PHRAJ
Public Health Risk Assesment Journal
PHRAJ 4(1): 36–57
ISSN 3025-1109

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Environmental impact of traditional medicines in pharmaceutical manufacturing: Using a life cycle assessment

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Received Date: June 2, 2026 Revised Date: July 11, 2026 Accepted Date: July 25, 2026

ABSTRACT

Background: The production of pharmaceutical products requires significant amounts of energy, raw materials, and chemical inputs, which may result in greenhouse gas emissions and other environmental burdens throughout the product life cycle. The manufacture of traditional medicines, which utilize natural resources such as herbal materials, likewise involves energy-intensive processes that may contribute to environmental degradation. This study aims to assess the environmental impacts associated with the production of traditional herbal cough medicines and compare them with non-herbal cough medicines and to identify critical points that contribute to greenhouse gas emissions. **Methode:** This study adopts a quantitative approach employing the Life Cycle Assessment (LCA) methodology in accordance with the ISO 14040 standard. The system boundary is defined as cradle-to-gate. The functional unit is defined as one metric ton of packaged traditional medicine products. Environmental impact assessment is conducted using the IPCC 2021 GWP100 V1.00 method through SimaPro 10.2.0.3 software, supported by the Ecoinvent 3.0 database. The analysis focuses on the Global Warming Potential (GWP) indicator. **Findings:** The results indicate that the production of traditional herbal cough medicines generates total emissions of approximately 47.5 tCO_2-eq per one metric ton, whereas the manufacture of non-herbal cough medicines produces a higher total of approximately 105.98 tCO_2-eq. Across both production systems, several utility processes were identified as contributing significantly to environmental impacts. In particular, HVAC system was identified as a critical hotspot, accounting for approximately 21.86% of total emissions due to its substantial electricity consumption, equivalent to 3.5 tCO_2-eq per one metric ton product. **Conclusion:** The life cycle assessment conducted for the production of non-herbal indicates generate higher CO_2 emissions compared to herbal products. **Novelty/Originality of this article:** This study compares the environmental impacts associated with the production processes of traditional herbal cough medicines and non-herbal cough medicines using the Life Cycle Assessment methodology.

KEYWORDS: environmental impact; pharmaceutical manufacturing; life cycle assessment.

1. Introduction

The manufacturing sector is among the most rapidly developing industries compared to other sectors. According to data from the World Bank (2023), sectors experiencing notable growth include energy, agriculture, plantations, marine industries, processing, and manufacturing. The manufacturing sector is often regarded as a primary sector, implying that development within manufacturing subsectors can stimulate growth in other sectors, such as agriculture and services.

Cite This Article:
Manurung, W. M., Agustina, H., & Sodri, A. (2026). Environmental impact of traditional medicines in pharmaceutical manufacturing: Using a life cycle assessment. *Public Health Risk Assesment Journal*, *4*(1), 36-57. https://doi.org/10.61511/phraj.v4i1.2026.3812

According to the Ministry of Industry of the Republic of Indonesia in 2022, the manufacturing sector constitutes one of the principal pillars of the Indonesian economy, contributing the largest share to the nation's Gross Domestic Product (GDP), amounting to 19.9%, which exceeds the global industrial average of 16.5% observed in other developed countries. This phenomenon may be attributed to Indonesia's population growth, which has led to increased demand for goods alongside improvements in living standards. Consequently, the manufacturing sector is widely regarded as playing a crucial role in enhancing both economic and social welfare. Furthermore, the expansion of the manufacturing industry facilitates employment generation, thereby increasing household income and fostering broader economic and social development within society.

One of the manufacturing subsectors experiencing significant growth is the pharmaceutical industry. It is widely recognized that the pharmaceutical industry is among the most profitable sectors globally, particularly given its capacity to leverage its influence in the healthcare domain to advance research through education and marketing activities (Goodman, 2009). According to data from Badan Pusat Statistik in 2023, there are currently 239 pharmaceutical companies operating in Indonesia. This trend is closely associated with evolving lifestyles and the increasing awareness among the Indonesian population regarding the importance of health, further supported by government-driven health programs. Consequently, the pharmaceutical industry in Indonesia has developed rapidly due to its strategic role. As stipulated in the Regulation of the Minister of Health of the Republic of Indonesia Number 1799 of 2010, the pharmaceutical industry is responsible for the production of medicines and/or pharmaceutical raw materials, as well as for conducting activities related to education, training, research, and development within the health sector.

However, alongside its rapid development, the pharmaceutical industry has also exerted significant environmental impacts. This is largely attributable to the increasing intensity of energy consumption, utilization of natural resources, and extensive use of chemical inputs (Chaturvedi et al., 2021). Moreover, each stage of the production process has the potential to generate waste and emissions if not properly managed, thereby contributing to pollution and a range of environmental issues. Pharmaceutical industrial waste typically contains active pharmaceutical ingredients (APIs), volatile organic compounds (VOCs), and other chemical substances that are persistent and resistant to natural degradation. The presence of pharmaceutical residues in the environment is classified as emerging contaminants due to their biologically active nature and their potential to cause long-term effects, even at low concentrations (Okeke et al., 2022). Empirical studies have demonstrated that substantial pharmaceutical pollution in surface waters has occurred globally, and such pollutants are now recognized as emerging contaminants in rivers and other aquatic systems (Patel et al., 2019).

The global pharmaceutical manufacturing industry has emerged as a major contributor to greenhouse gas (GHG) emissions. Across the entire life cycle—from production to use and disposal, it is responsible for a range of environmental impacts, most notably greenhouse gas emissions and ecotoxicity (Parker et al., 2024). The growth of greenhouse gas emissions within the global pharmaceutical sector has reached 77%, significantly exceeding the overall global increase of 49% (Hagenaars et al., 2025). This trend is largely attributable to the numerous chemical reaction processes involved in pharmaceutical production, which inherently require substantial energy consumption and generate considerable CO_2 emissions. Consequently, both energy demand and CO_2 emissions in the pharmaceutical industry are relatively high (Chaturvedi et al., 2017). The cumulative energy demand (CED) of pharmaceutical chemicals can be up to 20 times greater than that of basic chemical products, while their global warming impact (GW) may reach up to 25 times higher (Wernet et al., 2010). Therefore, the production of pharmaceutical products is highly resource-intensive and has the potential to generate significant environmental burdens (Parvatker et al., 2019).

Another segment of the pharmaceutical industry that has experienced significant growth is the production of traditional medicines. Indonesia is recognized as one of the countries with a long-standing history of traditional medicinal practices. To this day,

traditional medicines remain a widely utilized option among the population for maintaining health and treating diseases. Initially empirical in nature and rooted in cultural practices passed down through generations, traditional medicine has evolved through the incorporation of formal education and its integration into the national healthcare system. At present, numerous large-scale manufacturing industries are engaged in the production of traditional medicines. The expansion of this industry is inevitably accompanied by environmental, social, and economic challenges arising from its industrial value chain. Furthermore, the manufacturing of traditional pharmaceutical products can become a significant source of pollution, particularly in contexts where environmental regulations affecting pharmaceutical plant licensing remain insufficiently stringent. The presence of pharmaceutical residues in the environment has raised substantial concern due to their adverse effects on wildlife (Brodin et al., 2017; Jobling et al., 2006; Oaks et al., 2004). In addition to environmental exposure resulting from pharmaceutical residues, environmental impacts may also arise from various stages of the product life cycle, including production processes (e.g., energy and freshwater consumption), product packaging, distribution (including transportation and storage), and end-of-life stages (such as unused and improperly disposed medicines).

Environmental issues associated with pharmaceutical production constitute not only a challenge for the industry itself but also pose significant risks to the broader environment. Efforts to address industrial environmental impacts have been widely developed in various countries; however, these initiatives have predominantly focused on outputs of the production process, such as waste and emissions. Increasing international pressure has compelled organizations to adopt measures aimed at enhancing not only economic performance but also social and environmental performance. Fundamentally, environmental concerns do not arise solely from production processes but extend across the entire industrial value chain. Nevertheless, research on environmental management within the pharmaceutical industry remains limited, as most studies have concentrated on single-stage issues rather than adopting a comprehensive life-cycle perspective (Massoud et al., 2015).

One approach to mitigating the environmental impacts of industrial processes is the application of Life Cycle Assessment (LCA) principles. LCA is a methodological framework used to comprehensively analyze and evaluate the environmental impacts arising throughout the entire life cycle of a product. Further explain that, in practice, LCA can be applied to assess the environmental impacts of production activities. Steubing et al. (2016) highlight that LCA may also serve as a basis for determining appropriate scenarios to address environmental challenges. Such scenarios are utilized to analyze impacts and identify key contributing factors, which subsequently inform recommendations for improvement. From a business perspective, LCA is regarded as a strategic tool that provides added value by reducing environmental pollution, thereby enhancing product value while simultaneously lowering environmental management costs. Additional benefits of LCA implementation include product improvement, increased process efficiency, and support for strategic planning initiatives. Life Cycle Assessment represents a comprehensive framework for evaluating the full life cycle of a product, encompassing raw material extraction, transportation, processing, manufacturing, packaging, storage, distribution, use, maintenance, repair, and end-of-life stages such as disposal or recycling (Zhang et al., 2024). Through this holistic approach, LCA contributes to reducing significant energy consumption and supports the implementation of green manufacturing practices (Liu et al., 2024).

At each stage of the pharmaceutical industrial process, environmental impacts arise in the form of greenhouse gas (GHG) emissions resulting from energy consumption, raw material utilization, and processes that generate liquid waste, hazardous waste (B3), and non-hazardous waste (non-B3). According to Riikonen (2024), efforts to reduce GHG emissions based on LCA studies can achieve reductions of up to 20%; however, in 2024, emission reductions at PT X reached only 12%. This study aims to evaluate environmental impacts with a particular focus on total carbon emissions, expressed in CO_2-equivalent units, in order to quantify the Global Warming Potential (GWP) associated with production

processes in the traditional medicine industry. The total CO_2 emissions generated will be calculated across all unit processes for each production batch, equivalent to 184 kg of traditional medicine. Furthermore, this research seeks to identify key drivers for reducing greenhouse gas emissions and to determine environmental critical points (hotspots) at each stage of the production process. In this study, we aim to evaluate and compare the environmental impacts of traditional herbal cough medicines and cough medicines containing active pharmaceutical ingredients by employing an attributional Life Cycle Assessment (LCA) approach, using the IPCC 2021 GWP100 V1.00 method. By quantifying the emissions associated with each formulation throughout its life cycle, this analysis seeks to estimate the overall differences in environmental impacts between the two formulations, as well as to identify key processes or entities that contribute most significantly to climate-related emissions and other impact categories.

2. Methods

2.1 Study area

The traditional pharmaceutical industry utilizes natural materials derived from plant extracts as its primary raw materials. In addition, this sector is required to maintain competitiveness and ensure sustainability throughout its production processes. This study was conducted at a traditional medicine manufacturing facility located in the Pulogadung Industrial Estate, East Jakarta, situated at coordinates Latitude −6.2045241 and Longitude 106.9155157. The selection of the study site was based on several considerations, including the fact that the facility remains actively engaged in the production of traditional medicines and has demonstrated a continuous increase in output. Jakarta is recognized as one of the cities contributing significantly to greenhouse gas (GHG) emissions in Indonesia. Consequently, the presence of traditional medicine production activities within Jakarta further contributes to the city's pollution burden as a result of industrial operations. Moreover, Jakarta has established targets to reduce emissions by 30% by 2030 and to achieve net-zero emissions by 2050 (Gozali et al., 2026).

2.2 Research design and methodology

To determine the environmental impacts of production processes in the traditional pharmaceutical manufacturing industry, this study employs a quantitative approach using the Life Cycle Assessment (LCA) methodology in accordance with ISO 14040 (2006). The analysis is structured into four stages: the initial identification phase, the data collection phase, the data processing phase, and the interpretation of results and conclusion stage.

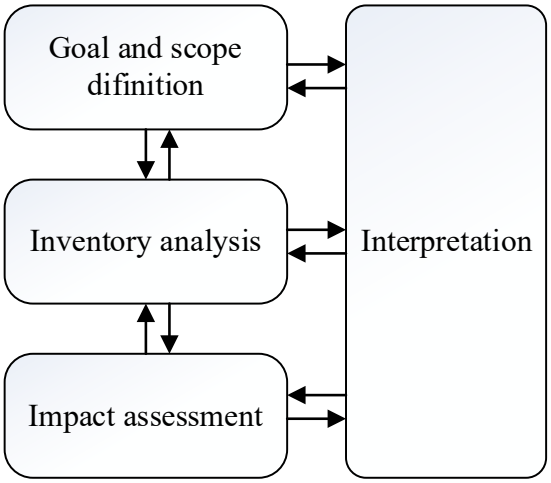

Fig. 1. Framework on life cycle assessment method
(International Organization for Standardization, 2006)

The primary objective of this study is to quantify the environmental impacts associated with the production of cough medicines formulated using traditional herbal ingredients and to compare them with those produced using active pharmaceutical ingredients. The environmental impact assessment is conducted in accordance with the defined goal and scope. The impact category considered in this study is Global Warming Potential (GWP), calculated based on the CO_2-equivalent emissions generated. The system boundary is established as cradle-to-gate, encompassing raw material extraction, the production processes of traditional medicines, and concluding at the packaging stage.

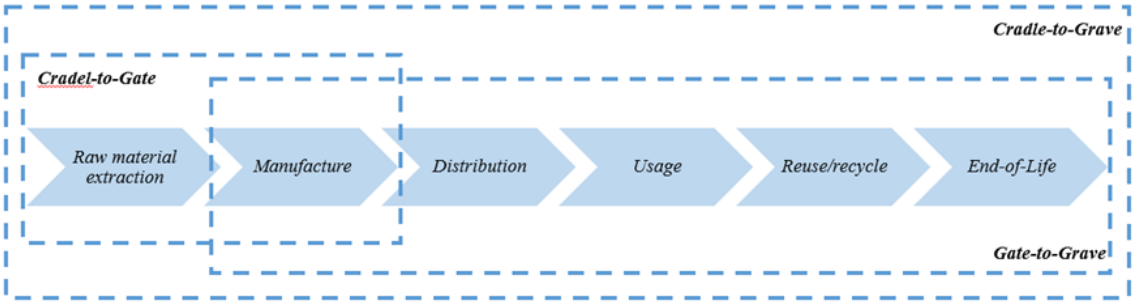

Fig. 2. Framework on life cycle assessment method
(International Organization for Standardization, 2006)

The selection of this system boundary is based on its suitability for capturing significant upstream impacts associated with the manufacturing processes of traditional medicines. This approach is aligned with the objective of providing a comprehensive environmental impact assessment up to the product packaging stage, thereby ensuring both relevance and specificity to the production processes under investigation. The system boundary defined in this study is illustrated in Figure 3.

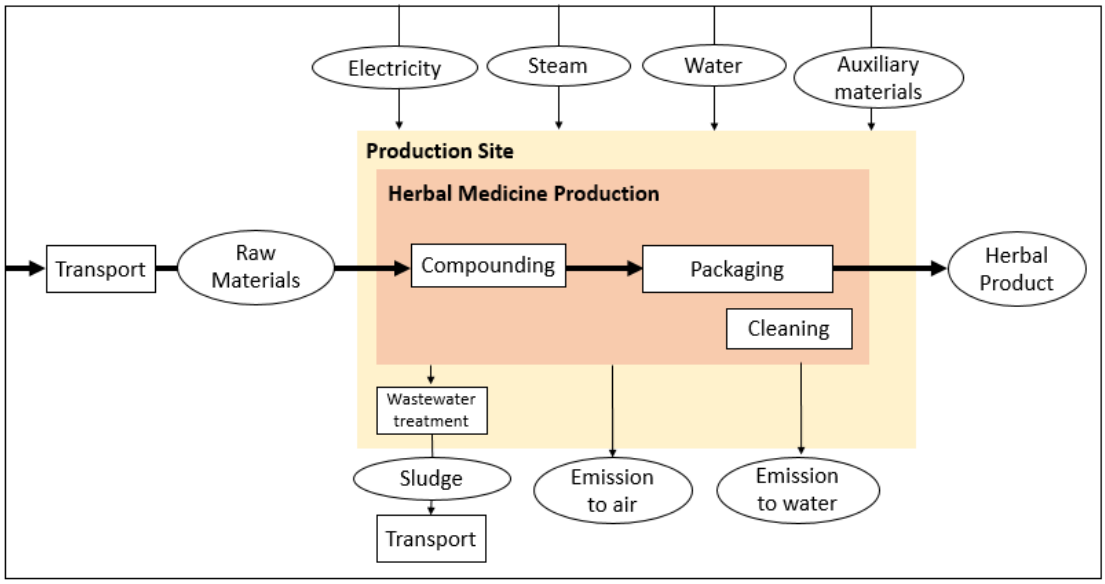

Fig. 3. Research system boundary
(Widya et al., 2025)

The functional unit established in this study is one metric ton (t) of packaged medicinal product. The impact assessment is conducted using the IPCC 2021 GWP100 V1.00 characterization method, given its high relevance and widespread application in Life Cycle Assessment (LCA) studies within the pharmaceutical industry. This study utilizes the Ecoinvent 3.0 database to model the background system, while the foreground inventory modeling is performed using SimaPro 10.2.0.3 software.

2.3 Data collection and inventory analysis

The inventory data in this LCA study consist of both primary and secondary data. Primary data refer to those obtained directly from environmental monitoring and on-site records. Environmental monitoring data are collected during field observations and can be directly utilized as inventory inputs. In addition, primary data may also be derived from calculated monitoring data that have been converted into appropriate units for use as inventory inputs in the LCA analysis (e.g., unit conversions of monitoring data). Secondary data, on the other hand, are obtained from datasets available within the SimaPro 10.2.0.3 software database. The inventory data in this LCA study are categorized into two groups, namely herbal cough medicine and pharmaceutical (non-herbal) cough medicine.

Based on the summary of total inventory data within the cradle-to-gate scope per unit product (one metric ton of product), corresponding to the defined functional unit, it is identified that the primary inputs for the cradle-to-gate stage of traditional herbal cough medicine include honey, **Zingiber** (red ginger), sugar (sucrose), and **Lagundi** leaf extract as the main raw materials. Analytical reagents and other auxiliary materials used in the production process are excluded from this study due to their negligible contribution (less than 1% of the total mass), and are therefore considered within the cut-off criteria. The outputs from the cradle stage consist of emissions to air resulting from raw material production and transportation, which are subsequently processed further in the manufacturing stage. The determination of primary and secondary data in the preparation of this inventory is based on the Product Category Rules (PCR): 2019 for pharmaceutical products and processes, issued by Technische Universität Berlin and recommended by the Global Pharmaceutical Industry Association (Siegert et al., 2019). The inventory data for the cradle scope of herbal cough medicine are presented in Table 1.

Table 1. Cradle process inventory data herbal (Ecoinvent database 3.0)

Process Unit	Dataset	Quantity	Unit
Raw Material	Planting tree {RoW}| planting, tree | Cut-off, U	19001	kg
Production	Sugar beet {CH}| production | Cut-off, U	36800	kg
Raw Material Transport	Transport, freight, lorry 3.5-7.5 metric ton, euro4 {RoW}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Cut-off, U	8152.26	tkm

The processes in the initial stage (cradle stage) comprise raw material production and material transportation. At this stage, the inventory is compiled using datasets from Ecoinvent 3.0, with the assumption that the production processes for auxiliary materials supplied by vendors are represented by data available in the database that correspond to activities similar to those performed by the suppliers. Furthermore, transportation processes are modeled based on the type of vehicle utilized and distance parameters, which are estimated using Google Maps. The inventory data for the gate scope of herbal cough medicine are presented in Table 2.

Table 2. Gate process inventory data herbal

Unit Proses	Input/Output	Quantity	Unit
	Input		
	City water	267.79	m^3
	Electricity	2,433.70	kWh
	Output		
	Water to Boiler	32,135	m^3
	Water to cleaning	120.5	m^3
	Water ke HVAC unit	66.94	m^3
	Water ke purified water	42.84	m^3
	CO_2 emission	1,752.27	kg
Purified Water	Input		
	Steam	120.4	ton
	Electricity	2,654.95	kWh
	Water to purified water	42.84	m^3

	Output		m^3
	Water to cleaning	32.54	m^3
	Water to QC analysis	17.34	m^3
	Waste water		m^3
	CO_2 emission	1,911.56	kg
General Maintenance	Input		
	Used rags	0.03	ton
	Output		
	Used rags	0.03	ton
Compressed air unit	Input		
	Filter	20	kg
	Electricity	3,761.18	kWh
	Air Dryer	1.5	ton
	Output		
	Compressed air	6745	m^3
	CO_2 emission	2,708.0	kg
Compressed air unit	Input		
	Filter	20	kg
	Electricity	3,761.18	kWh
	Air Dryer	13.5	ton
	Output		
	Compressed air	6745	m^3
	CO_2 emission	2,708.05	kg
HVAC unit	Domestic water	66.94	m^3
	Filter	0.45	ton
	Freon	0.11	ton
	Electricity	4,867.41	kWh
	Output		
	Air to mixing process	9745	m^3
	CO_2 emission	3,504.53	kg
Steam boiler	Input		
	Natural gas	302.42	mmBtu
	Recycled water	102	m^3
	City water	32.13	m^3
	Output		
	Steam to purified water	12.41	ton
	steam to HVAC	50.78	ton
	CO_2	0.006115672	ton
	NO_2	2.653503739	ton
	SO_2	0.049960551	ton
	CO	0.169131424	ton
	Particulate	0.126045486	ton
Cleaning	Input		
	Liquid cleaning material	26.8	L
	Purified water	120.5	m^3
	Chemical cleaning material	13	kg
	Electricity	1,991.212	kWh
	Output		
	Waste water	90	m^3
	CO_2	1,433.67	kg
Receiving	Input		
	Sucrose	36,800	kg
	Honey Liquid	73,600	kg
	Vitex negundo Folium Dry Extract	4,907	kg
	Succus Liquiritiae Rad Liquid Extract	4,097	kg
	Thymus Vulgaris Herba Liquid Extract	2,453	kg
	Zingiber off rosch rubrum Le	736	kg
	Minor material	6,808	kg
	Output		
	Sucrose	36,800	kg

	Honey Liquid	73,600	kg
	Vitex negundo Folium Dry Extract	4,907	kg
	Succus Liquiritiae Rad Liquid Extract A	4,097	kg
	Thymus Vulgaris Herba Liquid Extract	2,453	kg
	Zingiber off rosch rubrum Le	736	kg
	Minor material	6,808	kg
Preparation	Input		
	Sucrose	4,097	kg
	Honey Liquid	2,453	kg
	Vitex negundo Folium Dry Extract	736	kg
	Succus Liquiritiae Rad Liquid Extract A	6,808	kg
	Thymus Vulgaris Herba Liquid Extract		kg
	Zingiber off rosch rubrum Le	36,800	kg
	Minor material	73,600	kg
	Electricity	4,907	kWh
	Output	4,097	
	CO_2	159.29	kg
	Sucrose	36,800	kg
	Honey Liquid	73,600	kg
	Vitex negundo Folium Dry Extract	4,907	kg
	Succus Liquiritiae Rad Liquid Extract A	4,097	kg
	Thymus Vulgaris Herba Liquid Extract	2,453	kg
	Zingiber off rosch rubrum Le	736	kg
	Minor material	6,808	kg
Mixing process	Input		
	Sucrose	36,800	kg
	Honey Liquid	73,600	kg
	Vitex negundo Folium Dry Extract	4,907	kg
	Succus Liquiritiae Rad Liquid Extract A	4,097	kg
	Thymus Vulgaris Herba Liquid Extract	2,453	kg
	Zingiber off rosch rubrum Le	736	kg
	Minor material	6,808	kg
	Electricity	1,548.72	kWh
	Output		
	CO_2	1,115.07	kg
Filling process	Input		
	Bulk product	450	kg
	Electricity	2,212.46	kWh
	Output		
	CO_2	1,592.97	kg
	Foil sachet	300	kg
	Bulk in sachet	750	kg
Packaging process	Input		
	Electricity	1,548.72	kWh
	Solid supporting material	111	kg
	Bulk in sachet	750	kg
	Output		
	CO_2	1,115.08	kg
	Herbal Product	861.6	kg
Warehouse	Input		
	Electricity	884.98	kWh
	Herbal Product	861.6	kg
	Output		
	CO_2	637.19	kg
	Herbal Product	861.6	kg
Waste water treatment	Input		
	Waste water	90	m^3
	Electricity	126	kWh
	Output		
	Recycled water	20	m^3

	Condensate return	15	m^3
	Suspended Solids (TSS)	< 0.00018	ton
	Fenol	< 0.00000009	ton
	Total Nitrogen	0.00009	ton
	BOD_5	0.00054	ton
	COD	0.00261	ton
	Permanganat ($KMnO_4$)	0.00081	ton
	Amoniac	< 0.0000027	ton
	Oils & Fats	< 0.000144	ton
	Detergen (MBAS)	< 0.0000045	ton
	CO_2	90.72	kg
Hazardous waste	Input		
	Used Rags	0.03	ton
	Output		
	Used Rags	0.03	ton

The average daily production of traditional medicine is one batch, equivalent to 129,737 kg. The electricity consumption in this study is modeled using the Ecoinvent 3.0 database. The production process generates liquid waste, primarily originating from the washing of bin tumblers and mixing tanks. This wastewater is subsequently treated in a wastewater treatment plant prior to its discharge into surface water.

Table 3. Cradle process inventory data non herbal

Process Unit	Dataset	Quantity	Unit
Raw Material Production	Citric acid {CN}| production | Cut-off, U	16	kg
	Sugar beet {CH}| production | Cut-off, U	343	kg
	Chemical, organic {GLO}| production | Cut-off, U	97.85	kg
	Carboxymethyl cellulose, powder {RoW}| production | Cut-off, U	11.43	kg
	Sodium {GLO}| market for | Cut-off, U	13.71	kg
Raw Material Transport	Transport, freight, lorry 3.5-7.5 metric ton, euro4 {RoW}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Cut-off, U	30.37	tkm

Furthermore, based on the summary of total inventory data within the cradle-to-gate scope per unit product (one metric ton of product), corresponding to the defined functional unit, it is identified that the primary inputs for the cradle-to-gate stage of pharmaceutical (non-herbal) cough medicine include Guaifenesin, Dextromethorphan HBr, Chlorphenamine Maleate, and sucrose (granulated sugar). The inventory data for the cradle scope of pharmaceutical cough medicine are presented in Table 3 and the inventory data for the gate scope of pharmaceutical cough medicine are presented in Table 4.

Table 4. Gate process inventory data non herbal

Unit Proses	Input/Output	Quantity	Unit
Domestic Water	Input		
	City water	267.79	m^3
	Electricity	2,433.70	kWh
	Output		
	Water to boiler	32.13	m^3
	Water to cleaning	120.5	m^3
	Water to HVAC unit	66.94	m^3
	Water to purified water	42.84	m^3
	CO_2 emissions	1,752.27	kg
Purifed Water	Input		
	Steam	120.4	ton
	Electricity	2,654.95	kWh
	Water to purified water	42.84	m^3
	Output		
	Water to cleaning	32.54	m^3

	Water to QC analysis	17.34	m^3
	Water to limbah		m^3
	CO_2 emissions	1,911.56	kg
General Maintenance	Input		
	Fabric	0.03	ton
	Output		
	Majun fabric	0.03	ton
Compressed air unit	Input		
	Filter	20	kg
	Electricity	3,761.18	kWh
	Air Dryer	13.5	ton
	Output		
	Compressed air	6745	m^3
	CO_2 emissions	2,708,04888	kg
HVAC unit	Domestic water	66.94	m^3
	Filter	0.45	ton
	Freon	0.11	ton
	Electricity	4,867.41	kWh
	Output		
	Air to mixing process	9,745	m^3
	emisi CO_2	3,504.54	kg
Steam boiler	Input		
	Natural gas	302.42	mmBtu
	Recycled water	102	m^3
	City water	32.14	m^3
	Output		
	Steam to purified water	12.41	ton
	steam to HVAC	50.78	ton
	CO_2	0.006115672	ton
	NO_2	2.653503739	ton
	SO_2	0.049960551	ton
	CO	0.169131424	ton
	Partikulat	0.126045486	ton
Cleaning	Input		
	Liquid cleaning material	26.8	L
	Purified water	120.5	m^3
	chemical cleaning material	13	kg
	Electricity	1,991.21	kWh
	Output		
	Waste water	90	m^3
	CO_2	1,433.67	kg
Reciving	Input		
	Guaifinesin	8,495.98	kg
	Sucrose	101,951.16	kg
	Sodium citrate	4,757.82	kg
	Dextrome Thorphan HBR	1,274.5	kg
	Chlorphenamine Maeleate	169.92	kg
	Carboxyme Thylcellulose Sodiul	3,398.57	kg
	Sodium Cyclamate	4,757.82	kg
	minor material	4,906.5	kg
	Output		
	Guaifinesin	8,495.98	kg
	Sucrose	101,951.16	kg
	Sodium citrate	4,757.82	kg
	Dextrome Thorphan HBR	1274.5	kg
	Chlorphenamine Maeleate	169.92	kg
	Carboxyme Thylcellulose Sodiul	3,398.57	kg
	Sodium Cyclamate	4,757.82	kg
	minor material	4,906.5	kg
Preparation	Input		

	Guaifinesin	8,495.98	kg
	Sucrose	101,951.16	kg
	Sodium citrate	4,757.82	kg
	Dextrome Thorphan HBR	1274.5	kg
	Chlorphenamine Maeleate	169.92	kg
	Carboxyme Thylcellulose Sodiul	3,398.57	kg
	Sodium Cyclamate	4,757.82	kg
	minor material	4,906.5	kg
	Electricity	221.24	kWh
	Output		
	CO_2	159.29	kg
	Guaifinesin	8,495.98	kg
	Sucrose	101,951.16	kg
	Sodium citrate	4,757.82	kg
	Dextrome Thorphan HBR	1,274.5	kg
	Chlorphenamine Maeleate	169.92	kg
	Carboxyme Thylcellulose Sodiul	3,398.57	kg
	Sodium Cyclamate	4,757.82	kg
	minor material	4,906.5	kg
Mixing process	Input		
	Guaifinesin	8,495.98	kg
	Sucrose	101,951.16	kg
	Sodium citrate	4,757.82	kg
	Dextrome Thorphan HBR	1,274.5	kg
	Chlorphenamine Maeleate	169.92	kg
	Carboxyme Thylcellulose Sodiul	3,398.57	kg
	Sodium Cyclamate	4,757.82	kg
	minor material	4,906.5	kg
	Electricity	1,548.72	kWh
	Output		
	CO_2	1,115.08	kg
Filling process	Input		
	Bulk ruah	450	kg
	Electricity	2,212.46	kWh
	Output		
	CO_2	1,592.97	kg
	foil sachet	300	kg
	bulk in sachet	750	kg
Packaging process	Input		
	Electricity	1,548.72	kWh
	solid supporting material	111	kg
	bulk in sachet	750	kg
	Output		
	CO_2	1,115.08	kg
	Herbal products	861.6	kg
Warehouse	Input		
	Electricity	884.98	kWh
	Herbal products	861.6	kg
	Output		
	CO_2	637.19	kg
	Herbal products	861.6	kg
Waste water treatment	Input		
	Waste water	90	m^3
	Electricity	126	kWh
	Output		
	Recycled water	20	m^3
	Condensate return	15	m^3
	Total Suspended Solids (TSS)	< 0.00018	ton
	Fenol	< 0.00000009	ton
	Nitrogen Total	0.00009	ton

	BOD_5	0.00054	ton
	COD	0.00261	ton
	Permanganate Value ($KMnO_4$)	0.00081	ton
	Amoniak	< 0.0000027	ton
	Oils & Fats	< 0.000144	ton
	Detergen (MBAS)	< 0.0000045	ton
	CO_2	90.72	kg
Hazardous waste	Input		
	Fabric majun	0.03	ton
	Output		
	Fabric majun	0.03	ton

Chemical substances for which specific Material Safety Data Sheet (MSDS) information is unavailable are represented using general composition data or generic datasets. The production processes for raw materials and auxiliary materials supplied by vendors are modeled using data available in the Ecoinvent 3.0 database, under the assumption that these datasets adequately represent activities comparable to those conducted by the suppliers. Analytical reagents used in concentration analysis during the production process are excluded from this study due to their negligible contribution (less than 1% of the total mass), and are therefore considered within the cut-off criteria (Laurent et al., 2020).

2.3 Consistency analysis

Consistency check is a verification process to ensure that assumptions, methods, and data are applied consistently throughout the study and are aligned with the defined goal and scope prior to drawing conclusions. Maintaining consistency in assumptions, methods, and data is essential to enhance clarity and to prevent multiple interpretations in the LCA analysis. Furthermore, this process ensures that the final results of the analysis are coherent with the established objectives and scope of the study. The results of the consistency check analysis are summarized in Table 5 below.

Table 5. Consistency check

Assessment	Consistency	Description
Data Source	Not Consistent	Cradle scope 69% primary data 31% secondary data Gate scope 100% primary data 0% secondary data.
Data Accuracy	Consistent	Data are derived from monitoring and testing activities, ensuring a high level of accuracy.
Data Age	Consistent	The data have a temporal coverage of one year.
Technological Coverage	Consistent	The unit processes assessed include: Cradle encompasses the processes of raw material production and raw material transportation. Gate encompasses the following processes domestic water, Purified water, General Maintenance, Compressed air unit, HVAC unit, Steam boiler, Cleaning, Reciving, Preparation, Mixing process, Filling Process, Packaging Process, Warehouse, Waste water treatment, Hazardous waste, Domestic Waste, dan Waste Treatement to third party
Method Applied	Consistent	The study employs the ReCiPe 2016 method.
Temporal Scope	Consistent	The data utilized correspond to the year 2025.
Geographical Scope	Consistent	The study is conducted within the context of Indonesia.

3. Results and Discussion

3.1 Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) is the phase in which environmental impacts are evaluated using methods appropriate to the geographical context and materials under study. All impacts arising from resource use and emissions are classified and quantified into specific impact categories, which are subsequently weighted according to their relative contributions. In this study, the LCIA phase is conducted using SimaPro software, generating impact categories and corresponding characterization values. The environmental impact assessment is performed in accordance with the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number 1 of 2021 concerning Life Cycle Assessment aspects and Product Category Rules (PCR) for pharmaceutical products in Indonesia, issued by the Indonesian Pharmaceutical Association. The assessment is based on the IPCC 2021 GWP100 V1.00 method applied within the LCA framework. This study focuses exclusively on the Global Warming Potential (GWP) impact category to quantify total CO_2 emissions generated from each unit process. The method classifies GWP into three components: fossil, biogenic, and land transformation.

Within the life cycle scope, operational processes are modeled using datasets that represent raw material production and the transportation of raw materials to the manufacturing facility. However, the detailed discussion of impacts in this study is limited to the Global Warming Potential (GWP) category. The Life Cycle Impact Assessment (LCIA) stage aims to identify the contribution of each unit process to environmental impacts. Nevertheless, the interpretation of impacts based on the compiled datasets does not explicitly disaggregate contributions across all assessed impact categories, although contributor analysis is employed as a basis for identifying environmental hotspots. The results of the life cycle impact assessment for the cradle scope of non-herbal medicine production are presented in Table 6 and the results of the life cycle impact assessment for the cradle scope of herbal medicine production are presented in Table 7.

Table 6. Impact results of non-herbal and herbal cough medicine at the cradle scope

Impact category	Unit	Total	Raw Material Production	Raw Material Transport
Non-Herbal				
GWP100 - fossil	kg CO_2-eq	89,628.21	89,611.96	16.25
GWP100 - biogenic	kg CO_2-eq	139.16	139.16	5.65E-03
GWP100 - land transformation	kg CO_2-eq	194.40	194.39	0.0105
Herbal				
GWP100 - fossil	kg CO_2-eq	3,1362.6	27,000.27	4,362.3306
GWP100 - biogenic	kg CO_2-eq	73.09	71.57	1.52E+00
GWP100 - land transformation	kg CO_2-eq	38.27	35.44	2.83

Within the cradle scope, the greatest environmental impact is generated by the raw material production process, which is modeled using datasets representing both raw material production and the transportation of these materials to the manufacturing facility. The largest total emissions were observed in the GWP100 fossil category, at 89,628.21 kg CO_2 eq. This was dominated by the raw material production process, contributing 89,611.96 kg CO_2 eq. The contribution from raw material transportation was relatively small, at 16.25 kg CO_2 eq. In the GWP100 biogenic category, total emissions were recorded at 139.16 kg CO_2eq, almost entirely originating from raw material production (139.16 kg CO_2 eq), with only a negligible contribution from transportation (5.65×10^{-3} kg CO_2 eq). Similarly, the GWP100 land transformation category shows total emissions of 194.40 kg CO_2 eq, which are also largely dominated by raw material production (194.39 kg CO_2 eq), with a minimal contribution from transportation (0.0105 kg CO_2 eq).

The results indicate that the GWP100 fossil category is the dominant contributor, with

total emissions amounting to 31,362.6 kg CO_2 eq. The majority of these emissions originate from the raw material production stage (27,000.27 kg CO_2 eq), while the contribution from raw material transportation is comparatively lower (4,362.33 kg CO_2 eq). This finding suggests that fossil-based energy use during raw material production is the primary driver of greenhouse gas emissions (Wiesen & Wirges, 2017). In contrast, the GWP100–biogenic and GWP100 land transformation categories contribute significantly lower emissions, at 73.09 kg CO_2eq and 38.27 kg CO_2 eq, respectively. Within these categories, raw material production remains the main contributor compared to transportation, with emissions of 71.57 and 35.44 kg CO_2 eq, respectively. The contribution from transportation in these categories is minimal, accounting for only 1.52 and 2.83 kg CO_2 eq, respectively.

The Life Cycle Impact Assessment (LCIA) phase aims to identify the contribution of each unit process to environmental impacts. The unit processes evaluated within the gate scope include domestic water, purified water, general maintenance, compressed air systems, Heating, Ventilation, and Air Conditioning (HVAC) systems, steam boiler operations, cleaning, incoming raw materials, preparation, mixing processes, filling processes, packaging processes, warehousing, wastewater treatment, hazardous waste management, domestic waste, and third-party waste treatment. The following table presents the impact assessment results for the production of non-herbal cough medicine within the gate scope. The results of the life cycle impact assessment for the gate scope of non-herbal and herbal medicine production are presented in Table 7 and Table 8.

Table 7. Impact results of non-herbal and herbal cough medicine at the gate scope

Impact category	Unit	Total	Domestic water	Purified water	Compressed air unit	HVAC unit	Steam boiler	Cleaning	Prepara -tion
GWP 100-fossil	kg CO_2eq	1,6026.54	1,752.27	1,911.56	2,708.05	3,504.53	6.12	1,433.67	159.30

The discussion of environmental impacts in this study is limited to the Global Warming Potential (GWP) category. Within the cradle stage of the product life cycle, GWP impacts arise from two main unit processes: raw material production and raw material transportation. The unit process contributing most significantly to GWP is raw material production, accounting for 89.7% of total emissions, while raw material transportation contributes 10.3%. The largest contributors to GWP within the raw material production process are carbon dioxide emissions released into the atmosphere (70.8%), nitrogen monoxide emissions (10.09%), and methane emissions (8.11%). These emissions originate from the datasets utilized, which encompass material usage, fuel consumption, emissions to air, emissions to soil, and land use.

Table 8. Impact results of herbal and herbal cough medicine at the gate scope

Impact category	Unit	Mixing process	Filling Process	Packaging Process	Warehouse	Waste water treatment
GWP100- fossil	kg CO_2 eq	1,115.08	1,592.97	1,115.08	637.19	90.72

Subsequently, the impact assessment is conducted at the gate-level unit processes to identify the most significant environmental burdens arising from production activities. This study places greater emphasis on the gate scope, as it encompasses the full range of operational activities occurring at the research site. The analysis is specifically focused on the Global Warming Potential (GWP) category in order to quantify CO_2-equivalent emissions. Within the gate scope, GWP impacts are associated with several unit processes, including domestic water, purified water, compressed air systems, Heating, Ventilation, and Air Conditioning (HVAC) systems, steam boiler operations, cleaning, preparation, mixing processes, filling processes, packaging processes, and warehousing.

Table 9. Details of contributors to the gate scope of non-herbal cough medicine

Substance	Compartment	Unit	Total	Domestic water	Purified water	Compressed air unit	HVAC unit	Steam boiler
Total of all compartments		%	100	10.93	11.92749	16.90	21.86	0.03816
Carbon dioxide	Air	%	100	10.93	11.92749	16.90	21.86	0.03816

The unit process that contributes most significantly to the Global Warming Potential (GWP) within the gate scope is the HVAC system, accounting for 21.86% of total emissions. The primary contributor to GWP within this unit is carbon dioxide emissions released into the atmosphere, which likewise account for 21.86%. These emissions arise predominantly from electricity consumption within the HVAC system. The electricity is sourced from both the national grid (PLN) and solar power (PLTS). Based on the inventory data, the electricity consumption associated with the HVAC unit is the highest among all unit processes, thereby explaining its dominant contribution to GWP. A detailed of contributors within the gate scope is presented in the Table 9 above.

Table 10. Details of contributors to the gate scope of non-herbal cough medicine

Substance	Compart-ment	Unit	Cleaning	Reciving	Preparation	Mixing process	Filling Process	Packaging Process	Warehouse
Total of all compartments		%	8.945617	0	0.993972	6.96	9.939576	6.96	3.97
Carbon dioxide	Air	%	8.945617	0	0.993972	6.96	9.939576	6.96	3.97

In addition, the core processes, including cleaning, preparation, mixing, filling, packaging, and warehousing, are also subjected to impact assessment to determine their respective contributions to Global Warming Potential (GWP). The results of these contributions are presented in the following table 10. Wastewater treatment is carried out within the study site; therefore, it is included within the gate scope, although it is not considered part of the core processes. In contrast, the management of hazardous waste (B3) and domestic waste is excluded from this analysis, as these processes are handled by third-party entities and fall within the grave scope, which lies outside the defined system boundaries of this study.

3.2 Life cycle interpretation

Within the cradle scope for both product types—non-herbal and herbal—Global Warming Potential (GWP) impacts arise from all unit processes, namely raw material production and raw material transportation. These impacts are categorized into fossil, biogenic, and land transformation components (Sanyé-Mengual et al., 2022). For the non-herbal product, the unit process that contributes most significantly to GWP is raw material production, accounting for 99.98% of total emissions, while raw material transportation contributes only 0.02%. The primary contributors to GWP within the raw material production process are carbon dioxide emissions released into the atmosphere (84.04%), dinitrogen monoxide emissions (4.83%), methane emissions (10.89%), and sulfur hexafluoride emissions (0.16%) (Zhao et al., 2025). These emissions are associated with the datasets employed, which include material usage, fuel consumption, emissions to air, emissions to soil, and land use.

For the herbal product, the unit process contributing most significantly to Global Warming Potential (GWP) is raw material production, accounting for 86.09% of total emissions, while raw material transportation contributes 13.91%. The primary contributors to GWP within the raw material production process are carbon dioxide emissions released into the atmosphere (91.57%), dinitrogen monoxide emissions (3.5%), and methane emissions (4.58%). These emissions arise from the datasets employed, which encompass material usage, fuel consumption, emissions to air, emissions to soil, and land use. When comparing non-herbal and herbal products within the cradle scope, the non-

herbal product exhibits a higher overall environmental impact than the herbal product. This difference is primarily attributed to the greater quantity of raw materials required in the production of non-herbal formulations compared to herbal products. This comparison is shown in the Figure 4.

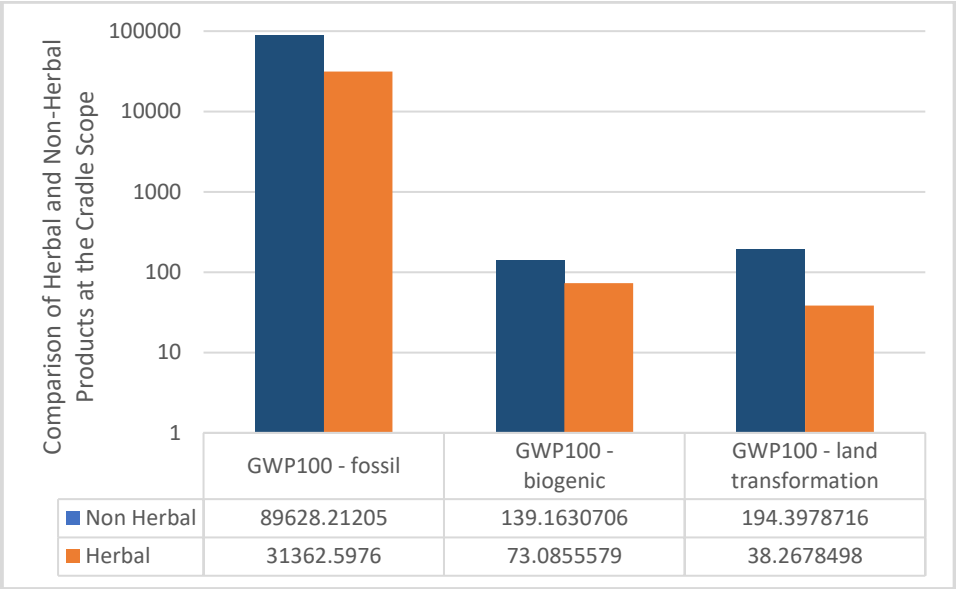

Fig. 4. Percentage of waste and leftover food produced in each stage of supply (Hanson et al., 2015)

Within the gate scope for both product types, non-herbal and herbal, Global Warming Potential (GWP) impacts arise from several unit processes, including domestic water, purified water, compressed air systems, Heating, Ventilation, and Air Conditioning (HVAC) systems, steam boiler operations, cleaning, preparation, mixing processes, filling processes, packaging processes, and warehousing. For the non-herbal product, the unit process contributing most significantly to GWP is the HVAC system, accounting for 21.86% of total emissions. The primary contributor within this process is carbon dioxide emissions released into the atmosphere, also representing 21.86%. These emissions are mainly driven by electricity consumption in the HVAC system, sourced from both the national electricity grid (PLN) and solar power (PLTS). Based on the inventory data, the electricity usage of the HVAC unit is the highest among all processes, thereby explaining its dominant contribution to GWP (Beck et al., 2025). A detailed breakdown of contributors within the gate scope is presented in the Table 10.

3.3 Hotspot analysis

Following the interpretation of all potential environmental impacts generated from the production processes of both non-herbal and herbal medicines, a hotspot analysis was conducted. This analysis focuses specifically on the Global Warming Potential (GWP) impact category, identifying unit processes with the highest contribution within the overall production chain. The hotspot analysis is limited to unit processes directly associated with operational production activities, serving as a baseline for developing improvement strategies in routine manufacturing operations.

Table 11. Sensitivity analysis of input and output HVAC unit process

Impact Category	Unit	Method	Impact Value
Global warming potential	kg CO_2 eq	IPCC 2021 GWP100 V1.00	1,826.81

After identifying the hotspot in the production of herbal medicine, an improvement scenario was developed. The HVAC unit was identified as the primary hotspot due to its high

electricity consumption, primarily sourced from the national grid (PLN), resulting in carbon dioxide emissions of 3,504.53 kg CO_2. Based on these findings, an improvement scenario was proposed by increasing the use of solar energy (PLTS). The electricity consumption from PLN, originally 4,867.41 kWh, is projected to decrease to 2,537.238 kWh. Consequently, the resulting carbon dioxide emissions are reduced to 1,826.81 kg CO_2. Based on this scenario, the resulting CO_2 emission reductions can be analyzed as shown in the Table 11.

3.4 Sensitivity and improvement analysis

Sensitivity analysis is employed to assess the reliability of the final results and conclusions by evaluating how they are influenced by uncertainties in data, allocation methods, or impact indicator calculations (Groen et al., 2017). In this stage, a comparison is conducted between results obtained from variations in input and output data, specifically by applying a ±25% variation from the baseline data. The inventory data for the HVAC unit process are adjusted by ±25% from their normal values, and the resulting environmental impacts are subsequently calculated using SimaPro software. The following section presents the input–output data for the HVAC unit process (Table 12).

Table 12. Sensitivity analysis of input and output HVAC unit process

Substance	Unit	Input Contributor of CO_2		
		-25%	Normal	+25%
Carbon dioxide	kg CO_2	2628.4	3,504.53	4,380.68

Based on the input–output data presented above, the next step involves calculating the environmental impact values using SimaPro software. The following section presents the potential environmental impacts under normal conditions as well as under ±25% variations from the baseline data. From the impact assessment and contribution analysis, it is identified that the primary issue requiring environmental improvement recommendations is electricity consumption.

Table 13. Improvement analysis

Impact Category	Normal	-25%	+25%
Global Warming	3504.5338	2.628.4	4,380.667

The highest priority is the electricity used in the HVAC unit, which is recognized as the main hotspot and the most significant contributor among utility processes. The proposed improvement analysis involves replacing existing equipment with more energy-efficient, high-efficiency systems. This is expected to reduce electricity consumption along the production line, thereby leading to a decrease in the Global Warming Potential (GWP) impact contribution.

Pharmaceutical manufacturing facilities require precise environmental control to ensure product quality, regulatory compliance, and operational efficiency. Heating, Ventilation, and Air Conditioning (HVAC) systems play a central role in maintaining optimal temperature, humidity, air quality, and pressure differentials across cleanrooms and production areas (Liu et al., 2021). Strict requirements imposed by Good Manufacturing Practice (GMP) guidelines stipulate that temperature must be maintained within ±0.5°C and relative humidity within ±5% to prevent microbial contamination, ensure chemical stability, and preserve drug efficacy (Marsit et al., 2025). This is further supported by previous studies indicating that HVAC systems account for up to 50% of total energy consumption in pharmaceutical manufacturing, making them one of the largest contributors to operational costs (Tomažič & Škrjanc, 2025). In addition, stringent air filtration requirements and differential pressure controls further increase the complexity of HVAC system operations (Cheng et al., 2022). Even minor deviations from GMP specifications can compromise product integrity, lead to regulatory non-compliance, and

result in significant financial losses due to product recalls or production shutdowns. Consequently, HVAC systems in such highly regulated environments are often designed with substantial redundancy, which in turn leads to excessive energy consumption and operational inefficiencies.

3.4 Limitations and further research

This study has several limitations. First, the research was conducted in only one pharmaceutical manufacturing company in Indonesia. In this study, the analysis was carried out on traditional medicine production processes in the Jakarta area, based on the consideration that companies in this region generally have implemented more systematic greenhouse gas (GHG) emission reporting standards. The findings from Jakarta are expected to provide higher strategic value for policymakers in developing baseline frameworks for routine improvement programs that are inclusive and can be replicated by similar industries in other regions.

Second, this study is limited by its exclusion of economic and social dimensions, despite the fact that the production and distribution of traditional medicines are often associated with improvements in community economic welfare. Therefore, future research is encouraged to incorporate these variables to examine potential positive economic effects. Subsequent studies may also explore social factors, considering that societal values related to sustainability in the traditional medicine industry can influence consumer preferences and purchasing decisions for herbal products. Third, the system boundary applied in this study is restricted to a cradle-to-gate scope; thus, future research should consider extending the assessment to a cradle-to-grave perspective. In addition, the use of datasets within the SimaPro software may introduce potential bias, particularly as the impact assessment is based on a single characterization method. Therefore, future studies should consider employing multiple assessment methods to improve robustness and comparability of results. Nevertheless, Life Cycle Assessment (LCA) studies on traditional medicines, particularly herbal-based products, remain limited and require further attention from the research community.

4. Conclusions

The increase in pharmaceutical production, including traditional medicines derived from natural materials, has led to higher energy consumption, greater use of raw materials, and increased greenhouse gas emissions. Therefore, an approach capable of comprehensively evaluating environmental impacts across the entire product life cycle is required. Life Cycle Assessment (LCA) is selected as the analytical framework to identify the environmental impacts of traditional medicine production processes and to determine critical points (hotspots) contributing to carbon emissions. This study employs a quantitative approach using the Life Cycle Assessment (LCA) methodology in accordance with the ISO 14040 standard, with a cradle-to-gate system boundary. The system boundary includes raw material production, raw material transportation, as well as manufacturing and packaging processes of traditional medicine products. The functional unit is defined as one metric ton of packaged pharmaceutical product. The analysis is conducted using the IPCC 2001 method with the assistance of SimaPro 10.2.0.3 software and the Ecoinvent 3.0 database. The data used consist of primary data obtained from field monitoring and secondary data sourced from relevant databases, enabling a more comprehensive evaluation of each unit process's contribution to Global Warming Potential.

The results of the analysis indicate that, within the cradle-to-gate scope, the production of non-herbal medicine has a higher environmental impact compared to herbal medicine production. This difference is primarily attributed to variations in raw materials used, where raw materials derived from natural sources exhibit lower environmental burdens. In addition, transportation processes also contribute to higher emissions in non-herbal products due to longer delivery distances to the manufacturing facility. The largest

contribution to Global Warming Potential (GWP) originates from raw material production processes, accounting for 89% of total impacts, while raw material transportation contributes 10.3%. Daily production is capable of generating eight production batches. The most dominant emissions are carbon dioxide, nitrous oxide, and methane, which are primarily generated during raw material production processes. Within the gate scope, the unit process that contributes most significantly to GWP is the HVAC system. The results show that the total Global Warming Potential associated with the HVAC system is 3,500 kg CO_2 eq per kWh per one metric ton product, contributing 21.86% of total emissions. On a daily basis, total CO_2 emissions from the HVAC system reach approximately 28 tons CO_2-eq. This high contribution is driven by substantial electricity consumption required to maintain production environmental conditions in accordance with Good Manufacturing Practices (GMP), which impose strict requirements for temperature, humidity, and air quality control.

Based on the results of the interpretation and sensitivity analysis, electricity consumption in the HVAC system is identified as the primary factor influencing the magnitude of carbon emissions in traditional medicine production processes. Therefore, improvement efforts are focused on enhancing energy efficiency through the use of more energy-efficient equipment and optimizing production utility systems. The implementation of energy efficiency strategies is expected to reduce greenhouse gas emission contributions and improve the environmental performance of the pharmaceutical industry. Overall, this study demonstrates that the application of the Life Cycle Assessment (LCA) method provides a comprehensive overview of environmental impacts in traditional medicine production processes and serves as a basis for formulating more sustainable environmental management strategies within the pharmaceutical sector.

Acknowledgement
The authors sincerely thanks the reviewers for their constructive feedback that significantly enchanched the manuscript.

Author Contribution
Conceptualization, W.M.M, and H.A.; Methodology, A.S.; Software, W.M.; Validation, W.M.M., H.A., and A.S.; Formal Analysis, W.M.M; Validation, W.M.M., H.A., and A.S.; Investigation, W.M.M.; Resources W.M.M.; Data Curation, W.M.M., H.A., and A.S.; Writing –Original Draft, W.M.M.; Writing –Review & Editing, W.M.M., H.A., and A.S.; Visualization, W.M.M.; Supervision, H.A., and A.S.; Project Administration, W.M.M.

Funding
This research received no external funding.

Ethical Review Board Statement
Not available.

Informed Consent Statement
Not available.

Data Availability Statement
Scope gate inventory data was obtained from primary data obtained during the research and raw material life cycle inventory data on the scope cradle was obtained from the Ecoinvent 3.0 dataset using the Simapro 10.2.0.3 software.

Conflicts of Interest
The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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