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Life Cycle Assessment and Life Cycle Cost Analysis of Small Scale Tempeh Industries

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ABSTRACT

The high activity of tempeh production has the potential to produce greenhouse gas emissions and liquid waste that impact the environment, as well as incur high operational costs. This study focuses on three tempeh MSMEs (Micro, Small, and Medium Enterprises), namely Tempe Pratama, Tempe Murni AMR, and Tempe Sumber Mas. Environmental impact analysis and life cycle costs were conducted using the Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methods. The LCA method is used to evaluate environmental impacts, while the LCC method is used to calculate the total production costs over five years. The results of the LCA analysis show that Tempe Pratama has the highest environmental impact per kg of raw material, with a GWP value of 1.02387 Kg CO_2-eq, especially in the boiling process using firewood. The results of the LCC analysis show that operational costs are the largest component of total production costs, and the highest NPC results for 5 years were obtained in Tempe Sumber Mas at IDR. 7,492/Kg. The simultaneous application of LCA and LCC provides a comprehensive picture of the efficiency and sustainability of tempeh production. Recommendations for improvements including the use of more environmentally friendly fuels to reduce environmental impacts and long-term costs for tempeh industry.

1. INTRODUCTION

The strategic role of micro, small, and medium enterprises (MSMEs) has been driving the rapid growth of the food industry in Indonesia, which elevates the national economy. The Ministry of Cooperatives and SMEs reports that the number of MSMEs reached 65.47 million in 2019 (Kemenkop UKM, 2022), demonstrating a significant contribution to creating jobs and increasing community income. One food product commonly produced by MSMEs is tempeh, a traditional Indonesian food with high nutritional value, including protein, iron, calcium, and flavonoid compounds that act as antioxidants (Adiwinata *et al.*, 2021).

One of the regions with the largest number of MSMEs in East Java is Jember Regency, known for its staggering number of MSMEs reaching 647,000 units in 2021 (Anggraini *et al.*, 2022). The tempeh production sector is one of the most rapidly growing businesses in this region. While it yields a positive economic impact, tempeh production also poses significant environmental challenges. Several tempeh MSMEs in Jember still use firewood to fuel their production, which can generate high levels of greenhouse gas emissions such as CO_2, CH_4, and N_2O. Furthermore, liquid waste from the production can pollute groundwater and rivers and produce an unpleasant odor (Mejia *et al.*, 2018).

Previous studies have demonstrated significant greenhouse gas (GHG) and black carbon mitigation through the transition from firewood to LPG (Adi *et al.* 2024; Serrano *et al.*, 2018). A systematic approach is therefore required to comprehensively assess the environmental impact and production costs of the tempeh production. In so doing, Life

Cycle Assessment (LCA) can help to evaluate the environmental impact of a product or process throughout its life cycle, while Life Cycle Cost (LCC) analyzes all costs incurred throughout the product's lifetime, from initial investment to final disposal (BSN, 2016).

While several studies have evaluated the environmental impact of tempeh production employing the LCA approach and assessed the economic aspects separately, studies integrating LCA and LCC in tempeh MSMEs remain limited. Furthermore, few studies have compared MSMEs with different technological characteristics and energy sources within a single sustainability analysis framework. This study aims to close that gap by integrating LCA and LCC analyses on three tempeh MSMEs with different production systems. In addition, the study seeks to raise recommendations concerning the trade-off between environmental performance and costs. The study is expected to establish a knwledge of the production stages that contribute significantly to environmental impacts and costs.

2. MATERIALS AND METHODS

This study was conducted in three tempeh industries in Jember with different capacity, namely Tempe Murni AMR (45 kg/day), Tempe Pratama (120 kg/day), and Tempe Sumber Mas (500 kg/day). Table 1 summarized description of the three tempeh industries. Data was collected through deep interview with industry owners, direct observation and measurement. Other information was gleaned from books, journals, and sources relevant to the study.

Table 1. Description of tempeh MSMEs in Jember

Description	**Tempe Murni AMR**	**Pratama**	**Tempe Sumber Mas**
Year of Establishment	2012	2000	1991
Type of Raw Material	Imported soybeans	Imported soybeans	Imported soybeans
Number of Employees	1 people	2 people	11 people
Production capacity	45 kg/day	120 kg/day	500 kg/day
Energy Type	-Electricity -Firewood	-Electricity -Firewood -Gasoline	-Electricity -LPG cylinder -Gasoline
Product Selling Price	2,500 – 5,000 100 Grams (2,500) 250 Grams (5,000)	1,500 – 5000 50 Grams (1,500) 130 Grams 3,000 250 Grams 5,000	2,500 – 15,000 100 Grams (2,500) 250 Grams (5,000) 400 Grams (7,000) 1 Kg (15,000)

2.1. Research Stages

This study engaged LCA to determine the environmental impacts generated during the tempeh production process, while the LCC aimed to investigate the tempeh production and determine production costs throughout the production, which will serve as the basis for seeking ways to elevate the business performance. The study uses a gate-to-gate approach, covering only one specific stage of the production process, encompassing all production activities from washing to fermentation and storage in the warehouse, excluding cultivation (upstream) or distribution, product use, and post-consumer waste management (Figure 1). The entire production was assumed to occur under normal operating conditions during the observation.

The functional unit under LCA was analyzed during one production run, with calculations per kilogram of raw material used to compare the highest to the lowest impact values. In contrast, the LCC was carried out over one year of production, with calculations per kilogram of raw material used to compare the highest to the lowest total production costs. The NPC was calculated over five years.

2.2. LCA Analysis

Life cycle inventory was documented through field observations and direct interviews with three owners of tempeh MSMEs. The analysis focused on raw material usage, electricity consumption, fuel consumption, and production output. The data were subsequently compiled into a Life Cycle Inventory (LCI) and modeled using OpenLCA software

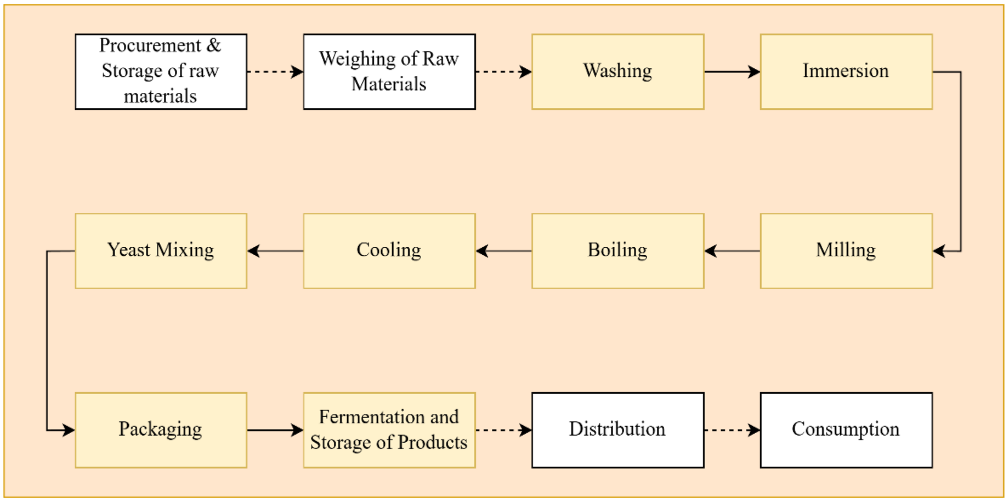

Figure 1. Boundary system used for gate-to-gate LCA and LCC analysis [⟶ Included in the LCA for production process in tempeh MSMEs; ⇢ Excluded in the analysis].

version 1.10.3. The emission factors under investigation referred to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, while the LCA modeling utilized the ecoinvent database version 3.4 as background data and emission parameters required for the analysis. The LCA was aligned with the ISO 14040:2006 standard (Zhou *et al*., 2025; Nandar *et al*., 2025) and ISO 14044:2006 standard (Koffler *et al*., 2020), which regulated the principles, framework, requirements, and guidelines for implementing Life Cycle Assessment.

The fuel and electricity energy consumption were calculated using Equations (1) and (2), adapted from Pujianto *et al*. (2022). The emission was quantified based on the method recommended in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, as shown in Equation (3). Fuel energy consumption was calculated using Equation (1):

$$\text{Energy} = \sum Q_i NCV_i \quad (1)$$

where Q is the amount of fuel (kg, L, kW), NCV is net calorific value (MJ/kg), and subscribe i is for fuel types (firewood, LPG, and gasoline). The electrical energy was calculated using conversion factor 3.6 MJ/kWh.

The amount of emission (E) was calculated based on the IPCC (2006) equation as follows:

$$\text{Emission} = \text{AD} \times \text{EF} \quad (2)$$

where AD is activity data (MJ), and EF is fuel emission factor (kgCO_2-eq), for different fuels is given in Table 2.

2.1.1. Analysis of Environmental Impact

Environmental impacts were analyzed using openLCA software version 1.10.3 CML 2001 method (da Silva et al., 2023), given its ability to evaluate various categories of relevant environmental impacts on food and agro-industrial production systems. Furthermore, this method has been widely used in similar studies, therefore allowing comparison across studies. The environmental impact was analyzed and classified based on the impact on Acidification, Eutrophi-

Table 2. Emission factors for different fuels (IPCC, 2006)

Emission Source	Emission Factor (g/MJ)				
	CO_2	CH_4	N_2O	SO_2	NO_x
Firewood	112.0	0.0300	0.0040	0.0113	0.05
Electricity	228.0	0.0833	0.0020	7.5000	1.20
Gasoline	69.3	0.0030	0.0006	0.0068	2.80
LPG	63.1	0.0010	0.0001	0.0870	0.50

cation, and Global Warming Potential (GWP). The impact on Global Warming Potential (GWP) was analyzed based on the content of CO_2, N_2O, and CH_4 converted to CO_2-eq, the impact of acidification was analyzed based on the content of SO_2 and NO_2 converted to SO_2-eq, and the impact on eutrophication was determined based on the content of N_2O and NO_x converted to PO4-eq.

2.1.2. Interpretation and Recommendations

This stage involves conducting an evaluation and drawing conclusions. The evaluation results guide the recommendations in reducing the environmental impacts of the production process.

2.1.3. LCC Analysis

This stage calculated the production costs of tempeh, including the costs of raw materials and production costs for each stage of the tempeh production process. Referring to Casella *et al*. (2025), the following formula was used to calculate life cycle cost (LCC) for tempeh MSMEs:

$$LCC = \mathrm{C} + \mathrm{M} + \mathrm{O} + \mathrm{D} \tag{3}$$

where *C* is initial investment cost, *M* is maintenance cost, *O* is operational cost, and *D* is disposal cost. The initial investment costs are costs incurred before production, such as the purchase of machinery, tools, and so on. The maintenance costs are the costs of maintaining the machinery and tools involved in the production. The operating costs are the total regular costs incurred to support the production, which include (a) Employee salaries, (b) Electricity costs, (c) Land and building tax, (d) LPG costs, and (e) Packaging costs. The disposal costs are costs that arise when a product reaches the end of its life cycle and must be disposed of, deleted, or recycled, such as waste transportation costs and recycling costs.

Equation (4) was used to quantify the present value of the LCC (Muthu, 2023), called net present cost (NPC).

$$\mathrm{NPC} = \Sigma \mathrm{Ct} \times \frac{1}{(1+i)^n} \tag{4}$$

where C_t is total costs in year *t* (e.g., investment, operational, etc.), *i* is discount rate (in decimal, so 8% = 0.08), and *n* is year (0, 1, 2, ..., *n*).

2.1.4. Interpretation of Results and Recommendations through the LCC Method

This stage sought to determine the highest costs through the LCC calculation. It allowed the researchers to draw recommendations for business improvements while making operational costs more efficient.

3. RESULTS AND DISCUSSION

3.1. Tempeh Production Process

Figure 2 summarizes process to produce tempeh observed in this study as well as Life Cycle Inventory to calculate the environmental impacts of the tree Tempe SMMEs (Murni AMR, Pratama, and Sumber Mas). The production flow diagrams indicate that increasing production capacity was accompanied by changes in process configuration and energy sources. The Murni AMR with a capacity of 45 kg/day employed a relatively simple sequence consisting of two boiling stages, milling, washing, immersion, cooling, fermentation, and packaging, with firewood serving as the primary thermal energy source. At the Pratama industry (with capacity of 120 kg/day), the process configuration changed, particularly with the inclusion of two immersion stages, while energy sources became more diversified through the use of firewood, gas, and electricity. The largest industry (Sumber Mas; 500 kg/day) exhibited a more complex sequence involving multiple washing, boiling, milling, and immersion stages and relied primarily on gas and electricity rather than firewood. These differences suggest that production scaling in MSME tempeh industries is associated not simply with a proportional increase in material throughput, but also with adjustments in processing configuration and energy utilization. The substantially larger production capacity of Sumber Mas therefore reflects a different production system rather than merely a larger version of the process employed by the smaller industries.

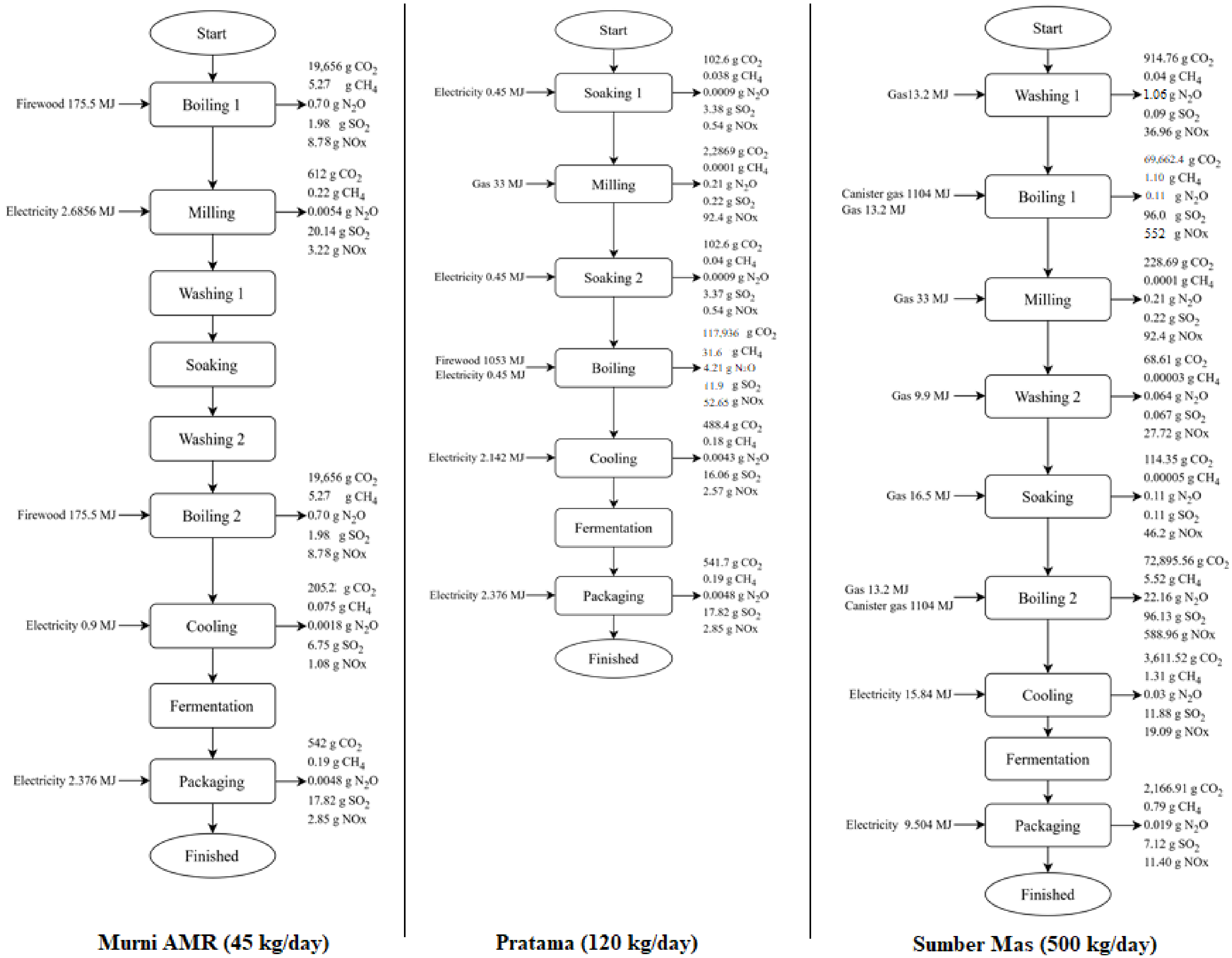

Figure 2. Energy consumption of tempeh industries in Jember Regency. From left to right: Murni AMR (45 kg/day), Pratama (120 kg/day), and Sumber Mas (500 kg/day)

3.2. Energy Consumption for Tempeh Production

Figure 2 illustrates the energy consumption flow across three MSMEs with production capacities of 45 kg/day (Murni AMR), 120 kg/day (Pratama), and 500 kg/day (Sumber Mas). The energy sources utilized include firewood, gas, and electricity, with consumption patterns varying by industry. Tables 3 and 4 summarize the fuel and electricity consumption for these three tempeh industries, respectively. In Tempe Murni AMR industry, energy is primarily consumed as firewood for the boiling process –specifically 175.5 MJ for each of the two boiling stages (Boiling 1 and Boiling 2)– resulting in a total firewood consumption of 351 MJ/day. Additionally, electricity is used during the milling, cooling, and packaging stages, totaling approximately 5.96 MJ/day. Consequently, the total energy consumption for Tempe Murni AMR is approximately 356.96 MJ/day, equivalent to 7.93 MJ/kg of soybean.

Table 3. Fuel consumption in the three tempeh industries

Tempeh Industry	Process	Machine or Equipment	Fuel	Fuel Quantity	Energy Value (MJ/unit)	Energy Consumption (MJ)
Murni AMR	Boiling 1	Boiling furnace	Firewood	22.5 kg	15.6	351
Pratama	Milling	Grinding machine	Gasoline	1 liter	33	33
	Boiling	Boiling furnace	Firewood	67.5 kg	15.6	1,053
Sumber Mas	Milling	Milling machine	Gasoline	1 liter	33	33
	Boiling	Gas stove	LPG	48 kg	46	2,208
	Water pumping	Water Pump	Gasoline	2 liter	33	66

Table 4. Electricity consumption in the three tempeh industries

Tempeh Industry	Process	Equipment	Rate (W)	Electrical Energy (kWh)	Energy Consumption* (MJ)
Murni AMR	Cooling	Electric Fan	50	0.25	0.9
	Milling	Electric Dynamo	373	0.746	2.6856
	Packaging	Sealing Machine	220	0.66	2.376
Pratama	Cooling	Fan	85	0.595	2.142
	Water Source	Water Pump	125	0.375	0.01125
	Packaging	Sealing Machine	220	0.66	2.376
Sumber Mas	Cooling	Fan	220	2.2	7.92
	Cooling	Fan	110	2.2	7.92
	Packaging	Sealing Machine	220	2.64	9.50

*) conversion factor from kWh to MJ is 3.6.

Tempe Pratama, with a production capacity of 120 kg/day, exhibits a more diverse energy usage pattern. Thermal energy is derived from firewood (1,053 MJ for the boiling stage) and gas (33 MJ for the milling stage), while electricity is used during the immersion, milling, boiling, cooling, and packaging stages. Based on the diagram, total electricity consumption is approximately 5.87 MJ/day. Thus, the total energy consumption for Tempe Pratama reaches approximately 1,091.87 MJ/day, or about 9.10 MJ/kg of soybean. Although its production capacity is roughly 2.7 times that of Tempe Murni AMR, its total energy consumption has more than tripled. This indicates that the increase in capacity at Tempe Pratama has not been fully matched by an improvement in energy efficiency.

Meanwhile, Tempe Sumber Mas industry –which has the largest production capacity at 500 kg/day– utilizes a combination of gas and electricity. Based on the diagram, gas is utilized during the washing, boiling, milling, and immersion stages, with gas canisters providing 1.104 MJ recorded for each of the Boiling 1 and Boiling 2 stages. Electricity consumption occurs primarily during the cooling and packaging stages, amounting to 15.84 MJ and 9.50 MJ, respectively. Summing all energy inputs listed in the diagram reveals that total energy consumption at Tempe Sumber Mas reaches approximately 2,332.34 MJ/day. Although it is the largest energy consumer in absolute terms, its specific energy consumption is only about 4.66 MJ/kg of tempeh, meaning Tempe Sumber Mas demonstrates the highest energy efficiency per unit of product among the three industries.

Specific energy consumption or energy intensity was analyzed as the ratio of total energy consumption to the amount of processed soybean. A lower energy intensity indicates more efficient energy use in the production process. The energy intensity during the tempeh production process for each MSME is displayed in Figure 3. These findings demonstrate that absolute energy consumption cannot be used directly to assess industrial energy efficiency. Although Tempe Sumber Mas consumes roughly 6.5 times more total energy than Tempe Murni AMR, its production capacity is more than 11 times greater. Consequently, specific energy consumption (Figure 3) in Tempe Sumber Mas industry is actually about 41% lower than that of Tempe Murni AMR industry and 49% lower than that of Tempe Pratama.

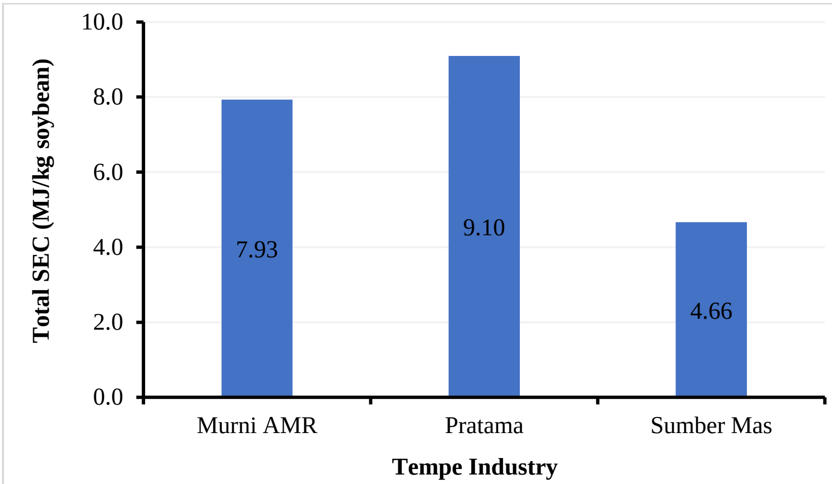

Figure 3. Total specific energy consumption (SEC) in MSME tempeh industries

This pattern indicates the presence of economies of scale in energy usage within the tempeh industry. At larger production scales, energy requirements do not increase in proportion to the increase in production capacity. Factors such as the use of higher-capacity equipment, more efficient energy distribution, and a reduction in fixed energy requirements per unit of product likely contribute to this decrease in specific energy consumption. However, these mechanisms should not be cited as definitive causes without supporting data regarding equipment capacity, boiler efficiency, processing time, or combustion efficiency.

The highest energy consumption is identified in Tempe Pratama, followed by the Tempe Murni AMR and the Tempe Sumber Mas. The difference is mainly influenced by the type of fuel used and the boiling process efficiency, which marked the highest energy consumption. The boiling process at Tempe Pratama and Tempe Murnin AMR used Firewood, while Tempe Sumber Mas used LPGs for the Boiling process. Research by Pujianto *et al*., (2022) shows that Boiling-based processing is a major contributor to energy consumption in small-scale agro-industries. Energy consumption in the Boiling process using wood fuel is higher than that using LPGs because wood has a low combustion efficiency of around 10–20%, resulting in incomplete combustion, and the resulting heat is not intensified directly on the boiling container (Hartini *et al*., 2024). These results suggest that MSMEs using LPG have lower energy intensity than MSMEs still using Firewood.

3.3. GHG Emission during Tempeh Production

Emissions are the release of substances or compounds into the environment, especially into the air, originating from natural processes or human activities. Emissions can be greenhouse gases or other air pollutants and particulates (Atamaleki., *et al* 2019; Nugraha., *et al*. 2024). This study limits to 5 types of gas emissions, namely CO_2, CH_4, N_2O, SO_2, NO_x, because these gases are needed to calculate the impact of GWP, Acidification, and Eutrophication, which are the most significant environmental footprints resulting from the tempeh production process, especially directly related to energy consumption and waste disposal. High energy consumption generally result in high emissions (Hartini *et al*., 2024).

Figure 2 also summarizes gas emissions from the tempeh production process. Emissions are categorized into greenhouse gases (GHGs) –comprising CO_2, CH_4, and N_2O– and non-GHG gases (SO_2 and NOx). Tables 5 through 7 detail gas emissions by process stage in tempeh production for the three MSMEs: Tempe Murni AMR, Tempe Pratama, and Tempe Sumber Mas. GHG emissions across the three industries exhibit varying patterns as production capacity increases. Tempe Murni AMR, with a capacity of 45 kg of tempeh/day, generates approximately 40.67 kg of CO_2/day, whereas Tempe Pratama, with a capacity of 120 kg/day, produces higher emissions at approximately 121.56 kg/day. For Tempe Sumber Mas, which has a production capacity of 500 kg/day, total emissions reach approximately 151.96 kg CO_2/day. Thus, in absolute terms, emissions rise alongside the increase in production scale. However, this rise in emissions is not proportional to the increase in production capacity. This is evident from the specific emissions, which reach approximately 0.3398 kg CO_2/kg soybean for Tempe Murni AMR, 1.013 kg CO_2/kg for Tempe Pratama,

Table 5. The emissions from Tempe Murni AMR (45 kg/day)

Process*	Emission Source	Energy Consumption (MJ)	Emission Gas (kg)				
			CO_2	CH_4	N_2O	SO_2	NO_x
Boiling 1	Firewood	175.5	19.65600	0.00527	0.00070	0.00198	0.00878
Milling	Electricity	2.6856	0.61232	0.00022	0.00000	0.02014	0.00322
Washing 1	None	-	-	-	-	-	-
Soaking	None	-	-	-	-	-	-
Washing 2	None	-	-	-	-	-	-
Boiling 2	Firewood	175.5	19.65600	0.00527	0.00070	0.00198	0.00878
Cooling	Electricity	0.9	0.20520	0.00008	0.00000	0.00675	0.00108
Fermentation	None	-	-	-	-	-	-
Packaging	Electricity	2.376	0.54173	0.00020	0.00000	0.01782	0.00285
TOTAL (unit/day)		356.96	40.67124	0.01103	0.00142	0.04868	0.02470
TOTAL (unit/kg soybean)		7.93	0.33983	0.00009	0.00001	0.00041	0.00021

*) No emission was released from these process: Washing 1, Soaking, Washing 2, and Fermentation

Table 6. The emissions from Tempe Pratama (120 kg/day)

Process	Emission Source	Energy Consumption (MJ)	Emission Gas (kg)				
			CO_2	CH_4	N_2O	SO_2	NO_x
Soaking 1	Electricity	0.45	0.10260	0.00004	0.00000	0.00338	0.00054
Milling	Gasoline	33	2.28690	0.00010	0.00020	0.00022	0.09240
Soaking 2	Electricity	0.45	0.10260	0.00004	0.00000	0.00338	0.00054
Boiling	Firewood	1053	117.93600	0.03159	0.00421	0.01190	0.05265
	Electricity	0.45	0.10260	0.00004	0.00000	0.00338	0.00054
Cooling	Electricity	2.142	0.48838	0.00018	0.00000	0.01607	0.00257
Fermentation	None	-	-	-	-	-	-
Packaging	Electricity	2.376	0.54173	0.00020	0.00000	0.01782	0.00285
TOTAL (unit/day)		1091.87	121.56	0.03219	0.00441	0.05615	0.15209
TOTAL (unit/kg soybean)		9.10	1.0130	0.00027	0.00004	0.00047	0.00127

Table 7. The emissions from Tempe Sumber Mas (500 kg/day)

Process	Emission Source	Energy Consumption (MJ)	Emission Gas				
			CO_2	CH_4	N_2O	SO_2	NO_x
Washing 1	Gasoline	13.2	0.91476	0.00004	0.00106	0.00009	0.03696
Boiling 1	LPG	1104	69.66240	0.00110	0.00011	0.09605	0.55200
	Gasoline	13.2	0.91476	0.00004	0.00008	0.00009	0.03696
Milling	Gasoline	33	2.28690	0.00010	0.00020	0.00022	0.09240
Washing 2	Gasoline	9.9	0.068607	0.00003	0.00006	0.00007	0.02772
Soaking	Gasoline	16.5	1.14345	0.00005	0.00010	0.00011	0.04620
Boiling 2	Gasoline	13.2	0.91476	0.00004	0.00008	0.00009	0.03696
	LPG	1104	69.66240	0.00110	0.00011	0.09605	0.55200
Cooling	Electricity	15.84	3.61152	0.00132	0.00003	0.11880	0.01901
Fermentation	None	-	-	-	-	-	-
Packaging	Electricity	9.504	2.16691	0.00079	0.00002	0.07128	0.01140
TOTAL (unit/day)		2332.34	151.96393	0.00462	0.00184	0.38285	1.41161
TOTAL (unit/kg soybean)		4.66	0.30393	0.00001	0.00000	0.00077	0.00282

and only 0.304 kg CO_2/kg for Tempe Sumber Mas. Consequently, while Tempe Sumber Mas generates the highest absolute emissions, it possesses the lowest emission intensity per unit of product.

The boiling stage is the dominant source of CO_2 emissions across all three industries. In Tempe Murni AMR, emissions from the Boiling 1 and Boiling 2 stages each amount to approximately 19.66 kg of CO_2; together, these two stages account for about 96.7% of the industry's total CO_2 emissions. A similar pattern is observed in Tempe Pratama, where the boiling stages generate approximately 118.08 kg of CO_2, representing about 97.1% of total CO_2 emissions. In Tempe Sumber Mas, the two boiling stages each produce approximately 73.00 kg of CO_2, cumulatively contributing about 95.4% of total emissions. The dominance of emissions during the boiling stage indicates that the thermal energy supply process is a greenhouse gas (GHG) emission hotspot in tempeh production.

The fact that the boiling stage is the primary source of emissions aligns with the high thermal energy demand of that stage. Tempe Murni AMR still relies on firewood as its main energy source for boiling, whereas Tempe Pratama uses firewood and Tempe Sumber Mas uses gas. Consequently, differences in fuel type and energy consumption during the boiling stage are key factors determining emission levels. Although Tempe Sumber Mas has a production capacity more than four times that of Tempe Pratama, the increase in its absolute emissions was relatively modest –rising from approximately 121.61 to 151.25 kg CO_2/day. This resulted in a decrease of emission intensity from approximately 1.013 to 0.306 kg CO_2/kg of soybean, demonstrating improved emission efficiency at a larger production scale.

These gas emissions come from the use of gasoline, electricity, firewood, and LPG. The table shows that the main environmental hotspot comes from the boiling stage, contributing more than 90% of total energy consumption. The dominant impact at this stage indicates that fuel type is the main determining factor in GWP. The use of firewood results in higher energy consumption due to low combustion efficiency, while LPG produces better thermal efficiency, therefore reducing emissions per unit of product. The milling stage also indicates a high rate, due to the use of gasoline. High fuel consumption will also result in high emissions (Hartini *et al*., 2024). In contrast to Tempe Sumber Mas, the results obtained by this MSME in the cooling and packaging stages are quite high because these stages use three large fans and also three sealing machines in the packaging stage. Higher electricity consumption results in higher greenhouse gas emissions (KLHK, 2022).

The relationship between production capacity and emission intensity was not linear. Although Tempe Sumber Mas exhibited the highest absolute CO_2 emissions, its emission intensity was substantially lower than those of Tempe Murni AMR and Tempe Pratama. In contrast, Tempe Pratama showed the highest emission intensity, suggesting that increasing production capacity alone does not necessarily guarantee improved environmental performance. The substantially lower emission intensity of Tempe Sumber Mas may be associated with its larger production scale and different process and energy configuration; however, this interpretation should be treated cautiously because the three industries differ not only in capacity but also in process configuration and energy sources.

3.3.1. Environmental Impact Analysis

The environmental impact was assessed using the CML 2001, a standardized approach widely used in environmental impact assessment within the LCA framework (Hartini *et al*., 2024). The environmental impacts include GWP (Global Warming Potential), AP (Acidification Potential), and EP (Eutrophication Potential). Table 8 presents the results assuming GWP factors of 25 for methane (CH_4) and 298 for N_2O. GWP is the potential emission of GHGs such as CO_2, CH_4, and N_2O, which contribute to global warming (Hasan *et al*., 2024). The analysis shows that the highest GWP values are found in MSMEs using firewood in the boiling process, namely Tempe Pratama and Tempe Murni AMR. The high GWP rate results from substantial thermal energy consumption and CO_2-eq emissions from firewood combustion. The boiling stage is the main hotspot because it needs the most energy compared to other production stages. Conversely, MSMEs using LPG produce lower GWP due to higher combustion efficiency, which implies lower energy consumption and GHG emissions.

The use of LPG by Sumber Mas MSME causes an increase in NO_x and SO_2 emissions from the combustion, leading to the dominant formation of acidic compounds in the atmosphere and increasing Acidification Potential. The same condition also occurs in eutrophication, where increased NO_x emissions contribute to the accumulation of nitrogen compounds that can trigger environmental eutrophication (Hasan *et al*., 2024; Athirafitri *et al*., 2021).

Table 8. Environmental impact on tempeh MSMEs in Jember per kg of soybean

MSME	GWP ($kg\ CO_2$-eq)	Acidification ($kg\ SO_2$-eq)	Eutrophication ($kg\ PO_4$-eq)
Tempe Murni AMR	0.3451	0.00147	0.00008
Tempe Pratama	1.0317	0.00135	0.00017
Tempe Sumber Mas	0.3042	0.00240	0.00039

Note: GWP factor: 25 for CH_4; 298 for N_2O. Acidification factor: 1 for SO_2; 0.7 for NO_x. Eutrophication factor: 0.27 for SO_2; 0.13 for NO_x.

3.4. LCC Inventory

The LCC data were obtained from the tempeh production in the field. This data included investment costs, maintenance costs, operational costs, and disposal costs within one year. One cycle in tempeh production starts from the washing process to packaging. Table 9 reports the LCC data from the three tempeh MSMEs during one production. The LCC data inventory for Tempe Pratama shows that one production cycle uses 120 kilograms of soybeans as raw material, 67.5 kilograms of firewood for the boiling process, and 120 g of yeast. Tempe Murni AMR uses 45 kg of soybeans, 22.5 kg of firewood for the boiling process, and 45 g of yeast in each production cycle. Meanwhile, Tempe Sumber Mas uses 500 kg of soybeans, 48 kilograms of LPGs for the boiling process, 1 L of gasoline for the milling process, 2 L of gasoline for operating the water pump motor, and 500 g of yeast per production cycle.

Table 9. LCC data inventory of tempeh MSMEs in Jember (per production cycle)

Inventory	Unit	Murni AMR	Pratama	Sumber Mas
Soybean	kg	45	120	500
Gasoline	liter	--	1	3
LPG (12 kg bottle)	kg	--	--	48
Firewood	kg	22.5	67.5	-
Electricity	month	1	1	1
Yeast	kg	0.45	0.12	0.5

3.5. Cost Analysis

Cost analysis quantifies the production costs in the MSMEs, which include investment costs before production, maintenance costs during the production life cycle, operational costs during production (related to the use of tools, labor, raw materials, and other operational costs), disposal costs such as waste disposal, and cleaning costs during production. Table 10 shows the total costs during the production process in the three tempeh MSMEs. It should be noted investment cost is incurred once only at the initial time.

Table 10. Total production costs for tempeh MSMEs in Jember assuming annual working day of 360 days

Cost Component	Tempe Murni AMR		Tempe Pratama		Tempe Sumber Mas	
	IDR/year	IDR/kg	IDR/year	IDR/kg	IDR/year	IDR/kg
Investment cost*	4,725,000	58.33	5,005,000	23.17	9,275,000	10.31
Maintenance cost	90,000	5.56	190,000	4.40	420,000	2.33
Operational cost	185,886,883	11,474.50	480,139,698	11,114.34	2,420,493,245	13,447.18
Disposal cost	0	0.00	240,000	5.56	600,000	3.33
Total cost	189,701,883	11,538.39	485,574,698	11,147.47	2,430,788,245	13,463.16

*) This cost is incurred once at the first time for investment cost

3.6. LCC Analysis

The Net Present Cost (NPC) was calculated to determine the total costs incurred over 5 years, presented as present value. The NPC includes all cost components, namely initial investment costs, operational costs, maintenance costs, and disposal costs over 5 years. This allows equal comparison in the same time unit. Pandey *et al*., (2025) points out that NPC allows for accurate decision-making in selecting investment and technology alternatives because it takes into account the overall cost over a specified period. This enables companies to assess alternatives with the lowest total costs over the long term. Based on Table 10, the detailed NPC calculation is prepared for life cycle of 5 years and discount rate of 8%/year commonly applied for MSMEs. The result is presented in Table 11 for Tempe Sumber Mas with cumulative NPC of IDR 9.678 billion, 900,000 kg of total soybean, and cumulative LCC of 10,753 IDR/kg. Figure 7 compares cumulative LCC of the three tempeh MSMEs evaluated in this study.

Table 11. Life cycle cost calculation for Tempe Sumber Mas

Year	C (IDR)	O+M+D (IDR)	Cash Flow (IDR)	Discount Factor	NPC (IDR)	Cumulative NPC (IDR)	Cumulative Production (kg)	Cumulative LCC (IDR/kg)
0	9,275,000	0	9,275,000	1.0000	9,275,000	9,275,000	-	
1	0	2,421,513,245	2,421,513,245	0.9259	2,242,141,894	2,251,416,894	180,000	12,508
2	0	2,421,513,245	2,421,513,245	0.8573	2,076,057,309	4,327,474,202	360,000	12,021
3	0	2,421,513,245	2,421,513,245	0.7938	1,922,275,286	6,249,749,488	540,000	11,574
4	0	2,421,513,245	2,421,513,245	0.7350	1,779,884,524	8,029,634,012	720,000	11,152
5	0	2,421,513,245	2,421,513,245	0.6806	1,648,041,226	9,677,675,238	900,000	10,753

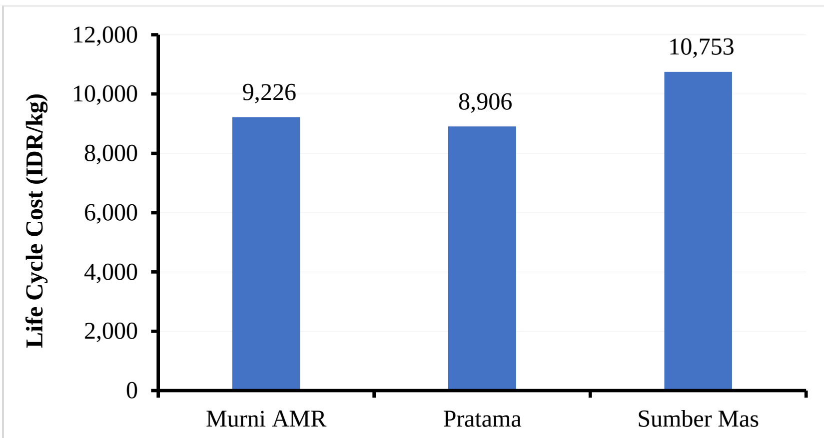

Figure 4. Life cycle cost for 5 years operation of the three of tempeh MSMEs in Jember presented in IDR/kg soybean

Figure 4 demonstrates that Tempe Sumber Mas has the highest total LCC, amounting to 10,753 IDR/kg of raw material. This high total NPC results from the use of operational materials used in this MSME, using LPGs as its boiling fuel, and using quite a lot of gasoline fuel. (Bantacut & Indriyani, 2022). mention that using LPGs and gasoline in large quantities can cause a spike in operational costs, especially without the efficiency of good equipment and production mechanisms. The Tempe Murni AMR has a total LCC of 9,229 IDR/kg of raw materials, which seems to result from high operational costs in paying PDAM water bills for its water consumption. França *et al* (2024) argue that a higher volume of water in the production process will incur higher costs. High total NPC occurs due to the dominance of accumulative long-term costs, especially from inefficient operational and maintenance aspects. The NPC value reflects the total costs brought to the present value, so that large and recurring annual costs will increase the total life cycle costs as a whole (França *et al*., 2021; Irawati & Kurniawati, 2020). These results indicate that these MSMEs need significant change to bring down the total NPC and use the lowest total NPC (Net Present Cost) as a reference for more efficient costs.

3.7. Recommendation for LCA Improvement

The environmental impact assessment of the three tempeh MSMEs was evaluated using 1 kg of raw material as the functional unit. The results showed that the boiling stage was the largest contributor to the Global Warming Potential (GWP) due to its high energy demand. Tempe Pratama consumed 8.775 MJ/kg of raw material during boiling using firewood, while Tempe Murni AMR consumed 7.80 MJ/kg of raw material because the boiling process was carried out twice. The high energy consumption in both MSMEs resulted in higher greenhouse gas emissions and consequently greater environmental impacts.

These findings indicate that improving the energy efficiency of the boiling process is an important strategy for reducing emissions and enhancing environmental performance. One possible approach is to use a more energy-efficient fuel under conditions where firewood combustion is inefficient. LPG has a higher calorific value (45–50 MJ/kg) than commonly used local firewood, such as rubber wood or sengon (14–16 MJ/kg, depending on moisture content) (Lestari *et al*., 2024). Owing to its higher energy content and more efficient combustion, LPG can reduce the amount of fuel required to produce the same amount of heat. This recommendation was shown in Table 11.

Table 11. Condition of MSMEs and Recommendations for LCA Improvement

MSME	Current condition	Recommendation
Tempe Pratama	Boiling using 67.5 kg of firewood as fuel	Boiling with the use of 23 kg of LPG
Tempe Murni AMR	Boiling using 22.5 kg of firewood as fuel	Boiling with the use of 8 kg of LPG

Based on the energy calculations in this study, the estimated energy requirement for the boiling stage could be reduced to 2.116 MJ/kg of raw material for Tempe Pratama and 0.736 MJ/kg of raw material for Tempe Murni AMR when LPG is used. These results suggest that improving the efficiency of the boiling process, including the use of more efficient fuels where appropriate, has the potential to reduce energy consumption and greenhouse gas emissions. However, the selection of fuel should be evaluated comprehensively by considering multiple environmental impact categories rather than relying solely on Global Warming Potential (GWP). The calculation of environmental impact for process improvement scenario was shown in Table 12.

Table 12. Results of environmental impact recommendation calculations

Fuel Type	Tempe Murni AMR			Tempe Pratama		
	GWP (kg CO_2-eq)	Acidification (kg SO_2-eq)	Eutrophication (kg PO_4-eq)	GWP (kg CO_2-eq)	Acidification (kg SO_2-eq)	Eutrophication (kg PO_4-eq)
Firewood	39.720	0.016	0.003	119.264	0.053	0.008
LPG cylinder	26.233	0.161	0.026	75.523	0.466	0.075

The two MSMEs use firewood and LPG in the boiling stage to achieve GWP. Lestari *et al*. (2024) state that the LPG yields a more efficient combustion process because its calorific value is higher and its combustion is more perfect. This can reduce wasted energy compared to firewood. However, there is an increase in the Acidification Potential (AP) and Eutrophication Potential (EP) due to increased NO_x and SO_2 emissions, which can trigger environmental acidification and eutrophication. The acidification calculated in Tempe Pratama and Tempe Murni AMR tends to increase because LPGs, when burned completely, produce lower CO_2 emissions than wood. Nevertheless, burning LPGs produces higher NO_x (nitrogen oxide) and SO_2 (sulfur dioxide) emissions compared to firewood and contributes greatly to the impact of acidification. Eutrophication results in MSMEs Tempe Pratama and Tempe Murni AMR also tend to increase. In this regard, LPG combustion at high temperatures produces higher NO_x emissions compared to firewood which can contribute to more intense eutrophication. This shows that the use of LPG will reduce the environmental impact on GWP due to reduced CO_2 and energy, but other emissions such as NO_x, SO_2 can increase because of fuel, processes, or waste. These outcomes can trigger acidification and eutrophication (Hasan *et al*, 2024; Parameswari *et al*, 2019). These findings demonstrate that improving one environmental impact category does not necessarily improve others. Therefore, sustainability assessment should not rely solely on GWP but should simultaneously consider multiple environmental indicators when evaluating alternative production scenarios.

Accordingly, the primary recommendation of this study is to improve the energy efficiency of the boiling process rather than simply replacing one fuel with another. Strategies such as increasing boiler efficiency, reducing heat losses, optimizing fuel consumption, and implementing appropriate emission-control measures can provide more balanced environmental benefits. Under conditions where firewood combustion is inefficient, LPG may serve as an alternative fuel because of its higher combustion efficiency; however, its application should be accompanied by measures to mitigate NO_x and SO_2 emissions. Consequently, fuel selection should be based on a comprehensive evaluation of trade-offs among greenhouse gas emissions, acidification, eutrophication, and overall process efficiency to achieve a more sustainable production system.

3.8. Recommendation for LCC Improvement

The calculation of the total NPC within an economic period of 5 years in the three tempeh MSMEs marked a comparison per kilogram of the current total cost. Tempe Murni AMRs and Tempe Sumber Mass have a high total NPC value due to high operational costs. High operational costs in Tempe Murni AMRs and Tempe Sumber Mass can be analyzed as controllable costs. Tempe Murni AMR on controllable operational costs are on water sources obtained by using PDAM water in the production process. Tempe Sumber Mas, controllable operational costs are in the milling stage using a gasoline-fueled generator engine and gasoline-fueled generator engine to retrieve its water source.

Table 13. The recommendations for LCC improvements

MSME	Current condition	Recommendation
Tempe Murni AMR	The water source obtained from PDAM water is 300 liters per day.	Water source obtained from drilled wells using an electric water pump.
Tempe Sumber Mas	● The milling machine uses a gasoline-fueled generator with a capacity of 1 liter for 500 kg of raw materials. ● The water pump generator uses a gasoline-fueled generator with a capacity of 2 liters for 500 kg of raw materials.	● Milling process using an electric dynamo ● Water source obtained using an electric water pump

Recommendations for cost improvements in Tempe Murni AMR include changing the water source from PDAM water to a drilled well supplied by an electric water pump. For Tempe Sumber Mas, cost improvements can be achieved by replacing the gasoline-fueled milling machine with an electric dynamo and replacing the gasoline-powered water pump used for supplying water from a drilled well with an electric water pump.

Table 14. LCC comparison of the existing vs. recommended conditions for Tempe Murni and Sumber Mas

Cost Component	Tempe Murni AMR		Tempe Sumber Mas	
	Current Condition	Recommendation	Current Condition	Recommendation
Investment Cost (IDR)	4,725,000	5,625,000	9,275,000	7,875,000
Maintenance Cost (IDR/year)	--	--	420,000	90,000
Operating Cost (IDR/year)	852,468	91,260	2,420,493,245	2,411,281,096
LCC (IDR/kg)	9,226	9,199	10,753	10,168
LCC decrease (%)		0.3		5.4

Table 14 shows the results of the comparison of MSME production costs with recommended improvement. The increase in investment costs in the Tempe Murni AMR is due to changes in water source costs from using PDAM to a drilled well, which require additional costs in the form of drilling and a water pump. Although the investment costs from using a drilled well are slightly more expensive than using PDAM water, the operational costs are more efficient. Febrianti (2019) underlines that the cost of using PDAM water tends to be higher than that of electric water pumps because it requires production, processing, distribution, pipe network maintenance costs, as well as administration and tax costs charged to PDAM consumers. This change potentially decrease the LCC by 0.3%. The recommendation for Tempe Sumber Mas managed to maintain low operational costs by using electric dynamos at the milling stage. This is in line with Bantacut & Indriyani (2022), reporting that electricity costs per kWh are usually lower than gasoline prices per liter in the long term. The LCC for Tempe Sumber Mas can be lowered by 5.4% by implementing recommendation.

The NPC calculation for 5 years shows that the recommendation costs for Tempe Murni AMR are greater than the current condition costs of MSMEs. This is because the investment costs of the recommendations are very high in drilling wells for water, despite the high investment costs, which can lower operational costs. Although operational costs are lower, the NPC can still be higher due to the large initial load and potentially inaccurate analysis (Rodrigues & da Silva 2024). In Tempe Sumber Mas, the recommended use of electric dynamos for the milling process and electric water pumps for water supply is considered more cost-efficient. This is because the cost of electricity is generally lower than the cost of gasoline on an equivalent operational basis, and electricity tariffs per kWh are typically lower than gasoline prices per liter for long-term operations. In addition, electric dynamos generally require less maintenance, whereas gasoline engines require more frequent and costly routine maintenance, including the replacement of oil, filters, and other components (Bantacut & Indriyani, 2022).

Production differences in LCA analysis lead to different measures in reducing global warming potential. In this case, a more thermally efficient production process will reduce the amount of fossil fuels burned per unit of product. In addition, this directly reduces GWP and greenhouse gas emissions (Hartini *et al*., 2024). Differences in production levels in the LCC analysis are directly related to variations in production costs. Rodrigues & da Silva (2024) explain that changes in production can contribute to reducing operational costs, minimizing raw material waste, lowering procurement costs, and improving the efficiency of material utilization.

4. CONCLUSION

The LCA results revealed substantial differences in the environmental performance of the three tempeh MSMEs in Jember. Tempe Pratama (capacity 120 kg soybean) exhibited the highest specific energy consumption of 9.10 MJ/kg soybean and GWP at 1.0317 kg CO_2-eq per kg soybean. The highest impacts for Acidification Potential (AP) and Eutrophication Potential (EP) were observed in Tempe Sumber Mas, at 2.40 g SO_2-eq and 0.39 g PO_4-eq, respectively. These variations reflect differences in production practices and resource utilization among the MSMEs. Economically, life cycle costs also varied considerably, namely 9,226 IDR/kg for Murni AMR, 8,906 IDR/kg for Pratama, and 10,753 IDR/kg for Sumber Mas. The findings highlight the need for cleaner production strategies, particularly improvements in energy efficiency and resource utilization, to reduce environmental impacts while maintaining economic performance. Tempe Pratama and Tempe Murni AMRs are suggested to change the use of fuel in the boiling stage from firewood to LPG to reduce the environmental impact. Tempe Murni AMR also needs to consider reducing high operational costs by replacing the PDAM water source with a drilled well water retrieved using an electric water pump. Likewise, Tempe Sumber Mas is advised to use electric motor at the milling stage electric water pump. Overall, the tempeh MSMEs need to consider the use of more environmentally friendly alternative technologies and fuels, such as switching from firewood to LPG or biogas, to reduce greenhouse gas emissions and other environmental impacts. The LCC analysis results indicate that the tempeh MSMEs should consider sustainable investments to reduce operational and maintenance costs.

AUTHOR CONTRIBUTION

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
NK	✓			✓					✓	✓	✓	✓	✓	✓
MC		✓		✓								✓	✓	
OMQ			✓		✓	✓	✓	✓	✓	✓	✓			

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

DECLARATION ON THE USE OF GENERATIVE AI

During the preparation of this work, the author used the ChatGPT service on a trial basis for data processing and to draft certain sentences within the manuscript. Following the use of this service, the author reviewed and edited the content as necessary and assumes full responsibility for the contents of this publication.

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