



Environmental Impact Analysis of Tofu Industry Waste on Coastal Resilience in Surabaya

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Abstract. Household-scale tofu industries in Surabaya, a strategic coastal city in East Java, play a vital role in the local economy but pose significant challenges to environmental sustainability. The discharge of untreated liquid waste from these industries into the city's river network eventually flows into the estuarine and coastal waters of the Madura Strait, threatening aquatic ecosystems. This study aims to analyze the environmental impact of tofu production activities on coastal environmental resilience and measure pollution potential using the Life Cycle Assessment (LCA) approach based on openLCA software. The LCA method was applied with a gate-to-gate boundary and a functional unit of 1 kg of tofu, covering input-output inventory and impact analysis using the ReCiPe Midpoint (H) method. The results indicate that the usage of combined firewood and LPG fuel generates the highest Global Warming Potential (GWP) impact of 529.5 kg/day. Furthermore, liquid waste discharge (9-13 L/kg of tofu) is identified as the primary contributor to water pollution, causing significant Eutrophication and Aquatic Ecotoxicity impacts, with values reaching 6.391 Kg 1,4-DCB/day. This high pollution load exacerbates the vulnerability of Surabaya's coastal water resources. To support the vision of a resilient and sustainable coastal city, this study recommends the implementation of cleaner production strategies, including fuel substitution, water recycling, and the conversion of liquid waste into organic fertilizer to mitigate environmental degradation.

Keywords: Cleaner Production, Coastal Resilience, Environmental Impact, Life Cycle Assessment (LCA), Tofu Industry Waste.

1 Introduction

The industrial sector is one of the backbones of the local economy in Indonesia, with small and medium-sized enterprises (SMEs) playing a crucial role. Among these, the tofu industry is highly significant due to tofu being a staple protein source for the population. In the context of Surabaya, a strategic coastal city in East Java, household-scale tofu industries are prevalent. However, while these industries provide economic benefits and food security, they also pose severe challenges to environmental sustainability, particularly concerning water quality and coastal resilience [1] can be found in Figure 1.



FIGURE 1. Tofu Production

The tofu production process is inherently resource-intensive, requiring substantial amounts of water and energy. In most household-scale factories, the technology used remains traditional and inefficient. The discharge of untreated liquid waste—characterized by high Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) levels—is often directed into the city's drainage systems and rivers. In a coastal city like Surabaya, these rivers eventually flow into the estuarine areas and the Madura Strait. This continuous influx of organic pollutants threatens aquatic ecosystems, reduces dissolved oxygen, and compromises the resilience of coastal environments against further degradation [2]. Furthermore, the environmental burden is not limited to water pollution. The use of traditional fuels, such as firewood combined with Liquefied Petroleum Gas (LPG) for the boiling process, contributes significantly to greenhouse gas emissions. Without a comprehensive evaluation of these impacts, it is difficult to formulate effective mitigation strategies. Therefore, a systematic approach is required to quantify the environmental load of these industrial activities [3] can be found in Figure 2.



FIGURE 2. River Condition

The Life Cycle Assessment (LCA) method is a standardized tool used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction to disposal. By applying the LCA approach with a gate-to-gate boundary, this study aims to identify the "hotspots" of pollution within the tofu production cycle in Surabaya. Specifically, this research utilizes openLCA software and the ReCiPe Midpoint (H) method to measure impact categories such as Global Warming Potential (GWP), Freshwater Eutrophication, and Ecotoxicity [4].

The primary objective of this study is to analyze the environmental impact of tofu industry waste on coastal resilience in Surabaya and to provide recommendations for cleaner production strategies. By understanding the magnitude of these impacts, stakeholders can implement better waste management practices, such as fuel substitution and waste-to-fertilizer conversion, thereby supporting the vision of a resilient and sustainable coastal city.

2 Method

The methodology of this research follows the international standards for Life Cycle Assessment (LCA) as defined in ISO 14040/14044. The study was conducted using openLCA 2.4.1 software, utilizing the Ecoinvent 3.8 database for background data and the ReCiPe Midpoint (H) method for impact characterization.

The primary objective is to evaluate the environmental burden of tofu production in Surabaya and its implications for coastal resilience. The functional unit (FU) is defined as 1 kg of tofu produced. The system boundary is set as gate-to-gate, which includes all processes starting from the arrival of raw materials (soybeans) at the production facility to the point where the finished tofu and its by-products (liquid and solid waste) leave the factory gates.

Primary data was collected through direct observation and interviews with household-scale tofu producers. The inventory includes input flows such as soybeans, process water, electricity, and fuels (firewood and LPG). Output flows consist of the main product (tofu), solid waste (okara/soybean dregs), and liquid waste. The average liquid waste generated ranges from 9 to 13 liters per kg of tofu produced.

The inventory data was processed to calculate potential environmental impacts across several categories. This study focuses on:

1. Global Warming Potential (GWP): Measuring CO₂-equivalent emissions from energy consumption.
2. Freshwater Eutrophication: Assessing the impact of organic-rich liquid waste on water bodies.
3. Freshwater Ecotoxicity: Evaluating the toxic effects of untreated waste on aquatic life in coastal ecosystems.

3 Result

Based on the Life Cycle Inventory and LCA simulation, the most significant environmental impact generated from the tofu production process in Surabaya occurs in the Freshwater Ecotoxicity category. The peak value reaches 6.391 kg 1,4-DCB per day, which is significantly higher compared to other impact categories. This high ecotoxicity value is primarily driven by the direct discharge of untreated liquid waste into the urban drainage system, which eventually flows into the Madura Strait. This waste contains high organic loads and toxic compounds that disrupt the equilibrium of estuarine and coastal ecosystems, thereby weakening the natural resilience of the Surabaya coastline. Information can be found in the Table 1.

TABLE 1. Daily Life Cycle Impact Assessment (LCIA) Results

Categories		Tofu Industries		
		A	B	C
Global Warming Potential	kg CO ₂ -eq	279,6	209,7	350,2
Freshwater Eutrophication	kg P-eq	0,036	0,027	0,046
Terrestrial Acidification	kg SO ₂ -eq	0,274	0,205	0,343
Freshwater Ecotoxicity	kg 1,4-DCB	3,356	2,517	4,198

The second highest impact is Global Warming Potential (GWP), with a value of 529.5 kg CO₂-eq per day. This impact arises indirectly from high emissions during the boiling process, which utilizes a combination of firewood and LPG. The combustion of firewood without emission control systems releases various pollutants, including carbon dioxide (CO₂), fine particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs), contributing to the industrial carbon footprint in the coastal region. Information can be found in the Table 2.

TABLE 2. Weekly Life Cycle Impact Assessment (LCIA) Results

Categories		Tofu Industries		
		A	B	C
Global Warming Potential	kg CO ₂ -eq	1957	1467	2451
Freshwater Eutrophication	kg P-eq	0,252	0,189	0,322
Terrestrial Acidification	kg SO ₂ -eq	1,918	1,435	2,401
Freshwater Ecotoxicity	kg 1,4-DCB	23,492	17,619	29,386

The Acidification category also shows significant figures, resulting from the disposal of liquid waste from the tofu coagulation process. The use of acetic acid (vinegar) as a coagulant produces acidic effluent that, when discharged without neutralization, increases the acidity of both soil and water bodies, potentially damaging the surrounding mangroves and coastal biodiversity.

The category with the lowest relative value is Freshwater Eutrophication, with a peak value recorded at 0.842 kg P-eq. Although lower in magnitude compared to ecotoxicity, this impact is critical for coastal areas. The discharge of "whey" (liquid waste) containing high levels of phosphates and nitrogen triggers excessive algal blooms (eutrophication), which depletes dissolved oxygen (DO) levels and endangers aquatic biota in Surabaya's coastal waters.

Environmental Risk Interpretation Analysis

1. Freshwater Ecotoxicity This category represents the highest environmental burden from tofu production. Based on benchmarking with previous studies [5] the values observed in Surabaya's tofu industries exceed safe

thresholds. The high impact is caused by untreated liquid waste (ranging from 9-13 L/kg of tofu) containing organic and toxic substances. This poses a severe threat to the stability of aquatic organisms and the overall health of the marine environment.

2. **Global Warming Potential** The GWP category shows that daily emissions reach 529.5 kg CO₂-eq, which is categorized as a high-risk level. This is predominantly caused by the inefficient use of traditional fuels. The simultaneous use of LPG and firewood to accelerate the boiling process increases the total thermal emissions, making it a critical "hotspot" for environmental intervention in the production cycle.
3. **Acidification** The acidification values recorded in this study exceed the reference standards established in previous environmental assessments [5]. The lack of a neutralization process for acidic waste before disposal directly increases environmental acidity. In a coastal context, this can lead to the degradation of water quality in the estuaries that are vital for local fisheries.

Freshwater Eutrophication In the eutrophication category, the results significantly exceed the reference standard of 0.02665 kg PO₄-eq [6]. This indicates that the impact on freshwater and coastal eutrophication is in the high-danger category. The disposal of nutrient-rich whey into water bodies is the primary driver, leading to oxygen depletion which is detrimental to the vision of a sustainable and resilient coastal city

4 Conclusion

This study reveals that tofu production activities within small and medium-sized enterprises (SMEs) in Surabaya, particularly those situated along the urban drainage and river networks flowing toward the coast, significantly contribute to environmental degradation. Based on the analysis, the most significant environmental impact originates from the Freshwater Ecotoxicity category, with a peak value of 6.391 kg 1,4-DCB. This is followed by the Global Warming Potential (529.5 kg CO₂-eq), along with notable levels of Acidification and Eutrophication. All values across these four impact categories exceed the safety thresholds established in previous studies, indicating that the current tofu production processes are major contributors to environmental pollution in Surabaya's coastal zones.

The primary factors driving this pollution include the direct discharge of untreated liquid waste into rivers that lead to the Madura Strait, the simultaneous use of firewood and LPG for production efficiency, and the application of acetic acid (vinegar) during the coagulation process. The liquid waste contains high levels of organic compounds, acidic substances, phosphates, and nitrogen, which contaminate the water and severely damage the aquatic and estuarine ecosystems.

Furthermore, in comparison to previous studies, the extended timeframe of the analysis in this research highlights a significant accumulation of environmental impacts. The longer the production activities continue without an adequate waste management system, the greater the cumulative damage to the environment. Consequently, the danger levels for all four analyzed indicator categories are considered high, emphasizing the urgent need for mitigation efforts and improved waste management among small-scale tofu industries in this region to enhance coastal resilience.

Despite these challenges, there are significant opportunities to reduce these impacts by processing liquid waste into liquid organic fertilizer (POC) and repurposing solid waste (tofu dregs) as raw materials for secondary products like *tempe gembus*. Thus, the Life Cycle Assessment (LCA) approach not only identifies critical environmental "hotspots" but also provides a scientific foundation for sustainable solutions, such as the adoption of clean energy, water recycling, and integrated waste management.

5 References

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