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Life Cycle Assessment Approach of the Tofu Industry in SSIC Balikpapan City to Support SDGs

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Abstract

The tofu industry accounts for the majority of enterprises in the Somber Small Industry Center (SSIC) of Balikpapan City, comprising 76% of the total units. Generally, these industries still rely on conventional production methods to minimize operating costs, which consequently imposes negative impacts on the environment. The Life Cycle Assessment (LCA) method can be used as a comprehensive approach to evaluate environmental impacts and formulate mitigation recommendations, thereby supporting the implementation of the Sustainable Development Goals (SDGs) across all industrial sectors. This study aims to assess the environmental impacts of the tofu industry in SSIC Balikpapan and formulate eco-friendly improvement strategies. This quantitative research employed a field survey approach covering all 56 operating tofu industries. Data collection was conducted through interviews, field observations, and documentation. The inventory data were subsequently analyzed using SimaPro software with the ReCiPe 2016 Midpoint (H) method. The system boundary for this assessment was limited to a gate-to-gate scope (from raw material inputs to the final tofu product) over one year. The analysis revealed that the environmental impacts were highly dominated by Human Carcinogenic Toxicity at 437000 pt, Freshwater Ecotoxicity at 19500 pt, and Marine Eutrophication at 7950 pt, primarily driven by fuelwood consumption and untreated wastewater generation. To mitigate these impacts, the recommended strategies include substituting fuelwood with Liquefied Petroleum Gas (LPG) and converting wastewater into liquid organic fertilizer. Implementing these measures significantly reduces Human Carcinogenic Toxicity to 26800 pt (93.85%), Freshwater Ecotoxicity to 18900 pt (3.08% reduction), and lowers Marine Eutrophication to 7940 pt. These findings demonstrate that the applied LCA approach effectively guides the tofu industry in SSIC of Balikpapan City toward supporting the SDGs (specifically Goals 6, 7, 12, and 13) in a sustainable.

Keywords: LCA, SDGs, SSIC Balikpapan City, Simapro, Tofu Industry

INTRODUCTION

The Central Bureau of Statistics (BPS) of the Republic of Indonesia recorded that the average tofu consumption among Indonesians continuously increased, reaching 0.152 kg/capita/week by 2025. This growing trend has stimulated the small-scale industrial sector across various regions in Indonesia, particularly in Balikpapan City. In an effort to boost the local economy and maintain regional food security, the Balikpapan City Government centralized tofu production into the Somber Small Industry Center (SSIC). This industrial center comprises 74 Small and Medium Enterprises (SMEs), 56 of which specialize in tofu production. To minimize operating expenses, the majority of producers still employ conventional methods, such as utilizing fuelwood for energy resources and directly discharging untreated wastewater into local rivers. According to the IPCC (2006) guidelines, fuelwood combustion generates emissions up to 112000 kg CO_2/TJ, alongside fine particulate matter (PM 2.5), carbon oxides (CO), and various volatile organic compounds. Concurrently, untreated liquid waste induces eutrophication, river sedimentation, and the destruction of aquatic ecosystems (Sala & Castellani, 2019). Consequently, these practices trigger cumulative negative ecological pressures and hinder the realization of sustainable SDGs implementation within the industry, specifically impeding Goal number 6 (Clean Water and Sanitation), Goal number 7 (Affordable and Clean Energy), Goal number 12 (Responsible Consumption and Production), and Goal number 13 (Climate Action).

To support the sustainable implementation of the SDGs within the tofu industry at SSIC Balikpapan City, a comprehensive environmental impact assessment of the existing production processes is highly required. Several approaches can be deployed, such as the Environmental Management System (EMS), which is oriented toward organizational institutional compliance; Design for Environment (DfE), which focuses on eco-friendly product design; and Life Cycle Assessment (LCA), which quantitatively evaluates environmental impacts at every process stage (Gunawan et al., 2020; Kelvin, 2021; Widiyanti, 2021). Furthermore, the LCA method offers a distinct advantage as it is globally recognized as a robust tool for achieving SDG 12 due to its holistic evaluation principles (Sala & Castellani, 2019). The implementation of LCA across several food sectors in Indonesia has successfully provided representative impact assessments, as demonstrated in the evaluation of tea commodities (Setiawan et al., 2019). Therefore, this methodology holds significant potential for application to the tofu industry in SSIC Balikpapan City.

The application of LCA to assess environmental loads in soybean-based industries has demonstrated successful outcomes. Research by Rosyidah et al. (2020) and Lusiana et al. (2021) confirmed that the ecological impacts of tofu production are significantly influenced by energy variables, raw materials, transportation, and end-of-pipe waste management. Furthermore, Hartini et al. (2024) demonstrated that waste recycling scenarios could significantly boost the eco-efficiency scores of tofu SMEs in Central Java. Locally, Lestari et al. (2024) evaluated the environmental impacts of tofu production in Balikpapan and stated that energy substitution yields positive results in reducing greenhouse gas emissions. However, previous studies conducted within SSIC Balikpapan City have not collectively covered the entire SME population. In addition, there is currently no comprehensive study that correlates LCA from tofu industry evaluation results directly with SDGs achievement targets.

The novelty of this study focuses on the integration of the LCA method with a gate-to-gate system boundary, directly applied to the entire population of tofu industries within SSIC Balikpapan City. This novel aspect is further supported by the development of alternative scenarios designed to accelerate the achievement of SDGs targets (specifically Goals number 6, 7, 12, and 13). All evaluation stages strictly comply with the ISO 14040:2006 and ISO 14044:2006 standards. Furthermore, the characterization step utilizes the ReCiPe 2016 Midpoint (H) method to ensure the validity and accuracy of the generated impact categories.

Based on the mentioned statements, this study aims to analyze the environmental impacts of the tofu production process at SSIC Balikpapan City using the LCA method with a gate-to-gate approach. Additionally, it seeks to identify the environmental hotspots within the production stages and evaluate the effectiveness of the proposed mitigation scenarios to support the achievement of the SDGs for the tofu industry within SSIC Balikpapan City.

METHODS

This study employs a descriptive quantitative approach using the LCA method. The research was conducted based on the ISO 14040 and ISO 14044 frameworks, which comprise four interconnected stages: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) utilizing specialized software, and Interpretation. The assessment was implemented using a gate-to-gate system boundary, encompassing all production activities from the raw material preparation to the final tofu molding stage. This research was carried out at SSIC Balikpapan City using a total sampling technique. The sampling involved the entire population of the tofu industry, a total of 56 SMEs. This comprehensive approach ensures that the gathered inventory data accurately represent the overall tofu production in SSIC.

Primary data were obtained through field observations and direct interviews with tofu operators. The collected dataset included raw material consumption, water utilization, electricity consumption, fuel usage, total product yield, by-products, and wastewater generation quantified at each stage of the production process. Concurrently, secondary data were gathered from various scientific literature and the Ecoinvent database (SimaPro). The inventory data compiled from all operating SMEs were subsequently aggregated to represent the comprehensive production conditions over one year.

Data analysis was conducted utilizing SimaPro software version 10 with the ReCiPe 2016 Midpoint (H) assessment method. The LCI stage was performed by compiling all input and output data across each production process. Subsequently, during the LCIA, the compiled inventory data were converted into specific environmental impact indicators. The normalization results were then analyzed to identify the dominant impact categories and the processes acting as hotspots. Based on the identified hotspots, several mitigation scenarios were developed and subsequently simulated using SimaPro to evaluate their effectiveness in reducing the environmental impacts.

RESULTS

The environmental impact assessment results of the production processes in the tofu industry using the LCA method are presented based on four main stages. Each stage provides sequential findings, detailed as follows.

1. Goal and Scope

This stage establishes the boundaries of the production process, which are illustrated in the mass balance diagram below.

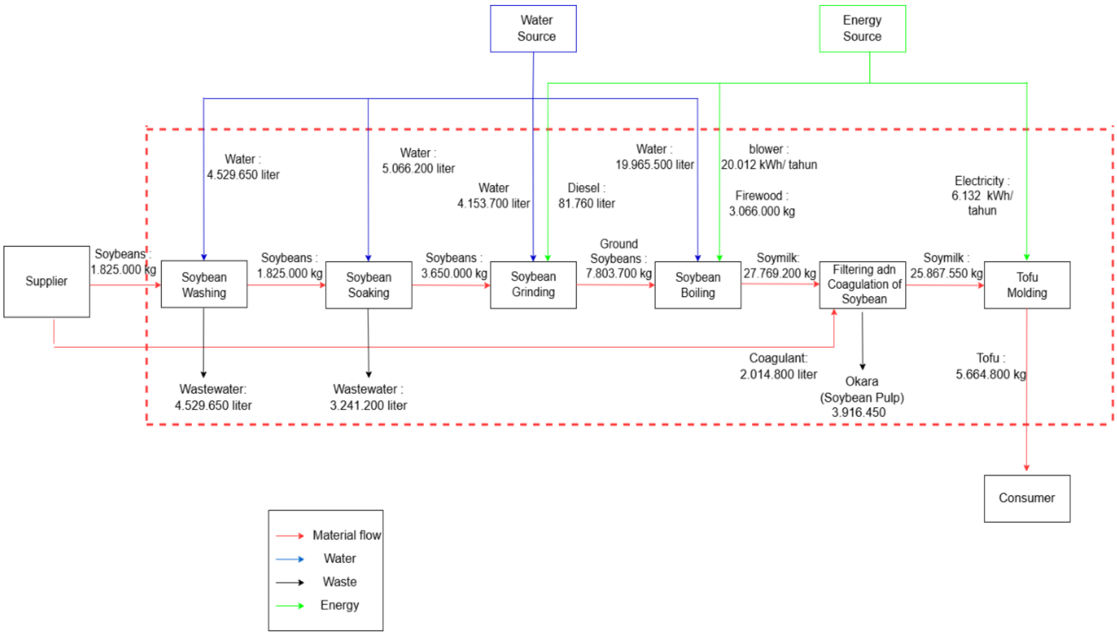

Figure 1. Mass Balance Diagram on SSIC Balikpapan City

2. Life Cycle Inventory (LCI)

The inventory data collected from the tofu production process contain the utilization of raw materials, additives, water, energy, fuel, total product yield, and generated waste within a single production cycle. Subsequently, these data were aggregated into annual metrics, as presented in Table 1 below.

Table 1. Inventory Data of the Tofu Industry in SSIC Balikpapan City

No	Process	Input/Output	Material	Value	Unit
1	Soybean Washing	Input	Soybeans	1.825.000	kg
			Water	4.529.650	Liter
		Output	Soybeans	1.825.000	kg
			Wastewater	4.529.650	Liter
2	Soybean Soaking	Input	Soybeans	1.825.000	kg

No	Process	Input/Output	Material	Value	Unit
			Water	5.066.200	Liter
		Output	Soybeans	3.650.000	kg
			Wastewater	3.241.200	Liter
3	Soybean Grinding	Input	Soybeans	3.650.000	kg
			Water	4.153.700	Liter
			Diesel	81.760	Liter
		Output	Ground Soybeans	7.803.700	Liter
4	Soybean Boiling	Input	Ground Soybeans	7.803.700	Liter
			Water	19.965.500	Liter
			Firewood	3.066.000	kg
			Blower	20.012	kWh
		Output	Soymilk	27.769.200	Liter
5	Filtering and Coagulation of Soybean	Input	Soymilk	27.769.200	Liter
			Coagulation	2.014.800	Liter
		Output	Soymilk	25.867.550	Liter
			Okara (Soybean pulp)	3.916.450	kg
6	Tofu Molding	Input	Soymilk	25.867.550	Liter
			Electricity	6.132	kWh
		Output	Tofu	5.664.800	kg

3. Life Cycle Impact Assessment (LCIA)

The midpoint (H) method was selected as it provides 18 distinct impact categories. This stage involves characterization to compare the LCI results within each impact category, followed by normalization, which divides the characterization values by a reference normalization factor. Consequently, this approach facilitates a more straightforward comparison of environmental impacts across different categories. The magnitude of the impacts for each respective stage is illustrated in Figures 2 and 3 below.

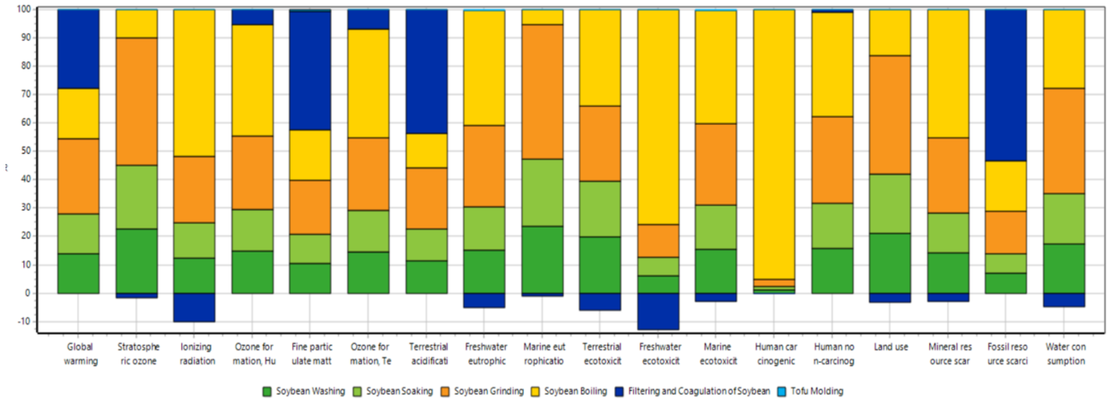

Figure 2. The Characterization Result of LCA

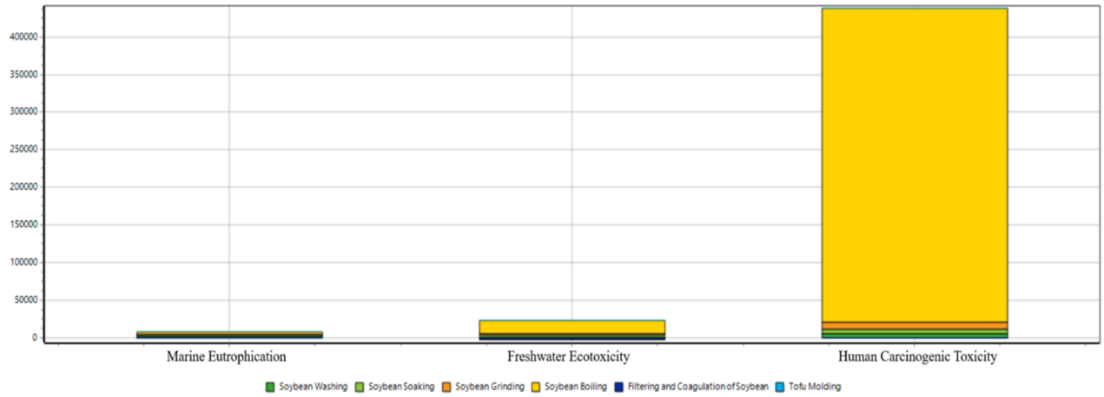

Figure 3. The Normalization Result of LCA

Based on Figure 3, the normalization values of the three primary environmental impacts for each production stage carried out by the tofu industries are presented in the table below.

Table 2. Total Value of Environmental Impact on Normalization Stage

Impact Category	Total (pt)	Soybean Washing	Soybean Soaking	Soybean Grinding	Soybean Boiling	Filtering and Coagulation of Soybean	Tofu Molding
Human Carcinogenic Toxicity (HCT)	437.000	5.400	5.400	9.880	417.000	-764	63,9
Freshwater Ecotoxicity (FE)	19.500	1.400	1.400	2.640	16.900	-2.890	13,7
Marine Eutrophication (ME)	7.950	1.900	1.900	3.800	414	-72,8	0,171

4. Interpretation

Based on the LCIA results with 18 impact categories, the three categories with the highest impact values were selected. As presented in Table 2, the highest value was observed in HCT at 437500 pt, which primarily originated from soybean boiling (417000 pt), milling (9880 pt), washing and soaking (5400 pt each), and molding (63.9 pt). Meanwhile, the filtration process yielded a negative value (−764 pt), indicating an environmental credit (avoided product) derived from the utilization of tofu dregs by-products.

FE reached 19500 pt, which originated from the boiling process (16900 pt), milling (2640 pt), washing (1400 pt), soaking (1400 pt), and molding (13.7 pt). Conversely, the filtration process provided a negative contribution of −2890 pt.

ME accounted for 7950 pt, driven by soybean milling (3800 pt), soybean washing and soaking (1900 pt each), and boiling (414 pt). Conversely, the filtration process yielded a negative impact (−72.8 pt). These quantified impact values subsequently serve as the baseline for determining effective recommendations and improvement scenarios.

5. Mitigation Scenario Assessment

Alternative environmental mitigation scenarios must be systematically compared to identify the option that generates the lowest environmental burdens. The HCT category is predominantly driven by the soybean boiling process, which relies heavily on firewood as its primary energy source. Concurrently, the FE and ME categories are significantly influenced by wet processing stages such as washing, soaking, milling, filtration, and molding. These generate liquid effluents (wastewater) rich in organic matter and nutrients. Based on these findings, the following alternative scenarios are proposed:

Table 3. Environmental Impact Mitigation Scenarios

Environmental Impact Mitigation	Processes	References
1st Scenario	Substitution of firewood with LPG as an energy source	Apriyanti, 2025
2nd Scenario	Utilization of waste water to liquid organic fertilizer (LOF)	Lailyana & Asri, 2022
3rd Scenario	Combination of 1st and 2nd scenarios	Author

Subsequently, these scenarios were evaluated and compared within the software system by substituting either the input materials or the specific production process stages. The comparative results are illustrated in Figure 4 below.

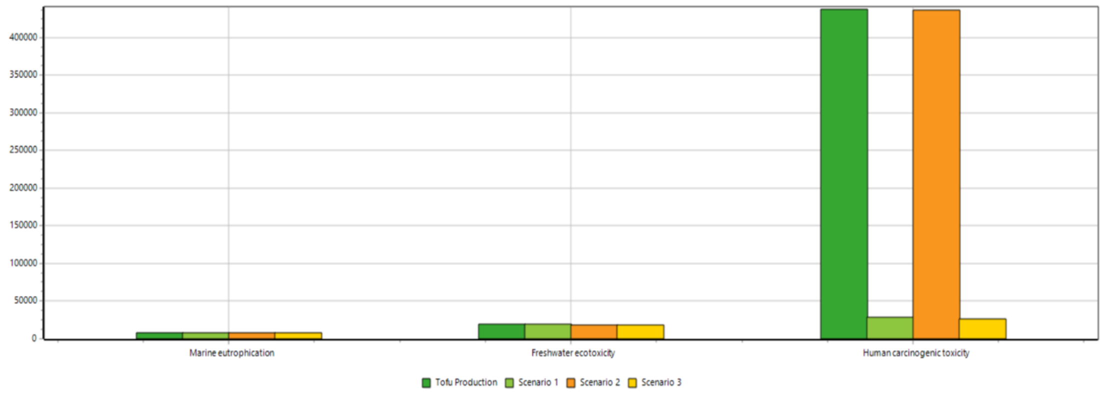

Figure 4. Comparison of Environmental Impact Mitigation Scenarios

Referring to the results illustrated in Figure 4, the 1st Scenario demonstrated the most significant reduction in the HCT category, decreasing by 93.5% from 437000 pt to 28200 pt. However, the FE category exhibited a slight increase from 19500 pt to 19900 pt, while ME remained relatively unchanged. 2nd Scenario led to a 5.1% decrease in FE, dropping from 19500 pt to 18500 pt, and reduced ME from 7950 pt to 7940 pt, whereas the HCT value showed no significant change. Conversely, the 3rd Scenario demonstrated a simultaneous reduction across all three impact categories; HCT decreased by 93.9% to 26800 pt, FE declined by 3.1% to 18900 pt, and ME was lowered to 7940 pt.

DISCUSSION

The LCA assessment results indicated that HCT at 437500 pt, FE at 19500 pt, and ME at 7950 pt constituted the highest environmental impact values in tofu production within the SSIC of Balikpapan City. In other words, every 1 kg of tofu produced contributes an impact burden of 0.077 pt for HCT, 0.0034 pt for FE, and 0.0014 pt for ME. These three categories primarily stem from energy consumption and the generation of liquid effluents. These findings align with previous studies by Rosyidah et al. (2020) and Lestari et al. (2024). Specifically, the HCT category is associated with the utilization of firewood as an energy source during the boiling process, which releases emissions such as Particulate Matter (PM 2.5), Carbon Monoxide (CO), Nitrogen Oxides (NO), Volatile Organic Compounds (VOCs), formaldehyde, and Polycyclic Aromatic Hydrocarbons (PAHs), posing high risks to human health (Riyanda, 2022; Huijbregts et al., 2017). Furthermore, the FE and ME categories are linked to wet processing stages (soaking, washing, milling, and filtration) which generate wastewater with high concentrations of organic matter (COD, BOD, and nitrogen) that exceed standard quality thresholds (Hardyanti et al., 2024; Huijbregts et al., 2017).

Based on these assessment results, energy consumption and liquid waste management serve as the fundamental aspects for developing the mitigation scenarios. These scenarios were formulated based on the identified hotspots (ISO 14044:2006; Huijbregts et al., 2017). As illustrated in Figure 4, the increase in the FE value in the 1st Scenario does not originate from the direct combustion of LPG, but rather stems from the upstream production stages, including crude oil and natural gas extraction, petroleum refining, and LPG distribution to consumers (Koimbla et al., 2023). Conversely, the environmental impacts of firewood combustion are purely derived from the localized burning process itself (Komang et al., 2024), which accounts for its relatively low contribution to the FE category. This comparison stated that a specific fuel type may offer superior performance in one impact category while exhibiting disadvantages in another.

Scenario 2 provided the highest efficiency in the FE category (5.13%) but only yielded a negligible reduction in HCT (0.26%). Conversely, Scenario 3 successfully resolved the trade-offs associated with single-scenario implementations by achieving mitigation efficiencies of 93.87% for HCT and 3.08% for FE, without inducing any impact shifting or increases in other categories as observed in Scenario 1. The reduction in HCT in Scenario 3 was driven by the substitution of firewood with LPG, while the decline in FE was achieved through the utilization of tofu wastewater effluent as a liquid organic fertilizer (LOF), which effectively reduced the volume of waste discharged into the environment (Hardyanti et al., 2024). This integrated approach aligns with the findings of Hartini et al. (2024), who asserted that waste recycling enhances the eco-efficiency index. Consequently, the combination of energy substitution and liquid effluent reuse provides the most consistent environmental impact mitigation across all primary impact categories evaluated in this study.

CONCLUSION

The LCA analysis of 56 tofu industries within the SSIC Balikpapan City revealed that the highest environmental impacts over a one-year production period were Human Carcinogenic Toxicity at 437500 pt, Freshwater Ecotoxicity at 19500 pt, and Marine Eutrophication at 7950 pt. These impacts were primarily driven by the reliance on firewood as an energy source and the direct discharge of untreated liquid effluents. To mitigate these burdens, an effective recommendation proposed is a combined scenario that substitutes firewood with LPG and repurposes the liquid waste into liquid organic fertilizer (LOF). This integrated scenario consistently reduces Human Carcinogenic Toxicity by 93.87%, Freshwater Ecotoxicity by 3.08%, and lowers Marine Eutrophication to 7940 pt, notably without inducing trade-offs or shifting impacts across other categories. Consequently, the realization of these impact reductions directly supports the achievement of the Sustainable Development Goals within the tofu industry in SSIC of Balikpapan City, specifically targeting Clean Water & Sanitation, Affordable & Clean Energy, Responsible Consumption & Production, and Climate Action.

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