an additional 11%–13% to the overall findings in scenario S4. Importantly, this adjustment does not alter the prevailing trend observed in the study. This limitation emphasizes the necessity of expanding boundary definitions in future evaluations for a more comprehensive assessment of environmental impacts.

The marked increase in water consumption in 2022 (0.079 to 0.181 m^3 water-eq/t cement) cannot be solely attributed to increased production, as total water withdrawal surged nearly 3.5 times while cement output grew by 52%. This increase was observed across all three cooling applications, with the most notable increases occurring in the gas conditioning tower (GCT) and the CCR cooling circuit. In 2022, the specific thermal energy consumption peaked at its highest level during the study period, reaching 859.8 kcal/kg of clinker, while the thermal substitution rate (TSR) dropped to 2.0%. This decline heightened the thermal load on the kiln exhaust, thereby escalating the water needed for gas conditioning prior to dedusting. Additionally, higher throughput in the cement mill necessitated increased water injection for mill temperature control, and evaporative and overflow losses in the open cooling circuits were not managed until the implementation of the RECAP recirculation program in 2024 and the Overflow Saver system in 2025. Previous studies have highlighted that optimization of cooling systems and internal water recirculation can substantially reduce the freshwater demand in cement manufacturing facilities (Candraningtyas et al., 2024; Marsh et al., 2022). In contrast, the impacts of climate change remained relatively constant (ranging from 656 to 651 kg CO_2-eq/t cement) as they are primarily influenced by clinker chemistry and fuel combustion rather than cooling requirements. Consequently, water consumption and climate change are driven by largely independent processes, which account for their differing trends.

3.2 Contribution Analysis of Environmental Impact Sources

Contribution analysis identified kiln operations as the dominant source of environmental impacts throughout the assessment period. Data from 2021 to 2025 revealed that limestone calcination was responsible for 62.43% of climate change impacts, with fuel combustion accounting for 37.57%, highlighting the kiln system as the primary hotspot within the gate-to-gate boundary of cement production. Regarding water consumption, the cement mill was the largest user at 45.14%, followed by the gas conditioning tower (GCT) at 33.17% and the clinker cooling reactor (CCR) cooling circuit at 21.69%, indicating that water functions mainly as a cooling and temperature control medium rather than a raw material.

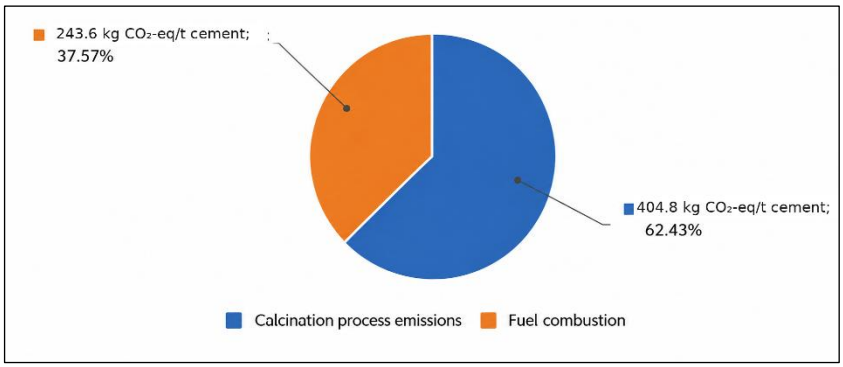


Figure 3. Contribution of emission inventory components to climate change impact

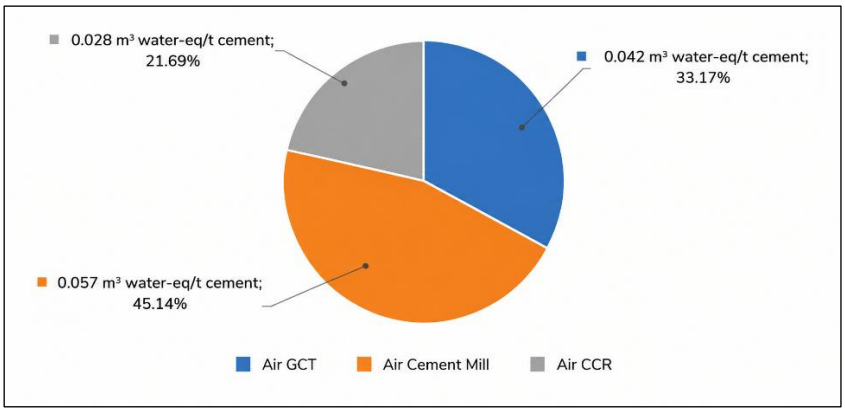


Figure 4. Contribution of water inventory components to water consumption impact

The dominance of kiln operations is expected because clinker production involves both fuel combustion and limestone calcination, which together represent the largest sources of greenhouse gas emissions in cement manufacturing (Mend et al., 2026; Wu et al., 2024). Similar findings have been reported by Su et al. (2025), who identified pyro processing as the principal environmental hotspot in cement production systems. Because the Climate Change results cover direct (Scope 1) emissions only, indirect emissions from purchased grid electricity (Scope 2) were not included. Their inclusion would increase the absolute results but would not change the dominance of the kiln system, which accounts for all direct emissions within the boundary. Consequently, decarbonization strategies that target clinker substitution, thermal efficiency, and alternative fuel use are likely to yield the greatest reductions in direct emissions (IEA and GCCA, 2024; Ige and Kabeya, 2025), while reducing grid electricity use would primarily lower indirect emissions outside the present boundary.

3.3 Robustness of LCA Results

The pedigree-based uncertainty of the annual results was approximately ±7% for climate change (e.g., 609–703 kg CO2-eq/t cement in 2021) and ±5% for water consumption (Figure 3; Table S4). Assigning the highest reliability score of 1 to the activity data resulted in an increased probability of a reduction occurring between 2021 and 2025, reaching only 0.937. This value remains below the established threshold of 95% (see Table S5).

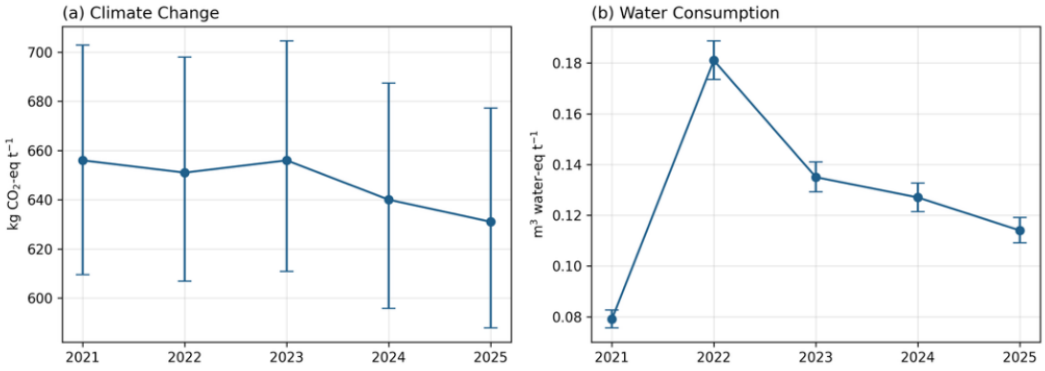


Figure 4. Deterministic results with 95% Monte Carlo intervals (N = 10000)

The year-to-year changes in climate indicators were indistinguishable. Between 2021 and 2025, a reduction of approximately 25 kg CO2-eq/t of cement was observed in 86% of Monte Carlo simulations (P = 0.861), falling below the 95% confidence threshold (Table 4). The linear trend suggested an annual decrease of – 6.1 kg CO2-eq/t (p = 0.050; Mann–Kendall p = 0.077). However, with only five data points, this trend is only indicative. Thus, we describe this change as a modest reduction in data uncertainty.

Table 3. Discernibility of changes in LCA results

Category	Period	Mean change	95% interval	P(decrease)	Verdict
Climate	21→22	-4.8	-49.7 to +39.9	0.579	Not discernible
Change	22→23	+4.9	-39.8 to +50.6	0.414	Not discernible
	23→24	-16.0	-61.1 to +29.1	0.756	Not discernible
	24→25	-8.9	-53.4 to +35.9	0.650	Not discernible
	21→25	-24.6	-69.7 to +20.8	0.861	Not discernible
Water	21→22	+0.102	+0.094 to +0.110	0.000	Discernible increase
Consumpt	22→23	-0.046	-0.056 to -0.036	1.000	Discernible decrease
ion	23→24	-0.008	-0.016 to +0.000	0.973	Discernible decrease
	24→25	-0.013	-0.021 to -0.006	1.000	Discernible decrease
	21→25	+0.035	+0.029 to +0.041	0.000	Discernible increase

In contrast, the water consumption changes were consistently identifiable, with an increase in 2022 followed by reductions in the subsequent years, culminating in a net increase of 0.035 m^3 water-equivalent per ton of cement by 2025. The inclusion of biogenic CO2 reduced the overall emission decrease from 25.0 to a range of 21.2–21.6 kg CO2-eq/t cement due to a marked increase in biomass use in 2025. The impact of CO2 from alternative fossil fuels was minimal, contributing less than 3 kg CO2-eq/t in any year (Table 4).

Table 4. Sensitivity of climate change results to carbon accounting (kg CO2-eq/t cement)

Years	So Base (net, biogenic = 0)	S1 + biogenic CO2	S2 + alt. fossil CO2 (gross)	S3 + both	S4 + scope 2 electricity
2021	656	661–662	657–659	663–664	741
2022	651	654	652–654	655–657	730
2023	656	659	658–659	660–662	747
2024	640	642–643	642–644	644–647	734
2025	631	640–641	632–633	641–643	715
Δ2025-2021	**-25.0 / -25.0**	**-21.6 / -21.2**	**-25.4 / -25.7**	**-22.0 / -21.9**	**-26.5**

S1–S3: Low/high IPCC (2006) emission factors. S4: Sumatera grid emission factor 0.89 t CO_2/MWh (JCM, 2021); details in Table S6.

Incorporating Scope 2 electricity emissions (S4) added 79–94 kg CO_2 per ton of cement, representing 11–13% of the total, resulting in 715–747 kg CO_2 equivalent per ton. However, this adjustment only slightly affected the projected reduction for 2021–2025, changing from –25.0 to –26.5 kg CO_2 equivalent per ton, remaining statistically non-significant (P = 0.874), indicating that conclusions are robust against excluding electricity emissions and reflect Scope 1 GHG intensity.

Finally, when examining changes through discernibility, the consistency between GIS and LCA was only partial (Table 6). The GIS metrics aligned with Water Consumption changes across all four periods, whereas Climate Change metrics lacked discernible changes above data uncertainty. This indicates that year-over-year comparisons of environmental performance should be presented alongside their associated uncertainties, especially when the observed changes are minor in relation to the precision of the data collected.

3.4 Evaluation of Green Industry Standard Indicators

The Green Industry Standard (GIS) evaluation demonstrated continuous improvement in the operational performance indicators throughout the study period. Throughout the study period, all technical GIS indicators for PT Semen Padang consistently remained within regulatory thresholds, specifically STEC at or below 860 kcal/kg clinker, a TSR of at least 1%, and a clinker-to-cement ratio not exceeding 82%, thereby allowing the company to sustain an annual Level 5 (“Very Green ”) rating. However, fluctuations were observed in the indicators: TSR decreased from 3.1% in 2021 to 2.0% in 2022 but subsequently demonstrated a gradual recovery, reaching 4.9% in 2025. This was largely attributed to the effective implementation of biomass utilization, which constituted 4.2% following the commissioning of new biomass handling and feeding facilities. The clinker-to-cement ratio rose to 70.3% in 2023, only to decline to 64.3% by 2025, while the STEC exhibited its highest measurement at 859.8 kcal/kg clinker in 2022. Overall, the GIS score fluctuated from 92.3% in 2022 to a peak of 98.6% in 2025, reflecting the dynamic nature of the company’s environmental performance.

Table 5. GIS performance indicators of PT Semen Padang during 2021–2025

Year	STEC (kcal kg^{-1} clinker)	TSR (%)	Clinker-to-Cement Ratio (%)	GIS Score (%)	GIS Achievement Level
2021	845.0	3.1	68.6	93.7	Level 5 (Very Green)
2022	859.8	2.0	70.2	92.3	Level 5 (Very Green)
2023	823.1	2.2	70.3	93.0	Level 5 (Very Green)
2024	804.2	2.4	68.5	94.4	Level 5 (Very Green)
2025	817.3	4.9	64.3	98.6	Level 5 (Very Green)
Threshold	≤860	≥1	≤82	> 90	

An increase in the TSR indicates a greater utilization of alternative fuels, which is one of the primary strategies recommended in international cement decarbonization roadmaps (IEA and GCCA, 2024). Similarly, the reduction in the clinker ratio contributes to lower process emissions because clinker production is responsible for the majority of the CO_2 emissions generated during cement manufacturing (Ige and Kabeya, 2025; Mend et al., 2026). These findings suggest that GIS indicators successfully capture important operational improvements related to industrial decarbonization. However, operational performance indicators alone may not fully represent actual environmental outcomes because environmental impacts are also influenced by production volume, fuel characteristics, and process conditions (Rihner et al., 2025; Su et al., 2025).

3.5 Effectiveness of Green Industry Standards in Representing Environmental Performance

Analysis of changes in discernibility reveals that the correlation between Green Industry Standards (GIS) scores and Life Cycle Assessment (LCA) results demonstrated partial consistency across all periods, as shown in Table 6. The GIS scores aligned with Water Consumption trends, decreasing when water intensity surged significantly in 2022 and increasing as it improved thereafter. However, changes in Climate Change metrics were not substantial enough to be distinguished from data uncertainties, indicating that while the GIS score effectively responded to variations in water performance, it failed to accurately reflect changes in Climate Change, which is critical for decarbonization efforts.

Table 6. Consistency between GIS indicators and actual environmental performance

Period	Climate Change	Water Consumption	GIS score change*	Consistency
21→22	No discernible change	Worsened	-1.40 (Worsened)	Partial
22→23	No discernible change	Improved	+0.70 (Improved)	Partial
23→24	No discernible change	Improved	+1.40 (Improved)	Partial
24→25	No discernible change	Improved	+4.20 (Improved)	Partial

**Improved/Worsened: change discernible in ≥95% of Monte Carlo iterations; otherwise, no discernible change. GIS direction based on the overall GIS score (all years, Level 5). Consistency: High = both LCA categories agree with the GIS direction; partial = one agrees; low = none agree.*

The transition to 2025 highlights this issue, with the Specific Thermal Energy Consumption (STEC) increasing by 1.6 percent and the Thermal Substitution Rate (TSR) more than doubling due to improvements in biomass fuels. Despite these significant shifts, the GIS score increased by 4.2 points, raising concerns about the effectiveness of compliance-based assessment frameworks. This situation prompts questions about the capacity of composite indices, such as GIS, to adequately capture individual technical indicators. The interdependent nature of its pillars allows compensatory mechanisms that can mask declines in specific areas, thereby maintaining a Level 5 status without truly reflecting underlying issues (Dwiprigitaningtias et al., 2025), because the management pillars were constant at their maximum, the compensation occurred with the production process pillar. This finding indicates that the current GIS evaluation framework may not be sufficiently sensitive to detect incremental environmental improvements when performance remains within the same achievement category. Similar concerns have been raised in studies evaluating environmental policy indicators, which found that compliance-based assessment systems may not always reflect actual environmental performance improvements

Therefore, the integration of Life Cycle Assessment and Green Industry Standard evaluation provides a more comprehensive framework for monitoring industrial sustainability. While GIS effectively promotes operational improvements, LCA provides quantitative evidence of the environmental consequences of these improvements. The combination of both approaches can support more adaptive and evidence-based industrial decarbonization policies in Indonesia (IEA and GCCA, 2024; Su et al., 2025).

4. Conclusions

This study assessed the ability of Green Industry Standard (GIS) indicators to reflect the environmental performance of Portland Composite Cement production at PT Semen Padang through the integration of GIS evaluation with gate-to-gate Life Cycle Assessment (LCA). The primary scientific contribution of this research lies in providing empirical evidence that high regulatory compliance scores do not inherently guarantee proportional environmental impact reductions. For instance, despite the successful implementation of decarbonization strategies, such as increasing the thermal substitution rate to 4.9% and lowering the clinker-to-cement ratio, led to a reduction in climate change impacts from 656 to 631 kg CO_2-eq/t cement by 2025. This reduction falls within the bounds of data uncertainty, with 86% of the Monte Carlo iterations presenting values below the 95% threshold. Furthermore, this finding

demonstrates robustness despite the incorporation of biogenic CO_2, alternative fossil CO_2, and Scope 2 electricity parameters. This demonstrates that compliance-based metrics may lack the sensitivity required to capture actual environmental performance dynamics.

Regarding policy implications, throughout the assessment period, PT Semen Padang maintained GIS Level 5, with GIS scores capturing changes in water performance but not in climate change indicators, resulting in only partial consistency. Owing to the management pillars remaining constant at their maximum thresholds, all variations in the GIS score are derived from the production-process pillar. Within this context, improvements in total specific resource (TSR) and clinker ratio can effectively mitigate declines in individual indicators, such as specific total energy consumption (STEC). These conclusions specifically address energy, material, and water-related criteria in the two impact categories and should not be extrapolated to the entire GIS framework. To enhance sensitivity to actual decarbonization outcomes, future studies should integrate quantitative, uncertainty-aware LCA indicators, extend the assessment boundary to cradle-to-gate, include additional impact categories, and account for plant-specific measurement uncertainties.

Ethics Statement

This study utilized semi-structured interviews with eight employees of PT Semen Padang, focusing strictly on technical and organizational aspects of cement production and the implementation of the Green Industry Standard. No personal or sensitive information was gathered, and participants were reported anonymously by unit. Data collection was conducted under a research permit from Universitas Andalas (Reference No. B/013/UN16.09.3.4/TA.00.00/2026, dated January 21, 2026) and with the approval of PT Semen Padang (Reference No. 0029/PENELITIAN/SP/08.2026, dated August 19, 2026). Participants were informed of the study's purpose, participated voluntarily, and provided [verbal / written] informed consent. Due to the non-sensitive nature of the information, formal ethics review was not required.

CRediT Author Statement

Rahma Fitrianti: collected data, conceived and designed analysis, wrote outline, and planned research. **Rizki Aziz:** planned research, managed research, and wrote paper. **Fadjar Goembira:** planned research, conceived and designed analysis, and wrote outline. **Muhammad Fachri Ridwan**: collected data, conceived and designed analysis, wrote paper

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