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CASE STUDY

Life cycle assessment and life cycle cost of tofu production and its extended recycling scenario

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ABSTRACT

BACKGROUND AND OBJECTIVES: The current literature on tofu production has predominantly focused on exploring the value-added potential of the waste generated during tofu production and conducting impact assessments related to this production. However, a noticeable gap remains in the research concerning the comprehensive examination of life cycle costs and eco-efficiency in tofu production and its associated waste. This study aims to assess the environmental and economic impacts of the implementation of recycling alternatives using a life cycle assessment and life cycle cost approach. The impact of waste recycling on the eco-efficiency of small and medium-sized enterprises in Sugihmanik Village, Grobogan Regency, Indonesia is also examined.

METHODS: To achieve this goal, this study employed life cycle assessment and life cycle cost methodologies to evaluate eco-efficiency. Data were collected through interviews and direct observations. Cradle-to-grave (tofu production) and cradle-to-cradle (tofu production and waste recycling) approaches were compared. Environmental impact was assessed by determining the 12 impact categories. Environmental cost was determined using the eco-cost 2023 method, and environmental and economic impacts were examined with SimaPro software version 9.4.

FINDINGS: Life cycle assessment analysis revealed eutrophication, carbon footprint, and freshwater ecotoxicity to be the categories with the most significant impact for each process. In particular, the eco-cost of the cradle-to-grave approach was 7.03 United States dollars, and that of the cradle-to-cradle approach was 7.90 United States dollars. Life cycle cost analysis yielded a net value of 1.33 United States dollars for the cradle-to-grave process and 38.16 United States dollars for the cradle-to-cradle process. According to the life cycle cost analysis, the recycling scheme increased the overall cost of production. Meanwhile, the eco-efficiency analysis demonstrated an increase in the eco-efficiency of tofu production (cradle-to-grave) and the recycling system (cradle-to-cradle). Waste recycling can increase the eco-efficiency index from 0.18 to 5.

CONCLUSION: Life cycle assessment identified eutrophication, carbon footprint, and ecotoxicity (freshwater) as the three major impact categories. Proper waste management in tofu production offers environmental benefits and significant profits, with the net value of the cradle-to-cradle process at 38.99 US dollars. The eco-efficiency values showed a substantial positive increase, and the waste processing scenarios were found to be sustainable and economically beneficial. These findings suggest new business opportunities through straightforward waste processing and affordable production costs. The scheme also reduces the environmental impact and increases the efficiency and profit of the overall tofu production system.

NUMBER OF REFERENCES
41

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4

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4

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INTRODUCTION

Tofu is preferred by Indonesians because of its affordability and abundant protein content (Zheng *et al.*, 2020). As highlighted by Plamada *et al.* (2023), tofu can be used as an alternative to cheese or milk-based products and as a meat substitute food for vegan. Data on the average per capita tofu consumption for 2021 in Indonesia revealed a weekly consumption of 0.3 gram (g), marking a 3.75 percent (%) increase from the preceding year's 0.293 kilogram(kg), (Hulu, 2023). This uptick aligns with the growth of small businesses and the tofu production industry. Hartini *et al.* (2021) emphasized that the surge in tofu enterprises has positive and negative consequences and fosters augmented income and job prospects, particularly in small- and medium-sized enterprises (SMEs) and the tofu production sector (Ratmono *et al.*, 2023). Conversely, the downside is related to the heightened environmental pollution arising from tofu production (Zheng *et al.*, 2020). Byproducts from tofu production are generated in the form of liquid (wastewater) and solid waste. Wastewater is produced during the stages of soaking, mixing, and tofu molding (Hartini *et al.*, 2021). Ajijah *et al.* (2020) reported that this wastewater contains high amounts of proteins (40% – 60%), fats (10%), and carbohydrates (25% – 50%) and has a biological oxygen demand (BOD) of 6,000 – 8,000 mg/L, a chemical oxygen demand (COD) of 7,500 – 14,000 mg/L, and a pH below 6. Solid waste is produced during cooking, filtering, and frying and constitutes approximately 25% – 35% of total tofu production. In SMEs, solid waste can be derived as tofu dregs, which can be converted to residual biomass for fuel (Hartini *et al.*, 2021). Bahri *et al.* (2021) reported that tofu dregs still contain high levels of nutrients, with 23.62% protein, 7.78% fat, and 65% fiber. When appropriately treated, solid waste (tofu dregs) can be used as a viable food ingredient (Xu *et al.*, 2020). In Indonesia, numerous studies have focused on the treatment of waste from tofu production. The Ministry of Environment and Forestry of Indonesia has highlighted diverse waste management strategies, including source reduction, reuse or recycling, and appropriate waste disposal methods (Budihardjo *et al.*, 2022; Kurniawan *et al.*, 2023). Various waste types that retain fibers, fats, proteins, carbohydrates, minerals, and organic acids have the potential to be transformed into alternative products with economic value (Esteban and Ladero, 2018; Samimi and Nouri, 2023). Many investigations have focused on the treatment of wastewater from tofu production to meet wastewater standards. For example, Zunidra *et al.* (2022) used a biofilter enriched with microorganisms in an anaerobic–aerobic system to treat wastewater containing tofu. Other studies explored the conversion of soy whey (Dai *et al.*, 2023) and wastewater (Nugroho *et al.*, 2019) from tofu production to organic fertilizers, biogas, and digestate (Sari *et al.*, 2021). Researchers also explored ways to elevate the economic value of wastewater while curbing its environmental impact. A promising approach is to transform tofu wastewater into nata de soya (Ropiudin and Syska, 2023). Wastewater shows potential in generating high-fiber nourishment for community consumption (Pérez-Marroquín *et al.*, 2023) because it contains sufficient fats, oils, pigments (Saba *et al.*, 2023), proteins, and carbohydrates (Karlović *et al.*, 2020). Diverse applications for process tofu dregs have also emerged, including the production of swollen tempeh (locally known as *tempe gembus*), animal feed, tofu dregs crackers, soy sauce, flour (Dewilda *et al.*, 2023), and fermented foods (Qiu *et al.*, 2022). Syarifuddin *et al.* (2021) explored the possibility of converting tofu dregs into fish feed. Gultom *et al.* (2021) harnessed tofu dregs to craft tissue paper. Waste recycling is always interesting because it is one of the components to achieve a circular economy and can preserve natural resources. Utilizing the byproducts of tofu production will generate sustainable benefits and circularity impact but great challenges (Colimoro *et al.*, 2023). Food safety is one of the main concerns in the recycling of byproducts, even though it may be simple and environmentally friendly (Pushparaj *et al.*, 2022). In an effort to address environmental pollution, SMEs engaged in tofu production are encouraged to broaden their focus beyond economic growth and undertake environmentally sustainable practices. An instrumental method frequently embraced in tackling environmental issues is eco-efficiency (EE). EE denotes the practice of manufacturing goods and rendering services while minimizing resource consumption, energy usage, costs, and waste generation (Al-Shami and Rashid, 2021; Moghadam and Samimi, 2022). It emphasizes the adoption of diverse environmental enhancement strategies that yield value-added advantages for industrial stakeholders (Mendoza *et al.*, 2019). Research on tofu production has predominantly focused on assessing its environmental ramifications by employing various methodologies, such as life cycle assessment (LCA) and environmental impact evaluation. Kurniawati *et al.* (2019) assessed the process, waste, and emissions released into the environment, with particular emphasis on global warming potential (GWP). Their findings revealed that manufacturing 1 kg of fresh tofu entailed 1.5269 MJ/kg energy consumption and resulted in the emission of pollutants such as carbon dioxide (CO_2), nitrogen oxide (NO_x), carbon monoxide (CO), and methane (CH_4), culminating in a total of 0.1766 kg of carbon dioxide equivalent (kg CO_2eq). These emissions collectively contribute to the overall potential GWP. Sari *et al.* (2021) conducted similar investigations to scrutinize the environmental implications of tofu production in West Jakarta, Indonesia. Their results underscored the notable environmental impact of tofu production with a substantial GWP value of 0.882 kg CO_2eq, constituting a significant portion of the process' overall 0.978 CO_2eq. Mejia *et al.* (2018) evaluated greenhouse gas (GHG) emissions associated with tofu production and showed that 16% of CO_2eq stems from packaging, 52% from tofu manufacturing, 23% from packaging, and 9% from transportation, collectively contributing to the cumulative emissions linked to the production of 1 kg of packaged tofu. This finding indicates that tofu production has a relatively modest GHG effect. Nevertheless, the economic performance and EE of tofu production and its recycling system has never been analyzed. Mendoza *et al.* (2019) highlighted the significance of life cycle cost (LCC) in bridging environmental concerns with economic strategies. This approach is interlinked with EE, which generates value with a minimal environmental impact throughout the lifecycle of a product. Employing LCC, LCA, and EE can shape strategies for environmental enhancement while prioritizing economic advantages (Budihardjo *et al.*, 2023). This viewpoint was supported by Jain *et al.* (2022), who advocated for the confluence of LCC and LCA owing to their complementary nature. Mendoza *et al.* (2019) evaluated economic and environmental benefits in disposable baby diaper production using an environmentally friendly design and revealed an 11% reduction in LCC; EE analysis showed a 7%–170% higher environmental friendliness compared with conventional diapers. Zhang *et al.* (2020) focused on assessing the environmental impact and aiding financial decision-making in PET bottle recycling for blanket production in China and demonstrated that replacing coal with natural gas will significantly reduce environmental impacts and economic burdens. Smith and Lal (2022) investigated the environmental and economic implications of apple juice production in the Northeastern United States and found that the 100% on-site distribution scenario exhibited the lowest carbon footprint at 0.91 kgCO_2eq and 2.31×10^{-3} kg nitrogen oxide equivalent ((NO_x)eq) per 12 ounces of apple juice portion, making it the most cost-effective approach that features a mere USD 1.43 per product while considering capital, fixed, operational, and environmental costs. The integration of LCA and LCC can be used for a comprehensive evaluation of the product lifecycle; however, its role in achieving eco-efficiency in the tofu industry is not yet understood. Drawing upon the outlined challenges and the existing research landscape, this study integrates LCC, LCA, and EE to comprehensively evaluate the economic and environmental aspects of solid and wastewater management in tofu production. The primary goal is to cultivate the development of a circular economy within SMEs operating in the tofu production sector of Sugihmanik Village in Grobogan Regency, Indonesia. The first objective is to assess the environmental impact of tofu production and its recycling alternatives using an LCA approach. The total costs required for waste recycling are estimated using the LCC approach. With Sugihmanik Village as a case study, this research analyzes the impact of waste processing on the enhancement of eco-efficiency in SME tofu production enterprises. By combining these three objectives, this study provides a holistic understanding of the environmental impact, costs, and efficiency of waste processing in tofu production enterprises in Sugihmanik Village. The study was conducted in Sugihmanik Village, Graimobogan Regency, Central Java Province, Indonesia in 2023.

MATERIALS AND METHODS

Several steps were taken to achieve these study aims. Data were collected for LCA and LCC calculations. The LCA for the tofu production and extended scenario consists of several steps, including goal and scope definition, life cycle inventories, life

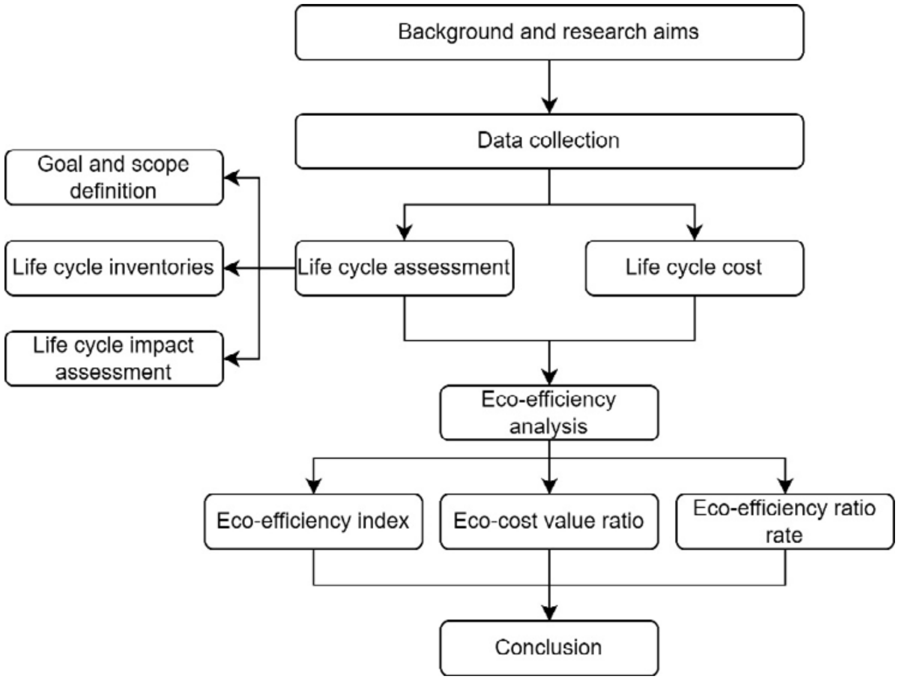

Fig. 1: Methodological framework of the study

cycle impact assessment, and interpretation. LCC calculations were conducted by determining the raw materials, production, transportation, and waste-processing costs. From the LCC and LCA results, EE can be determined by calculating the EE index (EEI), eco-cost value ratio (EVR), and eco-efficiency ratio rate (EER). Several conclusions were drawn from these results. The three main hypotheses were as follows: 1) the addition of waste recycling increases the environmental impact because it adds the number of activities, 2) the waste recycling scheme also increases the cost of production and maintenance, and 3) the recycling scheme in this study has a higher EE than others because of the product produced by the system. The methodological framework of this study is illustrated in Fig. 1. This study had some limitations, including failing to consider the transportation of the waste materials to the recycling facility and the possibility of substituting fuel for cooking and frying. In the case of Sugihmanik Tofu SME, corncobs were used for cooking and rice husk for frying. In the other tofu SMEs, the type of fuel could be different depending on the abundance of resources in the area. This activity may result in different environmental and economic effects in other areas.

Study location profile

Situated within the Tanggungharjo Subdistrict of the Grobogan Regency in Central Java, Sugihmanik Village spans an expanse of 1,286,600 hectares (ha) based on 2020 statistical records. This village is home to eight hamlets with a predominant portion of its population engaged in tofu production. Sugihmanik Village accommodates over 30 SMEs that continue to employ traditional methods for tofu production. On average, each SME yields 150 kg of soybean and consumes 3,000–5,000 L of additional water daily (Hartini *et al*., 2023). The substantial volume of tofu production in Sugihmanik Village is directly linked to considerable waste output. Hartini *et al.* (2021) conducted examinations on tofu wastewater and river water and found that tofu wastewater had BOD ranging 3,667 – 4,933 mg/L, COD ranging 7,668 – 9,736 mg/L, and total suspended solid (TSS) content of 701 – 1,189 mg/L. By contrast, the river water in Sugihmanik Village had a BOD of 367 mg/L and a COD of 738 mg/L. These measurements exceed the wastewater quality standards stipulated by Central Java Provincial Regulation No. 5 of 2012. The management of waste generated by tofu production remains a challenge, particularly the proper disposal of wastewater that poses a threat to the cleanliness of river ecosystems (Mihai *et al.,* 2021). The Ministry of Environment and Forestry of Indonesia highlights that wastewater from tofu production comprises dissolved or suspended solids that can undergo chemical, physical, and biological transformation. These wastewater components contribute to the discoloration and turbidity of river water, causing unpleasant odors and deterioration of river water quality (Hartini *et al.,* 2021). As indicated by these circumstances, the SMEs engaged in tofu production within Sugihmanik Village have not yet fully adopted effective waste management strategies. The SMEs in Sugihmanik Village are still representative of the industries characterized by suboptimal energy efficiency and elevated environmental pollution levels (Kurniawati *et al.,* 2019). From January to September 2021, the prevailing wind direction was from the south. According to data from the Semarang Climatology Station, the wind heading towards Sugihmanik village had speeds ranging from 3.00 – 6.00, accounting for 8.63% of the time, and speeds between 6.00 and 9.00, making up 2.63%. Winds exceeding 9.00 occurred 1% of the time. The highest sunlight duration in 2021 (January – September) was recorded in August, with an average of 8.95 hours per day. The average temperature in Sugihmanik village ranged from 26.71 °C to 29.00 °C, with average humidity levels between 70.6% and 91.4%. Throughout 2021, Sugihmanik has experienced rainfall ranging from 0 to 660 mm per month, which was significantly higher than the Indonesian average of 167 – 250 mm per month. The village of Sugihmanik is situated at elevations varying from 12 m to 60 m above sea level. Eko Budi Tofu SME (−7.097558, 110.616705) is one of the 30 tofu SMEs located in Sugihmanik Village (Fig. 2). This SME was established in 2015 and employs two workers responsible for processing raw soybean materials into fried tofu. Eko Budi Tofu SME typically produces tofu using soybean as the main ingredient, and the resulting tofu products are sold at Ganefo Market in Mranggen and Johar Market in Semarang City. Essentially, the tofu production in Sugihmanik Village is still carried out in a traditional manner with limited resources. Given that their production patterns can be assumed to be similar, this study focused on one SME as a representative of all tofu SMEs in Sugihmanik Village.

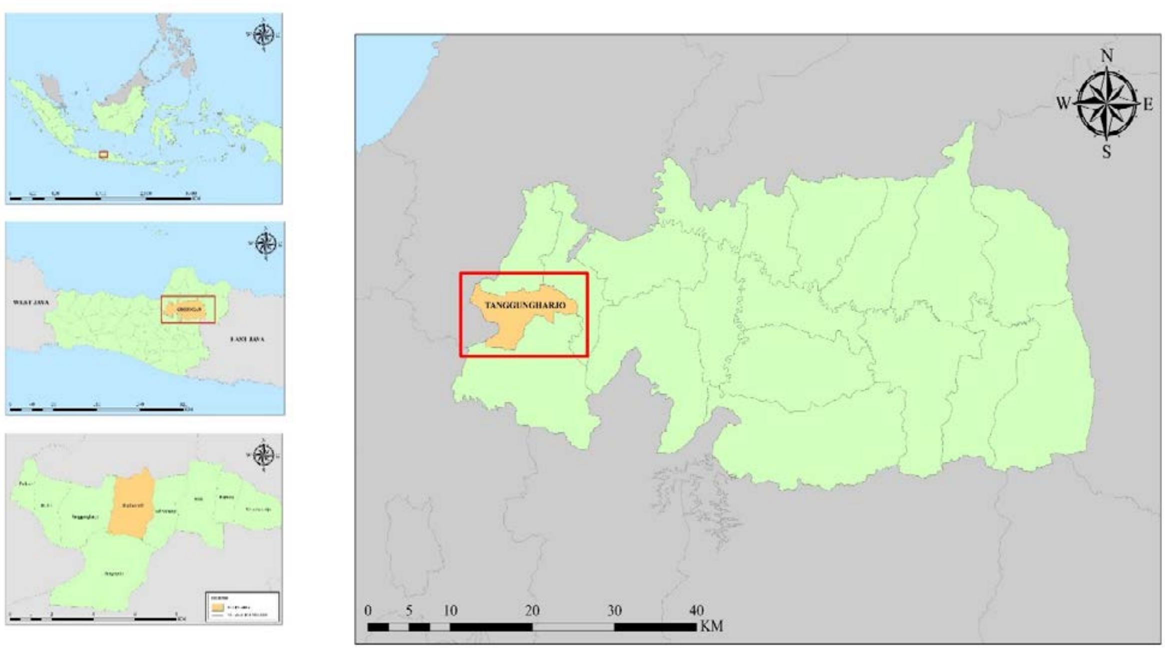

Fig. 2: Geographic location of the study area in Sugihmanik Village in Indonesia

Data collection

Interviews with workers at SMEs tofu production and individuals who could provide information regarding the processing of tofu production waste were conducted to obtain information that will be used to develop the life-cycle inventory for this study. The goal was to gather insights into the process, inputs, outputs, and associated costs that could help address this study problem.

Goal and scope definition

In the initial stage of the LCA, the study objectives and scope were determined. LCA was used to assess the life cycle of the tofu industry and its potential recycling scenario, which can be divided into four products: tofu as the main product and briquettes, swollen tempeh, and nata de soya as secondary or recycling products. This study focused on cradle-to-grave (tofu production) and cradle-to-cradle (tofu production to waste recycling) by examining the materials and energy production chain throughout all stages, from the extraction of raw materials through production, transportation, and use, until the end of the product's life cycle. The functional unit of this study was one batch production of tofu or 9 kg of fried tofu. The first assessment evaluated the existing tofu production process (cradle-to-grave), and several products were assessed as recycling systems. The goal of this step was to identify the environmental impacts and costs (eco-cost) of the tofu production and its waste recycling scenarios. The evaluated system encompassed the tofu production stages, which include soaking, mixing, cooking, filtering, clumping, molding, and frying. In LCA, inputs refer to the raw materials used during production, and outputs refer to the waste generated. Both were measured in units of mass (kg), volume (L), and electricity consumption (kWh). The goal of the second assessment was to identify the environmental impacts and eco-costs from the tofu production to the recycling of the generated waste (cradle-to-cradle). Three products were proposed as recycled and nontofu products. The first evaluated product was the conversion of wastewater to nata de soya, the second was the conversion of tofu dregs to tempeh, and the third was the use of husk charcoal as briquettes. The scope of the study and system boundaries are shown in Fig. 3.

Life cycle inventory (LCI)

In the second stage, the inputs and outputs for each scenario of tofu waste processing were identified. The information required at this stage includes energy requirements, materials used, and waste generated. Using input information from the previous stage, this process was accomplished with the SimaPro software version 9.4. LCI reveals the inputs and outputs associated with the tofu production and waste recycling scenarios as an extension of the conventional production system. The output network LCI diagram provides information about the relationships between each process that generate environmental impacts for the conventional and proposed scenarios. Table 1 lists the data inventories used in the impact assessments. The variable cost data in Table 1 were justified according to the respondents' experiences and best practices.

Life cycle impact assessment (LCIA)

In the third stage, an analysis was conducted to determine the types and magnitudes of the generated impact categories. LCIA uses the eco-cost 2023 method, which consists of four stages: characterization, normalization, weighting, and derivation of a single score. The eco-cost values were obtained from the LCIA stage and used to calculate eco-efficiency. Twelve impact categories were assessed: carbon footprint, acidification, eutrophication, photochemical ozone formation, particulate matter (PM), human toxicity (cancer and non-cancer), ecotoxicity (freshwater), metal scarcity, uranium use, land use, and baseline water stress.

LCC

LCC encompasses all the costs related to the lifecycle of a product spent by one or more stakeholders throughout the lifecycle. These types of costs include those incurred from production until the emergence of a finished product for each scenario of the tofu industry waste processing. Such as raw material, production (equipment), labor, marketing, and waste processing costs for each scenario of tofu production waste processing. Data were processed using the LCC method, which involves calculating the overall cost of tofu production for each scenario of tofu production waste processing. In this study, USD 1 was equal to IDR 15,590. LCC can be calculated using Eq. 1 (Mendoza *et al.*, 2019).

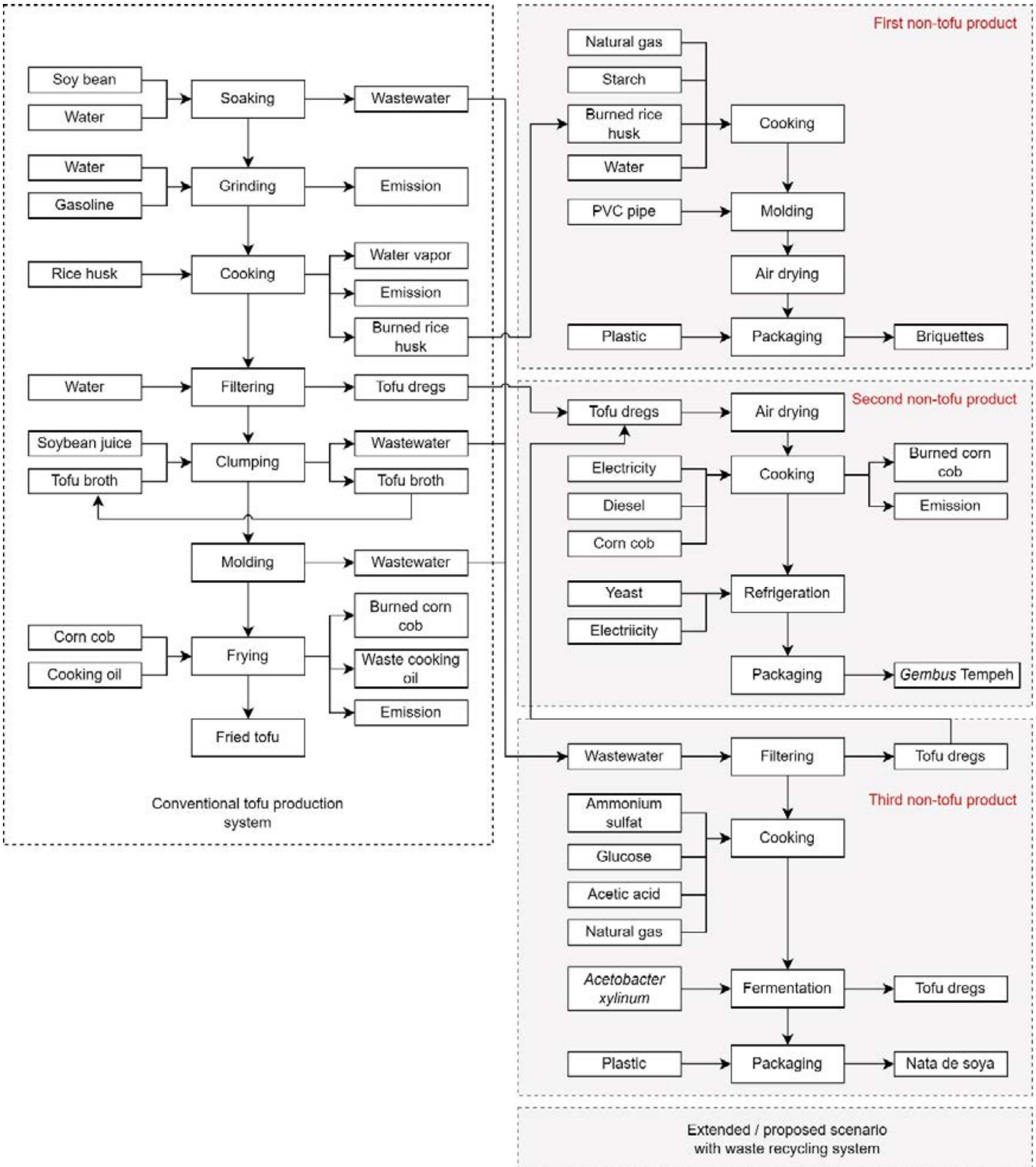

Fig. 3: System boundaries and input–output flow diagram

$$LCC = CRM + CM + CT + CWM, \quad (1)$$

where CRM is the raw material cost, CM is the product manufacturing cost, CT is the transportation cost, and CWM is the waste treatment cost. The net value calculation used for the subsequent eco-efficiency calculations employed in Eq. 2 (Hartini *et al*., 2021).

$$Net\,Value = Selling\ Price - Production\,costs \quad (2)$$

According to Hartini *et al.* (2021), the net value is the disparity between selling price and production costs. In the present study, the net value was determined via cost–benefit analysis based on the following assumptions for each scenario: 5 working hours daily, 25 days monthly, 90 L of wastewater,

Table 1: LCI and input–output amount

Process unit	**Input components (unit)**	**Amount**	**Output components**	**Amount**
			Conventional tofu production system	
Soaking	Soy bean (kg)	5	Soy bean (kg)	9
	Water (L)	12	Wastewater (L)	8
Grinding	Water (L)	14	Soy bean juice (kg)	23
	Gasoline (L)	0.13		-
	Soy bean (kg)	9		-
Cooking	Water (L)	60	Tofu porridge (kg)	79
	Rice husk (kg)	6.5	Water vapor (kg)	4
	Soy bean juice (kg)	23	Burned rice husk (kg)	1.6
Filtering	Water (kg)	30	Tofu dregs (kg)	10
	Tofu porridge (kg)	79	Soybean juice (kg)	99
Clumping	Soybean juice (kg)	99	Wastewater (L)	76
	Tofu broth (L)	23	Tofu juice (kg)	23
			Tofu broth (L)	23
Molding	Tofu juice (kg)	23	Wastewater (L)	14
			Raw tofu (kg)	9
Frying	Cooking oil (L)	0.9	Waste cooking oil (L)	0.3
	Corn cob (kg)	3.7	Burned corn cob (kg)	0.9
	Raw Tofu (kg)	9	Fried tofu (kg)	9
				Extended scenario
				Briquettes
Cooking	Water (L)	0.5	Raw material of briquettes (kg)	2.6
	Starch (kg)	0.5		
	Burned rice husk (kg)	1.6		
	Natural gas (kg)	0.1		
Drying	Raw material of briquettes (kg)	2.6	Briquettes (kg)	2.6
Packing	Briquettes (kg)	2.6	Briquettes (kg)	
	Plastics (kg)	0.0625		
				Swollen Tempeh
Drying	Tofu dregs (kg)	10	Wastewater (L)	1
			Tofu dregs (kg)	9
Cooking	Tofu dregs (kg)	9	Raw material of swollen tempeh (kg)	9
	Corn cob (kg)	2		
	Electricity (kWh)	0.03		
	Gasoline (L)	0.025		
Refrigeration	Raw material of swollen tempeh (kg)	9	Swollen tempeh (kg)	9.075
	Yeast (kg)	0.075		
	Electricity (kWh)	0.12		
Packing	Swollen tempeh (kg)	9.075	Swollen tempeh (kg)	9.32
	Plastic (kg)	0.25		
				Nata de Soya
Filtering	Wastewater (L)	90	Wastewater (L)	89
			Tofu dregs (kg)	1
Cooking	Wastewater (L)	89	Raw material of nata de soya (kg)	92.6
	Ammonium sulfate (kg)	0.45		
	Glucose (kg)	2.25		
	Acetic acid (L)	0.9		
	Natural gas (kg)	0.1		
Fermentation	Raw material of nata de soya (kg)		Nata de soya (kg)	93.5
	Acetobacter xylinum (kg)	0.9		
Packing	Nata de soya (kg)	93.5		
	Plastic	0.25		

Table 2: LCC inventory recapitulation

Component	Existing condition (USD)	Full extension (USD)	Existing + briquettes (USD)	Existing + swollen tempeh (USD)	Existing + nata de soya (USD)
Raw materials cost	4.60	21.83	4.89	5.45	20.64
Production cost	0.67	1.52	0.94	0.95	0.98
Transportation cost	0.46	1.48	0.74	0.99	0.74
Waste processing cost	15.39	-	-	-	-
Total cost	21.12	24.83	6.57	7.39	22.36

1.6 kg of solid waste (rice husk charcoal), and 10 kg of solid waste (tofu residue) per tofu production. Material costs were assessed by multiplying the material unit price by the quantity used, and material quantity was determined through direct observation and interviews. Equipment costs, which are incurred to support production, were calculated by multiplying the equipment cost by the number of units, and labor costs (i.e., operator count and batch wage cost). Overhead costs, including electricity and equipment depreciation, are considered additional costs. Marketing costs, including vehicle, fuel, and vehicle depreciation, account for the production cost. Table 2 presents the recapitulation of the LCC inventory.

EE

The EVR is used to determine the ratio of eco-cost to the net value generated by a product. Its output provides the ratio between the eco-cost and net value. This ratio helps to assess the environmental cost in relation to the economic value of a product or process, offering insights into the sustainability and efficiency of the system being analyzed. The final stage of data processing in this study involved calculating the output results from the LCA and LCC methods for tofu production waste processing scenarios. The EEI, EVR, and EER were calculated using Eqs. 3 to 5 (Hartini *et al*., 2021).

$$EEI = (Net\,Value)/(Eco\,Cost) \quad (3)$$

$$EVR = (Eco\,Cost)/(Net\,Value) \quad (4)$$

$$EER = (1 - EVR) \times 100\% \quad (5)$$

RESULTS AND DISCUSSION

Interpretation of LCIA

Tofu production can generate waste that may contribute to environmental degradation. As it is found in this study, 9 kg of tofu can generate 10 kg of tofu dregs, 98 liter of wastewater, and 1.6 kg of burned rice husk, 0.3 L of waste cooking oil, and 0.9 kg of burned corn cob. In this study, only three wastes were recycled, which were determined based on the possibility of a recycling system that can be developed in the area. Almost all tofu dregs, wastewater, and burned rice husks can be recycled without further waste. During tofu waste production, several direct emissions from grinding, cooking, and frying were recorded (Fig. 3). This study identified the significant environmental impacts in various categories. For instance, the carbon footprint category showed the highest impact on the production of tofu and conversion of wastewater to nata de soya. This process resulted in an emission of 3.955 kg CO_2eq, with the individual tofu production and waste processing phases contributing 2.03 and 2.434 kg CO_2eq, respectively. The acidification category had the most significant impact on the use of wastewater in production and conversion processes. The highest acidification impact was observed at 0.43 moles hydrogen ion equivalent (mol H^+eq), with distinct contributions from the tofu production and waste processing stages. Eutrophication analysis underscored that wastewater processing from tofu production to nata de soya conversion had the greatest impact of 4.6 kg of phosphate equivalent (PO_4eq). By contrast, the processing of rice-husk charcoal waste into briquettes demonstrated the lowest impact at 0.06 kg PO_4eq. The photochemical ozone formation category had the largest impact on tofu production to wastewater conversion into nata de soya, amounting to 0.406 kg of nonmethane volatile organic compound equivalents (NMVOC-eq). Similarly, particulate matter emissions showed the highest impact on tofu production to wastewater conversion to nata de soya (0.256 kg $PM_{2.5}$). The

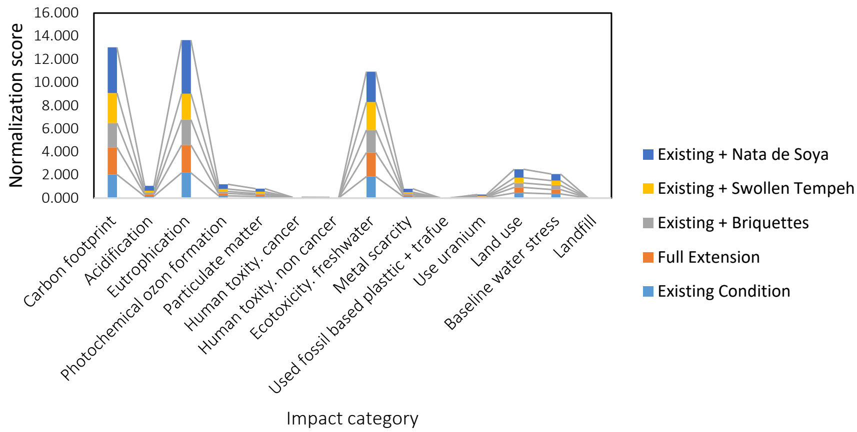

Fig. 4. Impact assessment results of existing condition vs. extended scenario

human toxicity category had the greatest impact on processing tofu waste for wastewater conversion (0.0159 comparative toxic units for humans (CTUh) for cancer and 0.016 CTUh for noncancer). In the freshwater ecotoxicity category, significant impacts were observed on tofu production waste to wastewater conversion to nata de soya (2.618 CTU-eq). Conversely, the lowest freshwater ecotoxicity impact was observed in the conversion of rice husk charcoal waste to briquettes (0.53 CTU-eq). The categories of metal scarcity, uranium use, land use, and baseline water stress were also explored for their respective environmental impacts with varying levels of significance (Fig. 4).

LCC assessment results

The calculations yielded the following LCC figures: USD 21.12 for the cradle-to-grave tofu production and USD 24.83 for the processes from tofu production to waste recycling (wastewater and solid waste). The highest LCC was attributed to the cradle-to-cradle process or waste recycling scenario. The high cost of waste recycling was primarily attributed to cumulative expenses from the derivation of the three nontofu products. The second highest cost was associated with waste processing in the production of nata de soya, owing to the significant wastewater portion in the tofu production (60%) and the use of costly starter bacteria, *Acetobacter xylinum*, during fermentation. The high eco-cost for the recycling system indicates a higher production cost for developing the recycling scenario. However, the environmental cost is even higher when no recycling system is applied, which is not good and efficient for the environment. This assertion was supported by Mendoza *et al.* (2019), who emphasized that raw materials constitute over 85% of the total product costs, followed by transportation and waste management at 7% and 3%. Manufacturing accounted for only 2% of the overall cost. After the LCC was obtained, the subsequent step involves calculating the net value for each process, which is pivotal for deriving the EEI. Net value calculations were USD 1.33 for cradle-to-grave and USD 38.99 for cradle-to-cradle tofu production and waste recycling. Table 3 presents the comparison results of eco-costs for the scenarios evaluated in this study.

EEI results

The EEI values categorized the products as follows. The processes of tofu production (cradle-to-grave) and the tofu production to solid waste processing (rice husk charcoal to briquette scenario) are deemed affordable and unsustainable. Conversely, the processes from tofu production to waste recycling, such as the conversion of wastewater to nata de soya, solid waste (tofu residue) to swollen tempeh, and solid waste (rice husk charcoal) to briquettes, fall under the category of affordable and sustainable. “Affordable” signifies economic efficiency and profitability, and “sustainable” implies that the production process has minimal environmental impact. The tofu production process lacks sustainability owing to factors such as the direct discharge of wastewater into rivers, accumulation of rice husk and tofu residue waste, electricity consumption for water pumps, and

Table 3: Eco-cost results comparison between scenarios (in USD)

No.	Impact Category	Existing condition	Full extension	Existing + briquettes	Existing + swollen tempeh	Existing + nata de soya
1	Carbon footprint	1.910	2.204	1.980	2.453	3.723
2	Acidification	0.129	0.160	0.133	0.164	0.405
3	Eutrophication	2.057	2.253	2.071	2.109	4.363
4	Photochemical ozone formation	0.169	0.198	0.160	0.206	0.382
5	Particulate matter	0.122	0.139	0.105	0.148	0.241
6	Human toxicity. cancer	0.008	0.009	0.009	0.010	0.015
7	Human toxicity. non cancer	0.007	0.008	0.007	0.009	0.015
8	Ecotoxicity. freshwater	1.739	1.952	1.838	2.286	2.464
9	Metal scarcity	0.107	0.126	0.113	0.127	0.274
10	Used fossil based plastic + trafue	0.000	0.000	0.000	0.000	0.000
11	Use uranium	0.039	0.047	0.038	0.050	0.107
12	Land use	0.411	0.446	0.359	0.433	0.690
13	Baseline water stress	0.331	0.360	0.349	0.368	0.543
14	Landfill	0.000	0.000	0.000	0.000	0.000
Total		7.029	7.902	7.162	8.362	13.222

resulting emissions. Inadequate waste disposal can result in harmful environmental impacts (Hartini *et al*. 2023). The evaluation demonstrated that the primary environmental impacts of the tofu production include carbon footprint, eutrophication, and ecotoxicity (freshwater) (Hartini *et al*., 2021). Similarly, the processes from tofu production to solid waste treatment (rice husk charcoal to briquette scenario) are unsustainable owing to several factors. First, the significant environmental impact of the initial tofu production influences the overall waste treatment. This assertion was further substantiated by the calculated EEI value for solid waste treatment when separated from the tofu production, which falls within affordable and sustainable categories. Second, the environmental expenses surpass the product profits. The limited net value stems from the fact that a single tofu production cycle produces 1.6 kg of rice husk charcoal waste out of 101 kg of waste. The profit or net value from converting solid waste (rice-husk charcoal) to briquettes (rice-husk charcoal to briquette scenario) does not adequately cover the requisite environmental costs. This finding was aligned with the study of Zuraida *et al.* (2022), who asserted that the environmental impact of a production process leads to high eco-costs borne by the company. Beyond potential unsustainability stemming from environmental impacts, production costs also shape a product's sustainability. High production costs are correlated with reduced process efficiency and potential for an unsustainable product.

EVR results

Table 4 indicates that the tofu production exhibited a relatively high EVR of 5.3. Its ecological dimension amounted to USD 7.03, and its economic dimension amounted to USD 1.33. The elevated EVR values for the processes from tofu production to converting rice husk charcoal to briquette stem from the eco-costs being two to five times higher than the net value, indicating inefficient production practices that result in negative environmental consequences. In general, a low EVR indicates an improved feasibility and suitability for product manufacturing. By contrast, the extension scenarios in this study displayed EVR values below 1, indicating their suitability for production. This result concurred with the study of Vogtlander *et al.* (2017), who stated that a small EVR signifies good suitability and feasibility for product manufacturing because enhanced production efficiency leads to diminished adverse environmental impacts.

EER results

Table 4 shows that the EER for the tofu production exceeded 100%, suggesting that the process falls short of satisfying the ecological and economic aspects. This finding aligned with the study of Hartini *et al.* (2021), who asserted that an EER value surpassing 100% indicates that the net value is inferior to environmental impact costs (eco-costs). To

Table 4: Eco-efficiency comparison

Assessment	Existing condition	Full extension	Existing + Briquettes	Existing + Swollen Tempeh	Existing + Nata de Soya
Eco cost (USD)	21.12	24.83	22.36	9.29	6.57
Net value (USD)	1.33	38.99	28.95	9.29	3.37
Eco-efficiency index	0.18	5	2.1	1.1	0.4
Eco-cost value ratio	5.3	0.2	0.4	0.9	2.1.
Eco-efficiency ratio rate	-430%	80%	60%	10%	-110%

enhance the EER of a product, either the net value must increase or the cost factors encompassing production and environmental costs (eco-costs) must decrease. Conversely, a decline in EER was observed for the processes from tofu production to proper waste processing for solids and wastewater. Initially at −430%, this shift in EER signifies that comprehensive waste recycling contributes to economic and environmental efficiency enhancement.

Overall results and significant findings

This study focused on the transformation of tofu production waste or recycling of tofu waste into several products or resources such as nata de soya, swollen tempeh, and briquettes. According to literature, GHG emissions from tofu production vary significantly. This study estimated 0.4 kg CO_2e which is lower than those from other analyses at approximately 1.0 kg CO_2e (Mejia *et al*., 2017) to 1.9 kg CO_2e (Blonk *et al*., 2008) per kg of tofu production. The differences in the estimation of GHG emissions are attributed to several factors, including the type of allocation method used (economic vs. attributional); inclusion of additional elements such as transportation to retailers, cooking, and waste disposal; differences in technology; and climatic conditions (Mejia *et al*., 2017). The forecasting result has a different pattern from the findings of Rosyidah *et al.* (2020), who found a high impact from human health, ecosystem quality, and resources. This difference in estimation is attributed to several reasons, including the use of different impact categories and characterization methods, and different assumptions on the material used for cooking and frying.

The high value of the eutrophication category is responsible for the excessive richness of nutrients in the water body, which leads to dense growth of plant life and aquatic animals due to a lack of oxygen. Tofu production, which produces an exceedingly high amount of wastewater, can contribute to high nutrients in the water body (Saba *et al.*, 2023). Regarding the carbon footprint, the GHG emissions from tofu production are high, indicating that tofu production has a high carbon footprint accumulating from its various processes such as frying and cooking and other activities that contribute to GHG emissions (Budihardjo *et al.*, 2023). Freshwater ecotoxicity refers to the potential for biological, chemical, and physical alterations in freshwater ecosystems. Tofu production has significant implications for freshwater ecosystems (Mendoza *et al.*, 2019). This study found that waste can be used to create a circular economy and sustainability in food processing by building a beneficial circular economy model. These alternative waste recycling techniques are simple, affordable, and available locally. The establishment of business-centered activities that focus on handling waste products could significantly boost the local economy. These businesses can be operated individually or by local communities to obtain value from the waste materials. An estimated net profit of USD 38.99 per tofu production can be scaled up to over USD 962.16 per day on the daily capacity of each tofu SMEs. This study highlighted the principles of a circular economy, which converts waste output into valuable input for a new process. This approach can generate economic value and promote sustainable waste reduction. Expanding the recycling model to include additional SMEs may enhance the environmental and economic benefits on a large scale (Zhang *et al*., 2020). In addition, LCA could be broadened to include the entire life cycle, encompassing a comprehensive range of inputs such as land use and environmental consequences. Directly comparing tofu with other foods, especially those that tofu might partially replace, would enhance the usefulness of this study. Expanding the analysis to include the health impacts of tofu consumption would also be beneficial. In summary, this study utilized a thorough, up-to-date, validated, original, and distinctive dataset obtained from a leading tofu producer in the United States. LCA from the point of cultivation to factory exit demonstrated that tofu, a protein-rich plant-based food, is associated with relatively low GHG emissions (Mejia *et al*., 2017).

CONCLUSION

This study provides an alternative for processing tofu production waste, which has been a problem for the community around Sugihmanik Village. The suggested waste processing alternatives are easy to understand, simple to execute, use materials readily available to the community, and most importantly, are relatively affordable. Their availability opens up new business ideas for the people around Sugihmanik Village by utilizing tofu production waste, which was previously discarded directly into the environment (waste), as the main material (resource). The establishment of new businesses related to tofu production waste processing will undoubtedly boost the local economy by adding value to this previously considered waste. The results of this study also illustrate that tofu production waste processing can yield higher profits than simply disposing of tofu production waste into the environment without proper processing. The net profit or earnings generated from the processing of tofu waste into three products—nata de soya, swollen tempeh, and briquettes—is USD 38.99 in one tofu production process. With a daily tofu production capacity of 30 times, this profit can reach over USD 962.16 per day from tofu production waste processing efforts. This study applies the concept of a circular economy by utilizing the outputs from tofu production process, such as liquid and solid waste, which were previously considered waste, as inputs (resources) for the subsequent process. The process involves treating waste using three waste recycling paths, resulting in the production of nata de soya, swollen tempeh, and briquettes. These products are then ready to be distributed to the community with added value from each waste product. This principle allows the reuse of waste from a process, creating a sustainable loop in resource utilization. LCA calculations revealed eutrophication, carbon footprint, and ecotoxicity (freshwater) to be the three largest impact categories for each process. According to the results of the eco-cost 2023 analysis, the eco-cost values for tofu production (cradle-to-grave) and extension scenarios were USD 7.03 and USD 7.90. LCC calculation showed that the largest LCC value originated from the recycling scheme, amounting to USD 24.83. The net value or profit generated from tofu production for overall waste processing was USD 38.99. The high net value or profit obtained from the cradle-to-cradle process reinforces that proper waste management during tofu production can yield substantial profits while reducing the negative environmental impacts of tofu production waste. The calculated eco-efficiency values from the conventional tofu production and the extended recycling scheme indicated a significant positive increase in EEI from 0.18 to 5. Waste processing scenarios involving nata de soya, swollen tempeh, and briquettes fell into the affordable and sustainable category. This finding suggested that the waste processing products from this study are suitable for recommendation because of their ability to enhance economic value and reduce environmental impact. Considering the simple waste-processing process, easily accessible materials, and affordable production costs, this scheme could potentially open new business opportunities for the community. Future studies should consider the impact assessment and environmental costs of processing tofu production waste in various scenarios and compare it with alternative methods, such as converting liquid waste into soy sauce and liquid fertilizer and processing solid waste (tofu dregs) into flour and crackers. Owing to its environmental and economic benefits, this recycling system should be endorsed for application to all SMEs to help determine which tofu production waste processing method has the lowest environmental impact and highest economic value enhancement.

AUTHOR CONTRIBUTIONS

S. Hartini performed the experimental design, analyzed and interpreted the data, prepared the manuscript text and edition. A.N. Fatliana performed the literature review, experimental works, compiled the data, and data analysis. N.U. Handayani helped in the data collection, literature review and manuscript preparation. Wicaksono P.A. contributed to the data analysis, prepared the manuscript text, and interpreted the results. B.S. Ramadan drafted the manuscript, reviewed the final version of the manuscript, and developed the experimental design.

T. Matsumoto reviewed the results and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
°C	Degree of Celsius
BOD	Biological oxygen demand
CH_4	Methane
COD	Chemical oxygen demand
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CTUh	Comparative toxic unit for human
EE	Eco-efficiency
EEI	Eco-efficiency index
EER	Eco-efficiency ratio rate
Eq.	Equation
EVR	Eco-cost value ratio
Fig.	Figure
GHG	Greenhouse gas
g	Gram
GWP	Global warming potential
ha	Hectare
kg	Kilogram
$kg\ CO_2eq$	Kilogram of carbon dioxide equivalent
kWh	KiloWatt hours
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventories
LCIA	Life cycle impact assessment
mm	Milimeter
mg/L	Miligram per liter
MJ/kg	Mega Joule per kilogram
$Mol\ H^+eq$	Moles hydrogen ion equivalent
NMVOC-eq	Non-methane volatile organic compound equivalents
NO_x	Nitrogen oxide
$(NO_x)eq$	Nitrogen oxide equivalent
PM	Particulate matter
PO_4eq	Phospate equivalent
SMEs	Small- and medium-sized enterprises
TSS	Total suspended solids
USD	United States Dollar

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