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Regional Case Study

Life Cycle Assessment of Aluminum Hydroxide Production in Tayan, Indonesia

Hanif Kusumasasmita[1*], Haryono Setiyo Huboyo[1], Sudarno[1], Mostafa Hamdy Marawan[2]

[1]Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Jalan Professor Soedarto, SH, Semarang, Indonesia 50275

[2]Cooperation Petroleum Company, 94 Kasr El Aini St., Garden City, Cairo, Egypt 11511

* Corresponding Author, email: hanifks@students.undip.ac.id

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Abstract

This study evaluated the *gate-to-gate* environmental impacts of producing one ton of aluminum hydroxide ($Al(OH)_3$) at the Tayan Alumina Plant, Indonesia, under the national bauxite downstreaming policy. Using primary operational data covering Bauxite Transport, Power Plant, Bayer Process, Hydrate Process, Calcination Process, Backup Power, and Landfill Red Mud, a Life Cycle Assessment (LCA) was conducted following the ISO 14040 and 14044 standards. Impact assessment via SimaPro 9.5.0 and the CML-IA Baseline method focused on Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), and Photochemical Ozone Creation Potential (POCP). Results indicate emissions of 1.61×10^3 kg CO_2-eq, 1.38×10^{-6} kg CFC-11-eq, 2.19×10^{-1} kg SO_2-eq, and 1.49×10^{-2} kg C_2H_4-eq per ton of $Al(OH)_3$. Power generation was the dominant contributor, accounting for over 59.4% of GWP and more than 78% of other impacts. Additional burdens stemmed from electricity and steam use in the Bayer Process and Landfill Red Mud. The findings emphasize improving energy efficiency, adopting cleaner fuels, and optimizing red mud management to advance sustainable alumina refining in Indonesia.

Keywords: Environmental impact; gate-to-gate; metal industry; red mud; waste

1. Introduction

The global demand for aluminum is very high, reaching 140.3 million tons in 2024 (Shanghai Metals Market, 2025). The demand for alumina is projected to reach 152 million tons, with an average growth of 1.3% per year until 2027 (ARENA, 2022). The alumina or aluminum oxide (Al_2O_3) industry is characterized by high energy consumption and a predominant reliance on fossil fuels for energy. Alumina is produced by calcining aluminum hydroxide ($Al(OH)_3$), which serves as the intermediate product in the Bayer process. As a result, the stages involving the purification and thermal conversion of $Al(OH)_3$ are notably energy-intensive in the production of alumina (Stopić et al., 2025).

Based on Law Number 3 of 2020 on Mineral and Coal Mining, Indonesia has gradually banned the export of raw minerals, especially bauxite ore, which is a raw material before it becomes alumina. This encourages domestic industries to establish mineral processing and refining plants. Bauxite must be processed to meet the specifications of raw alumina. Bauxite processing aims to increase the level of Al_2O_3 to > 52% and SiO_2 to 2% to make alumina production economical. Since the implementation of the

bauxite export ban, alumina refining output has increased significantly from 1.4 million tons in 2021 to 3.9 million tons in 2023 (Fastmarkets, 2024). The existing production capacity of alumina factories in the country is 4.3 million tons per year (Ministry of Economy, 2022). In addition, eight bauxite refining facilities with a production capacity of 4.98 million tons of alumina per year are planned (Ministry of Economy, 2022).

The alumina industry has significant environmental impacts, such as deforestation, landscape changes, and land degradation (Hoan et al., 2020). This industry requires intensive energy, which is mostly obtained from combustible materials such as coal and diesel, resulting in large emissions (Zore, 2024). Globally, converting bauxite into $Al(OH)_3$ via the Bayer process necessitates an energy input of 10.2 GJ and results in emissions ranging from 400 to 870 kg of CO_2 (Sáez-Guinoa et al., 2024; Zore, 2024). This process generates hazardous waste, producing 1–1.23 tons of red mud per ton of alumina produced.

Focusing on environmental management is a challenge for the industry as it seeks to increase the domestic alumina production capacity through sustainable practices. This requires LCA research on the alumina industry to align downstream policies with good environmental management (Byrne et al., 2025). The LCA helps decision-makers identify key issues in the product life cycle, improve process efficiency, reduce environmental impact, and meet regulatory and market demands. Additionally, LCA provides a data-driven basis for improving production processes, shaping company strategies, and making governmental policy decisions (Lian et al., 2025; Piron et al., 2024).

Although LCA has been extensively utilized to assess the environmental performance of the global aluminum value chain, its use within the Indonesian alumina sector remains limited. Research in Indonesia has largely concentrated on the macroeconomic dimensions of bauxite downstreaming policies (Supriyanto et al., 2023) and technical investigations into the application of bauxite residue (red mud) (Cheng et al., 2024). Indonesian industrial LCA studies have largely focused on agriculture, biofuels, and select manufacturing sectors, with limited granular primary operational data available (Dianawati et al., 2023; Sasongko et al., 2024). Local LCI datasets for emissions, energy use, and waste generation remain scarce across industrial processes, leading to a dependence on generic international databases that may misrepresent the Indonesian industrial reality (Sinaga et al., 2025). To date, no peer-reviewed research has thoroughly measured the environmental impacts of alumina production processes using primary operational data from Indonesian refineries. Moreover, there is a lack of local LCI data on energy use, material inputs, emissions, and waste production, compelling researchers to depend on generic international databases that may not accurately reflect Indonesian industrial conditions.

Research in major alumina-producing countries such as Australia, China, and some European nations has shown more progress in LCA. These studies include detailed process simulations, specific inventory datasets, and thorough environmental evaluations covering various life cycle stages from bauxite mining to alumina production (Ma et al., 2022). In contrast, Indonesia lacks local inventory data, recognized LCA methods, and refinery-level environmental assessments published in international journals. Although many international studies have used a *cradle-to-gate* approach, this study used a *gate-to-gate* system boundary. This choice focuses on identifying environmental hotspots and improvement opportunities within the refinery operations. The *gate-to-gate* boundary allows for a detailed examination of process units, energy use, emissions, and red mud generation during the conversion of bauxite into $Al(OH)_3$, thereby reducing uncertainties related to upstream mining and transportation data. Despite its narrow focus, this approach is useful for supporting operational decision-making and environmental management at the plant level in the short term.

This research is distinguished by the use of *gate-to-gate* LCA with primary data from an Indonesian alumina refinery to assess the environmental impact of producing one ton of $Al(OH)_3$. This is one of the first studies to offer a refinery-specific life cycle inventory (LCI) and environmental assessment of $Al(OH)_3$ production in Indonesia. This study aimed to evaluate the environmental impacts of producing one ton of $Al(OH)_3$ at an Indonesian alumina refinery using the LCA method. It focused on identifying major environmental issues related to energy use, greenhouse gas emissions, and red mud

generation, and provided recommendations for strategies to improve the environment, supporting industrial sustainability and decarbonization efforts.

2. Materials and Methods

This research was conducted at a bauxite processing and refining plant that produces chemical-grade alumina (CGA) products in the Tayan District, Sanggau Regency, West Kalimantan Province, Indonesia, with coordinates of approximately 110°08′30.77″E and 0°03′41.96″S. The Tayan Alumina Plant uses the Bayer process equipped with a calcination facility to process 850,000 wmt of bauxite with an installed production capacity of 300,000 tons of alumina per year.

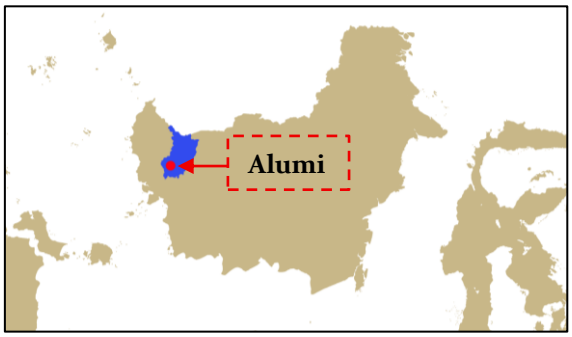


Figure 1. Location study

This study refers to the principles of ISO 14040 and ISO 14044 for conducting LCA in the alumina industry, although some externalities must be considered because of the limited scope of this research. One of the main characteristics of these standards is the division of LCAs into four phases: definition of purpose and scope, life cycle inventory, life cycle impact assessment, and interpretation of results.

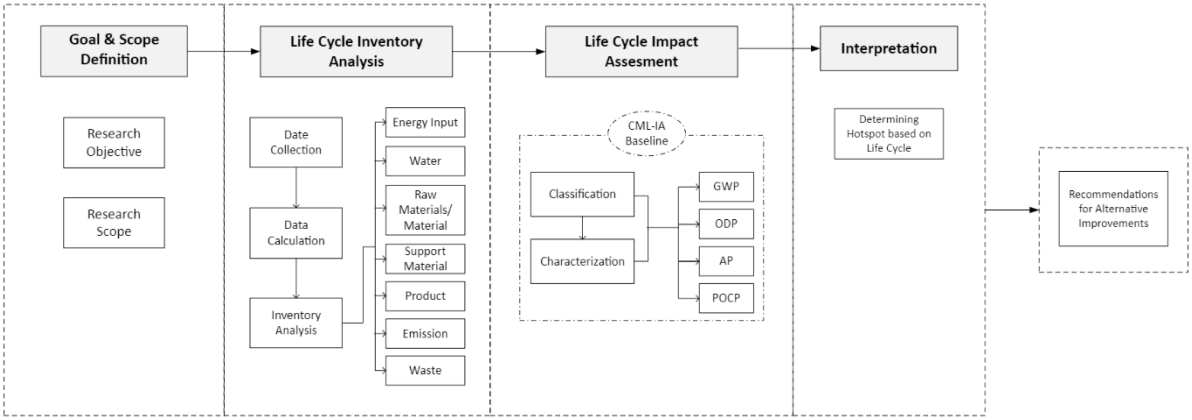


Figure 2. LCA technical flowchart

2.1 Goal and Scope Definition

The purpose of the LCA was to analyze the impact of processing bauxite into aluminum hydroxide ($Al(OH)_3$) at the Tayan Plant within a *gate-to-gate* scope. The LCA summarizes the inputs and outputs of bauxite transportation, alumina refining, and utilities. Transportation is included in the scope because it remains within the business process area of the plant. Cradle scope, bauxite ore mining activities are carried out by another company located within the same block area. Furthermore, LCA analyzes the significant environmental impacts of the life cycle to provide a theoretical basis for environmental improvement recommendations to reduce the environmental impact of diesel processing.

The product system used in this study was $Al(OH)_3$, with reference to the Product Category Rules (PCR) *Basic Inorganic Chemicals Not Elsewhere Classified Product Category Classification UN CPC 341,*

342, 343, 345 (Except Subclass 3451) version 1.1.1 for category 3423. Functional units are functional measures used to assess the potential environmental impact of a predefined product system. The functional unit used was 1 ton of $Al(OH)_3$ with a reference flow, which is a one-year production cycle (256,956 tons of $Al(OH)_3$).

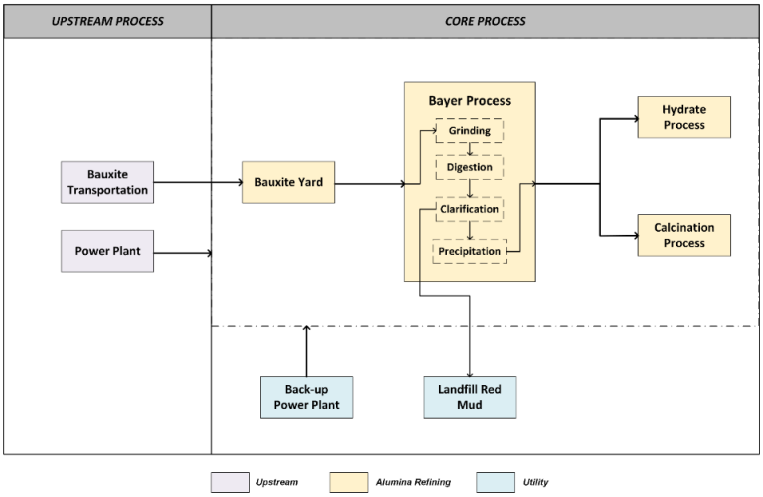


Figure 3. *Gate-to-gate* system boundary of the alumina production

The system limitations considered in this study are shown in **Figure 3**. The scope was grouped into two stages: the upstream process (bauxite transportation and power plant) and the core process (alumina refining and utility). In this study, utility was included because it plays an important role in the processing of bauxite into $Al(OH)_3$. The calcination process is used because the facility is an integrated alumina plant, where some of the $Al(OH)_3$ is later turned into Al_2O_3.

2.2 Life Cycle Inventory (LCI)

Inventory analysis includes data collection and procedures for calculating resource inputs and outputs, including input energy, materials, products, waste, and emissions. of the entire process by dividing the life cycle of the $Al(OH)_3$ industry into several subsystems that fall within the predetermined scope. Based on functional units, these materials were assigned LCI to form quantitative results, which were integrated calculations performed in SimaPro software with data quality. The primary/specific data collected came from the Alumina Plant in Tayan, West Kalimantan, Indonesia.

In the life cycle assessment, several assumptions were made to address data gaps and maintain consistency in the modeling approach. Firstly, it was assumed that the primary production data accurately represented normal operating conditions during the study's reference year. Secondly, due to the absence of a database in Indonesia, global datasets from Ecoinvent were employed as proxy datasets. Lastly, the calculation of air emissions from supporting materials and waste transportation was based on the distance traveled and the mode of transportation, utilizing the IPCC method.

Table 1. Life cycle inventory

Process	Inventor Data	Species	Data Activity	Unit
Bauxite Transportation (BT)	Energy Input [C]	Diesel	182	GJ
	Emission [C]	CO_2	14	t
		SO_2	0.05	t
		NO_x	0.04	t
Power Plant (PP)	Energy Input [DM]	Coal	118,829	t
		Diesel	1,049	GJ
	Water [IDM]	Demin Water	194,739	m^3

Process	Inventor Data	Species	Data Activity	Unit
	Product ^{DM}	Electricity	54,847,068	kWh
		Steam	255,104	t
	Emission ^{S}	CO_2	220,457	t
		NO_2	602	t
		SO_2	69	t
	Waste ^{DM}	Fly Ash	11,504	t
		Bottom Ash	582	t
Bauxite Yard (BY)	Energy Input ^{DM}	Diesel	2,293	GJ
	Emission ^{C}	CO_2	95.487	t
	Raw Materials ^{DM}	Bauxite	451,751	t
Bayer Process (BP)	Energy Input ^{DM}	Electricity	38,376,197	kWh
		Steam	255,104	t
	Raw Materials ^{DM}	Bauxite	451,751	t
	Water ^{DM}	Demin Water	3,564,000	m^3
	Support Materials ^{DM}	NaOH	39,865	t
		$Ca(OH)_2$	2,636	t
	Emission ^{IDM}	CO_2	119,338	t
	Product ^{DM}	$Al(OH)_3$	256,956	t
	Waste ^{DM}	Red Mud	193,335	t
		Wastewater	5,096,221	m^3
Hydrate Process (HP)	Energy Input ^{DM}	Diesel	8,101	GJ
		Electricity	2,910,009	kWh
	Emission ^{C}	CO_2	626.95	t
	Materials ^{DM}	$Al(OH)_3$	13,322	t
	Product ^{DM}	$Al(OH)_3$	13,967	t
Calcination Process (CP)	Energy Input ^{DM}	Diesel	371,319	GJ
		Electricity	2,244,378	kWh
	Emission ^{S}	CO_2	30,557	t
	Materials ^{DM}	$Al(OH)_3$	95,832	t
	Support Materials ^{DM}	AlF_3	9	t
		HCl	629	t
	Product ^{DM}	Al_2O_3	64,065	t
Back-up Power Plant (BPP)	Energy Input ^{DM}	Diesel	12,894	GJ
	Emission ^{S}	CO_2	1,070.09	t
	Product ^{DM}	Electricity	1,195,260	kWh
Landfill Red Mud (LRM)	Energy Input ^{DM}	Electricity	29,894	kWh
		Diesel	4,304	GJ
	Emission ^{C}	CO_2	179.25	t
	Waste ^{DM}	Red Mud	193,335	t
		Wastewater	343,668	m^3

Information: (^{C}) Calculation, (^{S}) Sampling, (^{DM}) Direct Measurement, (^{IDM}) Indirect Measurement

Inventory analysis includes all processes that fall within the predetermined scope, ranging from Bauxite Transportation, Power Plant, Bauxite Yard, Bayer Process, Hydrate Process, Calcination Process, Back-up Power Plant, and Landfill Red Mud. The following is an inventory flow diagram of the bauxite to $Al(OH)_3$ process at the Tayan Plant. The impact value per ton of product is calculated based on the actual annual throughput, not the plant's maximum capacity. The functional unit used was 1 ton of $Al(OH)_3$ with a reference flow, which is a one-year production cycle. Meanwhile, the Al_2O_3 stream of 64,065 tons per year comes from part of $Al(OH)_3$. Since 1 ton of Al_2O_3 equals 1.49 tons of $Al(OH)_3$. The maximum

capacity is not used as the divisor because it only shows the design capacity. Instead, impact allocation is based on the actual stream within the system boundaries from *gate-to-gate*.

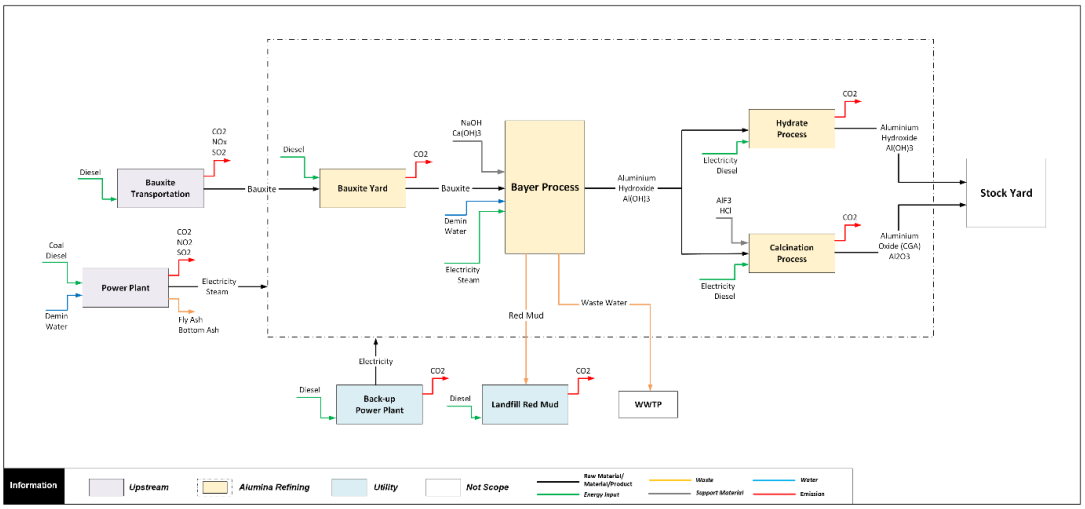


Figure 4. Flowchart inventory

Inventory analysis begins with analyzing data quality based on data sources and completeness or availability of data that can be seen in **Table 2.**

Table 2. Inventory data completeness and source

Inventory Data Type	Data Availability	Data Source			
		DM	IDM	S	C
Raw Materials/Materials	4	4	0	0	0
Support Materials	4	4	0	0	0
Energy Input	13	12	0	0	1
Emission	8	0	0	3	5
Product	6	6	0	0	0
Waste	6	6	0	0	0
Water	2	1	1	0	0

Information: (^{C}) Calculation, (^{S}) Sampling, (^{DM}) Direct Measurement, (^{IDM}) Indirect Measurement

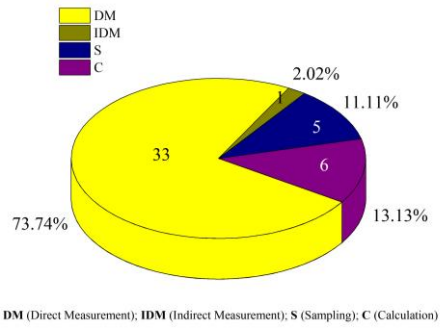


Figure 5. Data source percentage

Based on **Figure 5**, the data collected were primary data from the entire process, with 73.74% being primary data derived from direct measurement, 13.13% being primary data from partial data results assuming calculation with multiplier factors, 11.11% of primary data being data derived from sampling, and 2.02% of primary data being not directly measured data derived from the water data inventory used in power plants.

2.3 Life Cycle Impact Assessment (LCIA)

Impact assessment is the third step in the LCA. It uses methods and sets of categories to study how a process affects the environment and the human health. In this step, all inputs and outputs are checked to determine how they fit into the impact category chosen earlier. The cut-off criterion is established at 99% of the total flow coverage, ensuring that there is no significant impact on the overall result. Furthermore, no load allocation procedure is applied to the inputs and outputs of the process based on the product system under consideration. The results are presented in tables and graphs.

After examining the standards and major impacts on air quality (Zhang et al., 2021) four key factors were selected to measure environmental impact. The impact categories are GWP, ODP, AP, and POCP. The SimaPro Developer version 9.5.0 software was used for impact calculation with the CML-IA Baseline method. This method, from the Center of Environmental Science (CML Leiden), was selected because it includes these four factors and focuses on air quality impact (Pré, 2014). It is also commonly used in LCA studies to maintain consistent results (Handhayani, 2023).

Greenhouse effect is caused by greenhouse gases (GHG) introduced into the atmosphere, such as carbon dioxide (CO_2), methane, and freon. "GWP" describes how greenhouse gases contribute to global warming. We chose kg CO_2 eq as the reference (the equivalence coefficient was 1.0). ODP and emissions, such as chlorofluorocarbons (CFCs), contribute to ozone depletion. Due to their stable nature, CFCs can reach the stratosphere intact. CFCs are converted by ultraviolet radiation and emit chlorine, which is an ozone-depleting agent. We selected 1 kg of CFC-11 eq (equivalence coefficient of 1.0) as the reference. AP is caused by environmental acidification due to pollution. The acidity was indicated by the effects of these compounds. For reference, 1 kg of SO2 eq was used (equivalence coefficient of 1.0). POCP mainly arises from photochemical reactions caused by chemicals such as nitrogen oxides, hydrocarbons, and free radicals, resulting in photochemical pollution, phytotoxicity, and health issues. For the compounds in this process, kg C_2H_4 eq was chosen as a reference (equivalence coefficient of 1.0).

2.4 Interpretation

The final step in the LCA was interpreting the analytical findings by determining the key issues for each category that affect the entire process of processing bauxite into $Al(OH)_3$. According to Cornago et al. (2022), industrial processes with the greatest environmental impact pose the main challenges. Conclusions can be drawn, and recommendations for the best possible alternative improvements can be made for the important issues identified. Subsequently, an assessment can be made, and suggestions for the best alternative improvements can be provided.

A sensitivity analysis was conducted to evaluate the significance of the data and its effect on impact assessment outcomes (Villanova et al., 2020). This analysis focused on data related to key process issues, specifically emissions from PP. Emission data from the PP process unit were obtained through measurements conducted by the company using approved methodologies. For the sensitivity analysis, the emission data were adjusted by increasing and decreasing the values by 20% and 10%, respectively, to assess the sensitivity of the impact assessment results to variations in these critical issues.

Table 3. Sensitivity test results

Impact Categories	Indicator Category	Baseline	-20%	-10%	10%	20%
Global Warming Potential	kg CO_2 / t $Al(OH)_3$	1.61×10^3	1.42×10^3	1.52×10^3	1.71×10^3	1.81×10^3
	%Deviation		-11.90%	-5.95%	5.95%	11.90%
Ozone Depletion Potential	kg CFC_{11} / t $Al(OH)_3$	1.38×10^{-6}	1.14×10^{-6}	1.26×10^{-6}	1.50×10^{-6}	1.62×10^{-6}
	%Deviation		-17.39%	-8.69%	8.69%	17.39%
	kg SO_2 /	2.19×10^{-1}	1.83×10^{-1}	2.01×10^{-1}	2.37×10^{-1}	2.55×10^{-1}

Impact Categories	Indicator Category	Baseline	-20%	-10%	10%	20%
Acidification Potential	t $Al(OH)_3$					
	%Deviation		-16.54%	-8.27%	8.27%	16.54%
Photochemical Ozone Creation Potential	kg C_2H_4 / t $Al(OH)_3$	1.49×10^{-2}	1.27×10^{-2}	1.38×10^{-2}	1.60×10^{-2}	1.72×10^{-2}
	%Deviation		-15.15%	-7.58%	7.58%	15.15%

The results of the sensitivity analysis showed that the scenario of changing the value of all impact categories in the PP process unit did not have an impact on the result of the potential impact produced because the percentage deviation with the baseline was not greater than 20% and 10% and not less than -10% and -20%, so it can be concluded that the value of the potential impact was not sensitive to changes in the inventory value of the PP process unit. Among the four impact categories, ODP shows the highest sensitivity, whereas GWP exhibits the lowest sensitivity.

3. Result and Discussion

3.1 Life Cycle Impact Assessment

Table 4 summarizes the results of the calculation of the characteristic values of various bauxite processing unit processes for $Al(OH)_3$. This section describes and discusses the results of modelling based on the characteristic values of environmental impact types in relation to the different life cycle stages.

Table 4. Summary of characteristic value results

Process	GWP kg CO_2 eq/ t $Al(OH)_3$	ODP kg CFC_{11} eq/ t $Al(OH)_3$	AP kg SO_2 eq/ t $Al(OH)_3$	POCP kg C_2H_4 eq/ t $Al(OH)_3$	Emission Type
BT	5.37×10^{-2}	0	3.25×10^{-4}	2.91×10^{-5}	Direct
PP	9.60×10^{2}	1.20×10^{-6}	1.81×10^{-1}	1.13×10^{-2}	Direct
BY	3.78×10^{-1}	0	0	1.17×10^{-7}	Direct
BP	5.20×10^{2}	0	0	5.76×10^{-4}	Indirect
HP	2.45×10^{0}	0	0	6.07×10^{-7}	Direct
CP	1.19×10^{2}	0	0	2.89×10^{-5}	Direct
BPP	4.18×10^{0}	0	0	1.01×10^{-6}	Direct
LRM	7.85×10^{0}	1.80×10^{-7}	3.75×10^{-2}	2.98×10^{-3}	Direct

*Information: **(BT)** Bauxite Transportation, **(PP)** Power Plant, **(BY)** Bauxite Yard, **(BP)** Bayer Process, **(HP)** Hydrate Process, **(CP)** Calcination Process, **(BPP)** Back-up Power Plant, **(LRM)** Landfill Red Mud*

During the LCI and LCIA calculations, the distinction between utility generation and consumption was maintained. Consequently, the environmental effects of generating electricity and steam at the PP are transferred via utility flows and are not double-counted as direct emissions from the BP. In complex industrial processes, such as the Bayer Process, which is used to refine bauxite into alumina, energy inputs, such as steam and electricity, are critical. These energy forms are often produced in an associated power plant process that supplies energy to the refinery. When evaluating the carbon footprint of such a process, it is common to separate emissions into direct and indirect emissions according to established protocols, such as the GHG Protocol. Direct emissions are those emitted on-site in the process itself, whereas indirect emissions come from purchased energy, such as electricity or steam generated off-site (Bjørn et al., 2025).

In the PCR Basic Chemicals, $Al(OH)_3$ falls under the category of basic inorganic chemicals, CPC 3423. Therefore, if the research involves producing $Al(OH)_3$, the environmental impact should be reported per unit of $Al(OH)_3$. To effectively compare the environmental impacts of plants within a gate-to-gate scope, equivalent product units must be used. This is because LCA results are always tied to a

specific functional or declared unit. In the study by Kornelíusdóttir (2014), the functional unit was 1 ton of aluminum ingot (Al), whereas the current study used 1 ton of $Al(OH)_3$. Based on the mass balance in Al production, producing 1 ton of Al requires approximately 1.889 tons of Al_2O_3. In addition, considering the calcination reaction $2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$, this is approximately 2.89 tons of $Al(OH)_3$. Therefore, to ensure that comparisons are based on an equivalent reference flow and to avoid biased interpretations, the impact values calculated per tonne of Al must be adjusted to a per-tonne-of-$Al(OH)_3$ basis. The main focus of the impact stage is alumina refining, as it is the closest step to converting bauxite to $Al(OH)_3$.

Table 5. Comparison of characterization values for each category of Tayan and Norðurál plant impacts

Plant	GWP kg CO_2 eq / t $Al(OH)_3$	ODP kg CFC_{11} eq / t $Al(OH)_3$	AP kg SO_2 eq / t $Al(OH)_3$	POCP kg C_2H_4 eq / t $Al(OH)_3$
Tayan (Indonesia)	1.61×10^3	1.38×10^{-6}	2.19×10^{-1}	1.49×10^{-2}
Norðurál (Iceland)*	8.70×10^1	4.01×10^{-6}	3.84×10^1	2.48×10^{-1}
Ratio Tayan/Norðurál	185.47	0.34	0.057	0.06

Information: (*) Kornelíusdóttir, 2014

This study has limitations regarding the availability of specific local data; therefore, some information may rely on secondary data or approaches from the literature. This condition can affect the accuracy of the LCA results owing to differences in production process characteristics, energy sources, raw materials, and waste management between regions and industries. In addition, this study focused only on the production of $Al(OH)_3$ using a gate-to-gate approach and did not include the entire life cycle, such as distribution, use, and end of life; therefore, the results represent the environmental impact only at the production stage.

Another limitation is the use of a single case study at the Tayan Plant. This makes the findings suitable for describing the conditions of the examined plant, thus they may be applicable to the alumina industry in Indonesia with several adjustments. Nevertheless, this study contributes to the literature by providing an LCA-based overview of $Al(OH)_3$ production in Indonesia, particularly in the Tayan study.

3.1.1 Global Warming Potential (GWP)

The production of 1 ton of $Al(OH)_3$ has a global warming impact of 1.61×10^3 kg CO_2 eq/t $Al(OH)_3$, as shown in **Table 4**. Most of this impact comes from CO_2, which includes both biogenic and fossil CO_2. The PP process was the largest source of GHG, releasing 9.60×10^2 kg of the total 1.61×10^3 kg CO_2 eq/t $Al(OH)_3$, or 59.48% of the total. This is because coal and diesel used in steam power generators release a large amount of CO_2 when they are burned. Fossil fuels, such as coal and diesel, cause high CO_2 emissions. In Indonesia, over 40% of energy-related emissions originate from the electricity sector, mainly due to coal-fired power plants, making it the largest source of GHG. BP was the second-largest contributor to GWP, at 5.20×10^2 kg CO_2 eq or 32.21% of the total, owing to indirect emissions from electricity and steam consumption. The CP was the third-largest contributor to GWP, at 1.19×10^2 kg CO_2 eq or 7.39% of the total, because to diesel use in rotary kilns. Other processes had a small impact on GWP, with minor diesel use, mostly for heavy equipment.

Kornelíusdóttir (2014) studied the conversion of bauxite into Al at Norðurál in Iceland. The results showed a GWP value of 5,560 kg CO2 eq per ton Al. The alumina refining stage accounted for 45.2% of the total. When comparing the unit and scope, the GWP value was 8.70 kg CO2 per ton $Al(OH)_3$. The GWP at the Norðurál Plant (185.47×10^2)% was lower than that at the Tayan Plant owing to the different fuel usages. Norðurál uses heavy fuel oil (HFO) and natural gas (NG), whereas Tayan uses coal and diesel fuel. Tayan's GWP is higher because it relies more heavily on fossil fuels. Coal and diesel power plants produce emissions of 0.91–0.95 kg CO2 per kWh, whereas HFO generates 0.26 kg CO2 per kWh and NG produces 0.19 kg CO2 per kWh. This shows that coal and diesel remain common in Indonesia's

energy mix. Shifting to cleaner energy sources is important for reducing carbon emissions during the production process. This information can assist the government in managing air quality. An integrated system is required to achieve better outcomes.

3.1.2 Ozone Depletion Potential (ODP)

Based on **Table 4** in the production process of 1 ton of $Al(OH)_3$, a characterization value of the impact of ODP of 1.38×10^{-6} kg CFC_{11} eq. The characterization value is relatively low because the entire cycle under consideration includes minimal activities that generate gases contributing to the ODP, such as Chlorofluorocarbon (CFC). The formation of these gases necessitates specific halogenated reactions and inefficient combustion of halogenated substances. The production of $Al(OH)_3$ has a low ODP because it does not directly emit CFCs or involve halogenated precursors, and energy sources such as coal and diesel do not promote CFC production. Thus, the ODP values are minimal, indicating limited emissions of ozone-depleting compounds (Liu et al., 2024). The ODP mainly includes CFC gases. The processes that contribute indirectly to the characterization value of ODP are PP of 1.20×10^{-6} kg CFC-11 eq and LRM of 1.80×10^{-7} kg CFC_{11} eq. The produced characterization value is very small because, in both processes, the majority use coal fuel in the combustion process in PP and diesel in heavy equipment in LRM.

Kornelíusdóttir (2014) examined the process of converting bauxite into Al at Norðurál and determined an ODP value of 3.25×10^{-5} kg CFC_{11} eq per ton Al. The alumina refining stage accounted for 35.7% of the total ODP in this study. When the units and scope were equalized, the ODP value was 4.01×10^{-6} kg CFC_{11} eq/ton of $Al(OH)_3$. The ODP of the Norðurál Plant was 34% lower than that of the Tayan Plant owing to the use of different energy sources. The difference in energy sources between Norðurál and Tayan suggests that the environmental impact of each facility is significantly affected by its fuel composition. Norðurál utilizes HFO and NG to meet its thermal energy needs, whereas the Tayan facility employs coal- and diesel-fired power systems for its operational processes. Given that coal and diesel combustion typically results in higher air emissions than NG, the energy system at Tayan is likely to have a more substantial effect on impact categories. However, neither produces a large amount of ODP-causing gases, such as CFCs. As this study only examined the main processes, further research is required to determine the effects of burning fossil fuels in the alumina industry on the ozone layer.

3.1.3 Acidification Potential (AP)

Based on **Table 4**, producing 1 ton of $Al(OH)_3$ generates an AP of 2.19×10^{-1} kg SO_2 eq/t $Al(OH)_3$ for the entire production cycle. AP mainly includes acidic gases, such as SO_2 and NO_x. The PP process unit had an AP value of 1.81×10^{-1} kg SO_2 eq/t $Al(OH)_3$, and the LRM had 3.8×10^{-2} kg SO_2 eq/t $Al(OH)_3$, accounting for 82.72% and 17.13% of the total values, respectively. In BT, the AP value was very small. SO_2 in PP originates from coal and diesel combustion. In the LRM, heavy vehicles transporting red mud are responsible. The alumina industry requires a large amount of electricity, especially from coal-fired thermal power. Fossil fuels form the traditional energy structure of the alumina industry.

Kornelíusdóttir (2014) examined the conversion of bauxite into Al in Norðurál, Iceland. The study determined that the process emitted 80 kg SO2 eq per ton of Al. The alumina refining stage accounted for 13.8% of the total AP generated. When adjusted, this equals 3.82 kg SO_2 eq per ton $Al(OH)_3$. Comparing the Norðurál Plant in Iceland and the Tayan Plant in Indonesia, the difference in AP was 5.7%. Although they use different energy sources, their AP values are similar. Norðurál uses HFO and NG, whereas the Tayan Plant uses coal and diesel. Norðurál had a lower AP impact because of its energy sources. HFO can produce up to 0.001 g/MMBtu or 0.013 g/kWh of SO_2, and NG has very low SO_2 emission. Coal-fired steam produces 6.94–7.20 g SO_2/kWh and diesel produces 1.25 g SO_2/kWh. During the combustion of HFO, the nitrogen present in the fuel significantly contributes to the formation of NO_x. Conversely, in diesel, the reduced nitrogen content implies that NO_x production is predominantly attributed to elevated temperatures during combustion, leading to the generation of thermal NO_x (Pei et al., 2022).

The Tayan Plant's AP results were lower than Norðurál's, suggesting that industries should use low-sulfur fuels to reduce SO2 emissions and acid rain. This information helps the government manage air quality through Pollutant Release and Transfer Registers (PRTR), allowing for calculations of the SO_2 Footprint' and national 'SO_2 emission footprints' (Dehkhoda et al., 2024), similar to the Acid Rain Program and Toxic Release Inventory in the USA and the European Pollutant Release and Transfer Register (E-PRTR).

3.1.4 Photochemical Ozone Creation Potential (POCP)

In the process of making 1 ton of $Al(OH)_3$, 1.49×10^{-2} kg eq of POCP was produced. The PP process created a large amount of this oxidant, with a value of 1.13×10^{-2} kg, which was 75.76% of the total. The LRM increased by 19.98%, with a value of 2.98×10^{-3} kg. CP and BT also produce some oxidants, but in very small amounts. Pollutants such as NO_x, CO, and hydrocarbons from coal burning in PP and diesel use in LRM create photochemical haze when exposed to sunlight. This haze can harm animals, plants, and the environment as a whole. Therefore, PP and LRM are major sources of this oxidant.

The results of the research of Kornelíusdóttir (2014) related to the processing of bauxite into Al in Norðurál resulted in a POCP characterization value of 4.98 kg of C_2H_4 eq per ton Al, requiring alumina refining stage contributed 14.4% of the total POCP. By equalizing the functional units, the POCP characterization value became 2.48×10^{-1} kg C_2H_4 eq/t $Al(OH)_3$. A comparative analysis of the product systems of the Norðurál Plant in Iceland and the Tayan Plant in Indonesia was performed, as presented in **Table 5**. The ratio of the POCP difference in bauxite to $Al(OH)_3$ in these two places is relatively small at 6%. Although there are technological differences in the energy supply for the production process. Norðurál uses thermal energy from HFO and NG, whereas the Tayan Plant uses energy from coal and diesel steam power plants. The POCP results at the Tayan (Coal + Diesel) Plant, which has a value less than that of Norðurál (HFO + NG), can be considered by the industry to choose environmentally friendly fuels and implement the electricity mix while transitioning to fully green energy. This is also an input to the government regarding air quality control through Pollutant Release and Transfer Registers (PRTR). Therefore, there is an integrated system.

3.2 Interpretation Results and Discussion

After examining all impact categories, the main issues were identified based on which processes affected the environment the most in the product system. The analysis focused on the processes that contribute most to the environmental impact in the categories at the Tayan Plant. These processes were grouped into upstream, core alumina refining, and core utility processes using Pareto Rules. This helps prioritize the impacts and make clear improvement suggestions. In **Table 6**, the percentage of each process unit shows its share of the total potential impact in its category.

Table 6. Summary of the characterization ratios of each unit process

Impact Category	BT	PP	BY	BP	HP	CP	BPP	LRM
GWP	0.003%	59.48%	0.023%	32.21%	0.15%	7.39%	0.26%	0.49%
ODP	-	86.93%	-	-	-	-	-	13.07%
AP	0.15%	82.72%	-	-	-	-	-	17.13%
POCP	0.20%	75.76%	0.001%	3.86%	0.004%	0.19%	0.007%	19.98%

*Information: **(BT)** Bauxite Transportation, **(PP)** Power Plant, **(BY)** Bauxite Yard, **(BP)** Bayer Process, **(HP)** Hydrate Process, **(CP)** Calcination Process, **(BPP)** Back-up Power Plant, **(LRM)** Landfill Red Mud*

According to **Table 6**, the key problems in the PP process unit are in power production. Diesel emissions from rotary kilns are a concern in CP units. The LRM unit has problems with emissions from heavy equipment. The main problem in converting bauxite into $Al(OH)_3$ is in the PP and LRM units. The alumina industry is important for Indonesia's mineral plans but struggles with energy consumption and

pollution. It is important to improve efficiency and reduce emissions. The identified problem areas require focused management to ensure sustainable production. This supports the national goals of carbon neutrality, less pollution, and better governance.

3.3 Recommendations for Alternative Improvements

This study examined the challenges associated with converting bauxite into $Al(OH)_3$, primarily focusing on the use of fossil fuels for electricity and the production of harmful red mud. To address these issues, we suggest improving electricity efficiency, changing fuel sources, and finding new uses for red mud. We evaluated the effects of these suggestions on participants. Details on better electricity use in the Bayer and calcination processes are provided in Section **3.3.1** of this paper. For changing materials, using coal with IGCC + CCS technology is recommended as a short-term fix at the Tayan Plant, as explained in Section **3.3.2**. **Table 9** lists the three possible uses of red mud in the present study. We gathered the impact values for scenarios involving better electricity use, fuel changes, and red mud use using data from Sections **3.3.1**, **3.3.2**, and **3.3.3**, respectively. A summary of these values is presented in **Table 7**.

Table 7. Summary of characterization values for each improvement recommendation

Impact Category	Unit	Electricity Efficiency[a]	Fuel Substitution[b]	Redmud Utilization[c]
GWP	kg CO_2 eq/t $Al(OH)_3$	1.47×10^{1}	5.98×10^{1}	9.32×10^{-1}
ODP	kg CFC_{11} eq/t $Al(OH)_3$	-	2.72×10^{-8}	2.97×10^{-9}
AP	kg SO_2 eq/t $Al(OH)_3$	-	4.34×10^{-6}	1.54×10^{-4}
POCP	kg C_2H_4 eq/t $Al(OH)_3$	2.89×10^{-5}	1.74×10^{-7}	4.53×10^{-6}

Information: ([a]) Calcination Process & Bayer Process ([b]) Power Plant ([c]) Landfill Red Mud

3.3.1 Electricity Efficiency

Table 7 presents four strategies for enhancing the efficiency of electricity usage in the conversion of bauxite to $Al(OH)_3$. Electrifying the Calcination Process Alcoa Pinjarra is testing an Electric Calciner to replace burning, which could save approximately 75 kWh per ton (assuming 5% process efficiency) (Alcoa, 2018). Using electricity to produce hydrogen (H_2) for calcination can significantly reduce emissions if the grid intensity is ≤40 g CO_2/kWh (Mohammed et al., 2023), although producing and compressing H_2 adds approximately 30–50 kWh per ton of alumina. Improving the Evaporation Stage by Recovering Waste Heat The evaporation stage in the Bayer process uses a lot of energy (Çelikel et al., 2016); the report that using waste heat from flue gas boilers and steam traps can cut electricity use for pumps and vacuums by 3–8 kWh per ton. Choosing Bauxite Boehmite over gibbsite is better because it saves 7.2 kWh per ton of alumina during calcination owing to lower decomposition temperatures (Moya et al., 2015).

Table 8. Summary of alternative electricity use efficiency in Tayan plant

Process	Alternative	Percentage of Electricity Efficiency (%)	Electricity Consumption (kWh/t $Al(OH)_3$)	
			Baseline	Result
Calcination Process	Pilot Electric Calciner	50	35.03	10.51
	H_2-Assisted Electrification	20-30		
Bayer Process	Waste-heat recovery in evaporation	2-5	149.35	139.19
	Selection of Bauxite Boehmite	4.8		

In the Bayer process, using waste heat recovery and choosing boehmite saves 2.99 and 7.17 kWh per ton of $Al(OH)_3$, adding up to 10.16 kWh/ton. This reduced the energy use from 149.35 to 139.19 kWh per ton. Electrifying calcination with a pilot electric calciner and H_2 assistance saves 17.52 and 7.01 kWh per ton (20% efficiency), totaling 24.52 kWh per ton, and reduces the use of energy from 35 to 10.51 kWh per ton. These steps focus on the two largest energy users and significantly improve energy efficiency. The Bayer process can save energy through waste heat recovery and boehmite selection, totaling 10.16 kWh per ton, lowering the energy use from 149.35 to 139.19 kWh per ton. This is key for improving the Bayer and calcination stages and can be a part of an energy efficiency program.

3.3.2 Fuel Substitution

Coal (IGCC) can be replaced with cleaner fuels such as NGCC (natural gas), biomass co-firing, biogas, and low-emission hydrogen. NGCC releases approximately 400–650 lb CO_2/MWh. Mixing 30% biomass reduces emissions while maintaining steady efficiency (Xie et al., 2023). Biomethane from farm and animal waste can have a negative carbon footprint (up to 240% savings) by capturing CH_4 (EBA, 2020). Green or blue H_2 (electrolysis ± CCS) can reduce CO_2 emissions by more than 90% compared to fossil fuels in gas turbines.

Table 9. Summary of fuel substitution and technology in Tayan plant

Fuel	Technology	Emission Median kg CO2 eq / kWh	Percentage of CO_2 eq Reduction (%)	Emission kg CO2 eq / kWh	
				Baseline	Reduction
Coal	IGCC + CCS	0.28	93%		3.74
Natural Gas	NGCC	0.49	88%		3.53
Biomass	IGCC Biomass Co-Firing	0.23	94%	4.02	3.79
Hydrogen	H_2 Electrolysis + CCS	0.03	99%		3.99

*Information: **(IGCC)** Integrated Gasification Combined Cycle, **(NGCC)** Natural Gas Combined Cycle, **(CCS)** Carbon Capture Storage*

The Tayan Power Plant uses coal and pulverized coal to generate electricity. This process results in the emission of CO2. The plant emitted 2.20×10^8 kg of CO_2 for 5.48×10^7 kWh of electricity. This means that the plant emits 4.02 kg of CO_2 for each kWh of electricity generated. **Table 8** presents the average CO_2 emissions for the different fuels and technologies (Krey et al., 2014). Compared to the baseline, using coal IGCC + CCS reduced emissions by 93%, natural gas NGCC by 88%, biomass IGCC by 94%, and H_2 electrolysis + CCS by 99%. This indicates a significant reduction in CO2. In the short term, the Tayan Plant can use biomass co-firing with IGCC or coal with IGCC + CCS. Later, NGCC can be used. In the long term, H_2 (electrolysis) + CCS and renewables can be used. These plans help to reduce greenhouse gas emissions and meet net-zero goals.

3.3.3 Utilization of Red Mud

Red mud is an alkaline byproduct of the Bayer process. It can replace raw materials in different areas, such as construction and metal recovery. For example, Alcoa Pinjarra uses it for dikes and road compaction (Alcoa, 2018). The IAI suggests using 10%–20% of it to replace clinker in cement to lower carbon emissions (Healy, 2022). Bauxite, red mud, and fly ash can form strong blocks for construction (Agrawal and Dhawan, 2021). The Tayan Plant could provide red mud to the cement industry, keeping 58,001 tons (30% of the original amount) out of landfills.

Metals can be extracted from red mud using magnetic separation and leaching. This process yields iron slag and sodium alumina with 30%–60% Fe_2O_3 and 10%–20% Al_2O_3. Another method involves mixing red mud with fly ash (80:20) and using carbothermal reduction to produce pig iron. The Tayan Plant could use these methods to turn waste into products that sell well. This would meet the high demand for iron and alumina, both locally and globally. This could reduce red mud in landfills by 87,000 tons, which is 45% of the original amount. Red mud can absorb carbon and pollutants. It absorbs 0.2 tons of CO_2 per ton of red mud (Cooling, 2018), 11.7 g of CO_2 per kg at 80–100 mesh (Fan et al., 2024), and 0.25 g of CO_2 per gram when mechanically activated (Ilahi et al., 2024). It also captures NO_x or SO_x and balances the pH levels. Using surfactants and surface carbonation can remove up to 60% of SO_3 from FCC exhaust. TiO_2 modification helps to break down VOCs using light. At the Tayan Plant, these methods could reduce red mud to 19.333 tons (10% of the original amount). **Table 9** presents the simulation results.

Table 10. Summary of red mud utilization scenarios at Tayan plant

Utilization of Red Mud	Utilization Percentage* (%)	Red Mud in Landfill (t)	
		Baseline	Scenario
Clinker Substitutes	30	193,335	135,335
Metals and Minerals Recovery	45		106,334
Absorbent	10		174,002

(*) Utilization Assumptions

This scenario addresses bauxite residue by repurposing red mud, improving energy efficiency, and reducing emissions, in alignment with circular economy principles. Further research is required to quantify the benefits of red mud reuse in the alumina industry. It can serve as a sustainable program that addresses energy efficiency, emissions reduction, and hazardous waste management.

4. Conclusions

The evaluation in this research for the environmental effects of producing $Al(OH)_3$ at the Tayan Alumina Plant in Sanggau Regency, Indonesia, were evaluated using a *gate-to-gate,* with LCA methodology on a functional unit of 1 ton of $Al(OH)_3$ and employed the CML-IA Baseline method to analyze four impact categories related to air quality: GWP, ODP, AP, and POCP.

The results indicate that producing 1 ton of $Al(OH)_3$ has environmental impacts. GWP is the biggest environmental issue, mainly because of the extensive use of fossil fuels such as coal and diesel for electricity and steam. The analysis revealed that the Power Plant was the main source of most impacts. The other processes are the Bayer Process, Calcination Process, and Landfill Red Mud.

This study implies that decarbonization and pollution reduction in the Indonesian alumina industry should focus on improving electricity efficiency, substituting cleaner fuels, and utilizing red mud for useful materials. The research results aid industry decision-making, enhance environmental performance based on sustainable development, improve air pollution management, and contribute to national decarbonization efforts. Future studies should broaden the system boundary to encompass bauxite mining, transportation, chemical production, and alumina or aluminum processing, enabling *cradle-to-gate* or *cradle-to-grave* analysis.

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