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PRODUCTION ENGINEERING ARCHIVES 2023, 29(4), 452-460

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at https://pea-journal.eu

Framework for Increasing Eco-efficiency in the Tofu Production Process: Circular Economy Approach

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Article history
Received 13.07.2023
Accepted 04.09.2023
Available online 30.10.2023

Keywords
Circular economy
Environmental impact
Eco-efficiency
Life cycle assessment
Tofu wastewater

Abstract
This research aims to design recommendations for improving the tofu production process in Sugihmanik Village. Over 30 tofu small medium enterprises (SMEs) generate solid and liquid waste, which pollutes the river. An eco-efficiency strategy was implemented and began by identifying the tofu production process. The life cycle assessment (LCA) method and the SimaPro software were used to calculate eco-cost and eco-efficiency levels. Based on the calculations, the eco-cost value per batch is USD 10.76. If 30 batches are produced daily, the eco-cost value in one of the tofu SMEs is USD 9.10. Tofu production has an eco-efficiency index (EEI) value of 0.12. This value shows that tofu products are only affordable but have yet to be sustainable. The researchers then recommend using biogas from wastewater treatment to replace rice husks and corncobs. This study also develops a circular economy framework in the tofu production system. The output is expected to suppress the discharge of water and solid waste to increase the EEI value of the tofu production process in the future.

DOI: 10.30657/pea.2023.29.50

1. Introduction

Tofu production produces solid and liquid waste, which can negatively impact the environment if not correctly handled. Solid waste from filtering can be used as animal feed and raw food materials. Other solid waste in the form of burnt husks can be used as organic fertilizer (Faisal et al., 2016), but much of it is still disposed of. Meanwhile, liquid waste from washing, boiling, pressing, and moulding tofu that is disposed into rivers without treatment can contain high levels of organic compounds, high levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and Pha (Hartini et al., 2021a), which can produce biogas through anaerobic processes (Faisal et al., 2016). However, many small and medium-sized enterprises (SMEs) in the tofu industry need more resources or technology to properly treat their liquid waste, leading to water pollution and other environmental issues. Public awareness of the importance of waste treatment also contributes to this problem.

The tofu production industry in Sugihmanik Village, Tanggungharjo, Grobogan, Indonesia, is causing high water pollution due to the inadequate treatment of liquid tofu waste. More than 30 tofu production houses have an average capacity of around 150 kg of soybeans/day/SMEs. The total amount of soybeans produced into tofu is 4 tons/day, and which tofu production process produces wastewater that is discharged into the river without going through processing. Laboratory tests have shown that the BOD and COD levels in the liquid waste from tofu production far exceed the threshold levels specified by local regulations (Regulation of Central Java Province No. 5 of 2012). The river laboratory test showed that the BOD content was 367 mg/L and COD was 738 mg/L (Hartini et al., 2021a). This high level of organic content in the river water leads to anaerobic conditions and the formation of ammonia, carbon dioxide, acetic acid, and methane, which can cause unpleasant odours and water discolouration. This water pollution is also impacting agricultural productivity in the area. These findings indicate that the tofu industry in this region is a significant source of environmental pollution (Kurniawati et al., 2019).

Evaluating the eco-friendliness of tofu production can aid in identifying ways to enhance sustainability and provide companies with a deeper understanding of the environmental impact of their products. Eco-efficiency measures a company's ability to produce goods and services while minimizing the environmental impact of its operations (Zielińska-Chmielewska et al., 2021). By understanding and improving the eco-efficiency of the tofu production process, companies can help ensure that their products are produced sustainably. Additionally, consumers with high environmental awareness are increasingly looking for products that are produced in an eco-efficient way (Pagan & Prasad, 2007; Poczta-Wajda & Sapa, 2020). By improving the eco-efficiency of tofu production, businesses may be able to attract and retain environmentally conscious customers.

2. Literature review

2.1. Eco-efficiency in small and medium enterprises

Efficiency has become an interesting topic of research in a wide range of production activities (Susanty et al., 2015). Eco-efficiency is a term that describes the practice of using natural resources efficiently and reducing the negative environmental impact of production and consumption (Zielińska-Chmielewska et al., 2021). This concept was introduced in 1991 by the World Business Council for Sustainable Development (WBCSD), which defined eco-efficiency as the ability to deliver goods and services at competitive prices while minimizing environmental impact throughout the entire life cycle of a product or service (WBCSD, 2006). The goal of eco-efficiency is to create more value while using fewer resources, such as materials and energy (Vásquez-Ibarra et al., 2020). This can be achieved by developing innovative technologies and processes that reduce waste and pollution and using renewable resources and energy-efficient practices.

Eco-efficiency is often seen as a way for businesses to balance economic and environmental performance and sustainably promote growth and competitiveness. By adopting eco-efficient practices, companies can reduce their environmental footprint and improve their financial performance, creating a win-win situation for both the environment and the business (Heikkurinen et al., 2019). Efficiency is crucial for achieving sustainable development and creating a more sustainable and equitable future.

In developing countries, eco-efficiency can be particularly useful for small and medium-sized enterprises (SMEs) like Venezuela in public administration (Fernández-Viñé et al., 2013), Mexico in a plastic manufacturer (Besné et al., 2018), and Vietnam in coffee production (Ho et al., 2018), as these companies often lack the resources and technological capabilities of larger organizations. By implementing eco-efficient practices, SMEs can save money on raw materials, energy, and other inputs, avoiding repetitive activities, and reducing their environmental impact (Vásquez-Ibarra et al., 2020). This can help to make these businesses more competitive and sustainable in the long run. Eco-efficiency can also help customers identify products and services that have a lower environmental impact and can help farmers and other businesses in the construction industry (Tatari and Kucukvar, 2012), and the mining industry (Catarino et al., 2016), besides biodiesel (Hartini et al., 2020), agriculture (Ho et al., 2018), and petrochemicals (Besné et al., 2018; Catarino et al., 2016; Changwichan et al., 2018; Ho et al., 2018; Tatari and Kucukvar, 2012) implement sustainable management systems. By using eco-efficiency metrics, businesses can differentiate themselves from competitors and demonstrate their commitment to sustainability, which can attract environmentally conscious consumers (Müller et al., 2015). Some of the methods used are data envelopment analysis (DEA), life cycle assessment (LCA), life cycle costing (LCC), statistical approach, sustainable value methodology (SVM), and carbon footprint, the details of which can be seen in Table 1.

Table 1. The method used in eco-efficiency

Author	Country	Sector	Method
Tatari and M. Kucukvar (2012)	USA	Construction material	DEA, LCA, and LCC
Fernandez et al (2013)	Venezuela	Public administration	Statistical approach
Catarino et al (2015)	Portuguese	Mining (marble sector)	SVM
Muller et al. (2015)	New Zealand	Farming	Carbon footprint
Bonfiglio et al (2016)	Italy	Farming	DEA
Ho et al. (2017)	Vietnam	Coffee production	DEA
Besne et al. (2018)	Mexico	A plastic product	LCA and fuzzy logic
Changwican et al (2018)	Thailand	Bioplastic	LCA
Hartini et al. (2020)	Indonesia	Biodiesel production	LCA

2.2. Measuring eco-efficiency in food processing enterprises

The Organization for Economic Co-operation and Development emphasizes the importance of using resources efficiently to meet human needs and suggests that eco-efficiency can be improved by either increasing output while keeping environmental impact constant or reducing environmental impact while maintaining the same output level. There are several indicators for measuring eco-efficiency in food processing enterprises (Zielińska-Chmielewska et al., 2021), shown in Table 2. Several methods can be used to measure eco-efficiency with its advantages and constraints. One of the popular analytical tools for measuring a product or service's environmental impact based on a process's input-output is the life cycle assessment (LCA) used in this study. It allows businesses to identify areas where they can improve their eco-efficiency and make more sustainable choices. Using LCA, businesses can assess the environmental impact of all their resources, from raw materials to energy and waste disposal. This can help them make informed decisions about reducing their environmental impact and improving their eco-efficiency. There are four phases of LCA studies defined in the ISO14040 standard: 1. Definition of objectives and scope phase, 2. life cycle inventory analysis (LCI) phase, 3. life cycle impact assessment (LCIA), 4. interpretation phase (Hartini et al., 2020, 2019; Prastawa and Hartini, 2019; Hartini et al., 2021b).

Table 2. Several indicators used to measure the Eco-efficiency index

Specification	Main Indicator	Supplementary Indicators
Energy	An energy meter shows the amount of energy used within the project from all sources, measured in megajoules [MJ].	Life cycle energy intensity, excess energy intensity, transportation energy of materials/energy, transportation energy of personnel
Waste	The indicator counter can be calculated as the difference between the weight of materials input into the project and the weight of materials in the final product or as the total mass of wasted, emitted into the air or water, stored, or recycled.	Waste utilization indicator
Water	The indicator is measured in cubic meters [m3]. It does not include the water content of raw materials or precipitation such as rain or snow.	Water discharge intensity Water consumption
Pollutant dispersion indicators	It is one of the most used meters of eco-efficiency indicators, which are greenhouse gas emissions (total CO_2 equivalent emissions, including those from energy and waste management), acid rain precursors, smog precursors, and ozone depletion	

2.3. Eco-efficiency index

Calculating the eco-efficiency level starts with cost-benefit analysis, eco-efficiency index, and eco-cost value ratio. A cost-benefit analysis was performed to evaluate the overall financial worth of the product. The net value is calculated by subtracting the costs of producing the product, including materials, labour, energy, and overhead, from the selling price of the product (Equation 1). This helps the company determine the overall value of the product.

The eco-efficiency index (EEI) is a product feasibility measure developed by Vogtlander (2010). It is a strategy for using natural resources that combines economic and ecological efficiency concepts (Hartini et al., 2020; Hartini et al., 2021b, 2021c; Purwaningsih et al., 2020; Vogtlander et al., 2017). EEI is calculated by dividing the net value by eco-cost (Equation 2). When a product's EEI exceeds 1, it signifies that the net value generated surpasses the environmental costs incurred. In other words, the product's economic benefits are sufficient to offset the associated environmental expenses. Therefore, the product is said to be affordable and sustainable. Conversely, suppose the product has an EEI of less than 0. In such a scenario, the product incurs a loss, making it both unaffordable and unsustainable. When a product falls within an EEI range of 0 to 1, it is economically profitable. However, the profit generated is insufficient to offset the environmental costs associated with the product. Consequently, the product is considered affordable but not sustainable. (Lee et al., 2011).

$$\text{Net Value} = \text{Selling Price} - \text{Cost} \quad (1)$$

$$\text{EEI} = \text{Net Value} / \text{Eco-cost} \quad (2)$$

Eco-cost is a measure that assesses the environmental impact of a product based on the costs associated with reducing pollution and depletion of resources to levels the environment can sustain. These costs, which are referred to as "hidden obligations" or "external costs" in environmental economics (Vogtlander et al., 2017), are calculated using a life cycle assessment approach and specialized software such as SimaPro. The calculation considers the materials, energy, and waste used in producing the product (Margono and Sharma, 2006; Prastawa et al., 2018). The Eco-Value Ratio (EVR) is a measure of eco-efficiency that reflects the environmental impact of a product concerning its economic value. It is a dimensionless number that represents the balance between economic benefit (profit) and environmental protection (planet), as well as the inclusion of social considerations (people) in the Triple P model (Hartini et al., 2019; van der Velden and Vogtländer, 2017). This metric assesses a product's eco-efficiency and overall contribution to environmental and economic sustainability (Equation 3).

$$\text{EVR} = \text{Eco-cost/value} \quad (3)$$

3. Methodology and case study

This research aims to measure the environmental impact by measuring eco-costs using a life cycle assessment (LCA). By looking at the product's entire life cycle, from raw material extraction to disposal, LCA can provide a clear picture of the environmental impacts and help identify areas for improvement. The observed scope is limited to the tofu product production process (gate-to-gate). Life Cycle Inventory (LCI) is used to identify inputs and outputs related to products throughout the product life cycle that has been implemented. Data was collected by direct observation and interviews at SMEs in one of the SMEs with a unit of analysis of 1 batch with 9 kg of tofu. Data collection was carried out in August 2022 with 30 observations for each activity. Based on central limit theorem (CLT), A sample size of 30 will result in a sampling distribution that is close to normal (Islam, 2018). Each data is tested for data adequacy, data uniformity and data normality. The data used can represent the tofu production process as an object. The Life Cycle Impact Assessment (LCIA) evaluates environmental impacts related to tofu production systems. At this stage, the output of data processing is in the form of categories of potential damage generated to the environment based on the input of LCI results.

This research calculated the eco-efficiency level involving a cost-benefit analysis, which evaluates the potential costs and benefits of a project or decision. The eco-efficiency index and eco-cost value ratio can help determine a product or process's eco-efficiency. The calculation is assisted by SimaPro 9.1.0.11 software, which is a widely used tool for calculating the environmental impact of products and processes (Vogtlander et al., 2017). The eco-cost 2017 v1.5 is a database of environmental impact data that can be used with the SimaPro software to calculate eco-efficiency. The calculation involves several stages: characterization, normalization, weighting, and single scoring. The outputs generated by SimaPro are in Euros and then converted to USD. The steps for calculating the eco-efficiency index are explained in Table 3.

Table 3. Calculation of the eco-efficiency index

Step	Input	Data collection	Output
Life Cycle Assessment	Soybean raw material weight (kg) Weight of water requirement (kg) Tofu liquid waste weight (kg) Engine fuel volume (liters) Weight of coagulant (kg) Weight of corn cobs (kg) Cooking oil weight (kg) Rice husk weight (kg) Burnt husk weight (kg) Weight of roasted cob (kg) Weight of waste cooking oil (kg	Observation and interview	Environment Impact and eco-cost
Cost-Benefit Analysis	Production Cost (USD) Product selling price (USD)	Interview and secondary data	Net value
Eco-Efficiency Index	Net value product (USD) Eco-cost (USD)	Cost-Benefit Analysis and SimaPro software	Sustainability category
Eco-Cost per Value Ratio	Net value (USD) Eco-cost (USD)	Cost-Benefit Analysis and SimaPro software	EVR

3.1. Case study

This research was conducted based on a case study in tofu SMEs in Sugihmanik Village, owned by Mr. Eko Budi. Based on the field survey, a similar activity is conducted in the other Tofu SMEs in Sugihmanik, thus, one SME may represent the overall activity of the tofu industry. Their final product is fried tofu. The primary raw materials for making tofu are soybeans and water. The process begins by soaking the soybeans for approximately 2 hours to soften them. Subsequently, they are ground into a paste using a grinding machine while adding water. The ground soybeans are then boiled at around 70°C for 10-15 minutes. After boiling, the soybean paste is filtered to eliminate solids and coagulated with tofu whey to create the dough. This tofu dough is then pressed into moulds to achieve the desired shape. Finally, the tofu is cut into small pieces and fried. The fried tofu is then ready for delivery to customers the following day. Figure 1 illustrates the tofu production process in an input-output diagram.

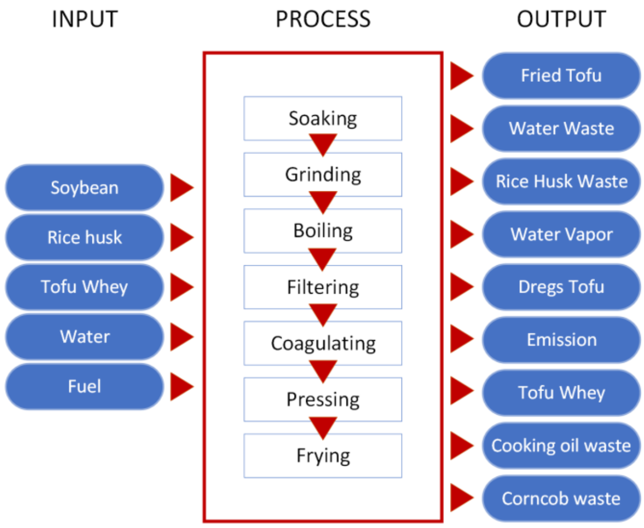

Fig. 1. The tofu production process depicted input-output diagram

3.2. Production cost

Production costs are the cost of goods sold which consist of material costs, equipment costs, labour costs, overhead costs, and marketing costs (Behrens and Hawranek, 1978). Table 4 shows the production cost of a batch of tofu products. In the tofu production process, a total production cost of USD 5.82 for each batch was obtained, while the market selling price was USD 7.14. Calculation of the benefit-cost of this tofu product produces a net value of USD 1.33 per batch. The net value is the difference between the selling price and the production costs. Material costs account for most production costs (80.05%), followed by labour costs (11.17%), marketing costs (8.19%), overhead costs (0.35%), and equipment costs (0.23%). Based on these findings, recommendations for improvement can be focused on lowering material costs associated with the tofu production process. One of the researchers' suggestions for improvement is the replacement of raw materials.

Table 4. Recapitulation of production cost

Item	Unit	Unit cost (USD)	Volume	Total (USD)
A. Material Cost				
Soya bean	kg	6.49×10^{-1}	5	3.25
Rice Husk	kg	3.99×10^{-2}	6.50	2.60×10^{-1}
Cooking oil	kg	1.08	0.90	9.74×10^{-1}
Corn Core	kg	2.95×10^{-2}	3.70	1.09×10^{-1}
Fuel	Liter	4.97×10^{-1}	0.13	6.46×10^{-2}
Material Cost				4.65

Item	Unit	Unit cost (USD)	Volume	Total (USD)
B. Equipment and machine				
Grinding Machine	Hour	4.03×10^{-3}	0.2	8.05×10^{-4}
Tofu Mold	Hour	2.01×10^{-3}	0.07	1.41×10^{-4}
Chiffon Fabric	Hour	6.38×10^{-3}	0.07	4.46×10^{-4}
Big Bucket	Hour	2.22×10^{-4}	3.15	7.00×10^{-4}
Small Bucket	Hour	9.68×10^{-5}	0.03	2.90×10^{-6}
Wok	Hour	1.29×10^{-3}	0.23	2.96×10^{-4}
sieve iron	Hour	2.68×10^{-4}	0.05	1.34×10^{-5}
Tray	Hour	2.42×10^{-4}	0.05	1.21×10^{-5}
Knife	Hour	8.05×10^{-5}	0.03	2.42×10^{-6}
frying pan	Hour	4.81×10^{-5}	0.03	1.44×10^{-6}
Well Column	Hour	1.07×10^{-3}	0.18	1.93×10^{-4}
Small skillet	Hour	2.42×10^{-4}	0.03	7.25×10^{-6}
Water barrel	Hour	1.37×10^{-3}	8.00	1.10×10^{-2}
Water hose	Hour	4.29×10^{-5}	0.07	3.00×10^{-6}
Equipment cost				1.36×10^{-2}
C. Labor				
Labor	Man	3.25×10^{-1}	2.00	6.49×10^{-1}
Labor cost				6.49×10^{-1}
D. Overhead				
Electricity	kWh	8.78×10^{-2}	0.21	1.84×10^{-2}
Tool depreciation				2.47×10^{-3}
Overhead cost				2.09×10^{-2}
E. Marketing				
Vehicles	Hour	1.61×10^{-1}	2.00	3.22×10^{-1}
Benzine	Liter	4.97×10^{-1}	0.22	1.09×10^{-1}
Depreciation				4.60×10^{-2}
Marketing cost				4.77×10^{-1}
Total cost (A+B+C+D+E)				5.82

4. Results and discussion

The value of the eco-cost is the cost of mitigating environmental impacts that must be incurred for every time production of tofu. The total eco-cost value of this tofu production using the SimaPro software, denominated in Euros then converted into USD, was USD 10.76 for one batch produced 9 kg of tofu. The EEI value is an indicator value for the environmental impact of a product. This value shows that a product is affordable (financially affordable) and sustainable (environmentally friendly). The EEI value of tofu processing per batch is 0.12. It belongs to the value category equal to or between 0-1, meaning the product is affordable but has yet to be sustainable. Unsustainable tofu products are caused by various factors, including water waste from tofu production being discharged directly into rivers, piling up rice husk and corn cob waste, cooking oil waste, the utility of electric water pumps, and the emissions generated.

The conducted measurements reveal that the most substantial environmental impacts stemming from the tofu production process are primarily associated with climate change, acidification, and ecotoxicity in freshwater. This impact leads to the introduction of environmental impact costs, often referred to as eco-costs, which companies must bear to mitigate and address the environmental consequences. In addition, production cost factors also affect product sustainability. A higher production cost for a product is indicative of an inefficient process, which can render the product unsustainable.

4.2. Eco-cost value ratio (EVR) analysis

The Eco-Cost Value Ratio (EVR)-serves as a means to compare the eco-cost of a product with the net value that it generates. The calculated EVR value for tofu is 8.10, which is deemed high because the eco-cost value is eight times greater than the net value. A high EVR value indicates that the production of the product is inefficient and may harm the environment. Typically, a lower EVR value is favourable as it suggests that the product's production is more efficient with a reduced environmental impact. This EVR value is subsequently used as an input in the calculation of the eco-efficiency ratio rate (EER).

4.4. Recommendation for Improvement

According to the environmental impact assessment results, the cooking and frying steps of tofu production have the highest single score. This is due to the high energy usage from water pumps that rely on fossil fuels for electricity and the use of rice husk and corncob as fuels for boiler engines, respectively. Using corncob as fuel in frying also influences the environment's negative impact. Therefore, switching to renewable energy sources is a potential option for reducing the environmental impact of the cooking and frying processes in tofu production. It would reduce the reliance on fossil fuels and decrease greenhouse gas emissions.

Tofu SMEs Sugihmanik produces wastewater with a debit of 40 m^3/day. The wastewater contains an organic pollutant load of around 188 kg/day, of which the COD content is 6502 mg/l, BOD is 4704 mg/l, and TSS is 326 mg/l. Anaerobic digester technology is capable of decomposing as much as 95% of COD and BOD and 65% of TSS content of the total organic pollutant load (Polprasert, 2015). Furthermore, this technology can also produce as much as 78.7 m^3 of methane gas per kg of COD, which is the output of the degradation of organic compounds. The development of a digester for a portion of these wastes is estimated to capture approximately 78.7 m^3 of methane gas. The daily production of CH_4/kgCOD is 121 kg. This biogas can serve as an alternative energy source for the cooking process.

Based on Rosyidah et al. (2020), biogas is an alternative to repairing firewood in cooking because it can reduce greenhouse gas emissions and improve air quality. It also can result in a cleaner cooking process due to the absence of smoke. The use of biogas can also reduce the dependence on conventional fuel, which can help conserve natural resources. The biogas conversion equation is carried out with rice husks and corncobs for total biogas. Every kilogram of corn cob is equivalent to 0.22 m^3 of biogas (Li et al., 2015), and one kilogram of rice husk is equivalent to 0.25 m^3 of biogas (Hartini et al., 2021a). SimaPro can be used to analyze further the potential environmental benefits of using biogas for cooking.

Table 5 compares the characterization values before and after improvements in the tofu production process. Based on the characteristic results, the utilization of biogas can significantly decrease environmental impacts, particularly in the areas of climate change, acidification, eutrophication, and waste. Table 6 presents a comparison of the characterization before and after the improvement, expressed in USD. The eco cost decreases from 10.76 to 9.10.

Table 5. Comparison of characterization before and after improvement

Impact Category	Unit	Before improvement	After improvement
Climate change	kg CO_2 eq	47.93	41.90
Acidification	kg SO_2 eq	0.21	0.16
Eutrophication	kg PO_4 eq	0.07	0.05
Photochemical oxidant formation	kg C_2H_4 eq	0.0017	0.0018
Fine dust	kg $PM_{2.5}$ eq	0.01	0.01
Human toxicity	Cases	4.E-07	4.E-07
Ecotoxicity (freshwater)	PAF.m_3.day	10326.43	10219.39
Metals scarcity	Euro	0.51	0.55
Oil & gas depl. excl energy	kg Oil eq	0.35	0.35
Waste	MJ	27.32	0.10
Land-use	Bio factor	0	0
Water stress indicator	WSI factor	0.22	0.25

Table 6. Comparison of characterization before and after improvement in USD

Impact Category	Before	After
Climate Change	6.16	5.39
Acidification	2.03	1.58
Eutrophication	0.32	0.13
Photochemical Oxi-	0.02	0.02
Fine Dust	0.30	0.29
Human Toxity	0.42	0.42
Ecotoxicity (Fresh-	0.06	0.06
Metals Scarcity	0.56	0.61
Oil & Gas Depletion	0.31	0.31
Waste	0.33	0.00
Land-use	0.00	0.00
Water stress indica-	0.24	0.28
Total	10.76	9.10

Table 7 illustrates the production cost of one batch of tofu after implementing the biogas improvement. The utilization of biogas will lower the expenses associated with rice husks and corncobs. This initiative results in a reduction in production costs from USD 5.82 to USD 5.45. As a result of this cost reduction, the net value will increase from USD 1.33 to USD 1.70.

Table 8 compares the EEI, EVR, and EER values before and after the improvement in tofu production. The tofu production process resulted in a total production cost of USD 5.82 for each batch, with a market selling price of USD 7.14. The net value is the difference between the selling price and the production costs. The benefit-cost of this tofu product is calculated to be USD 1.33 per batch. Material costs account for most production costs (80.05%), followed by labour costs (11.17%), marketing costs (8.19%), overhead costs (0.35%), and equipment costs (0.23%). Based on these findings, recommendations for improvement can be focused on lowering material costs associated with the tofu production process. One of the researchers' suggestions for improvement is the replacement of raw materials.

Table 7. The production cost of 1 batch of tofu after improvement

Item	Unit	Unit cost (USD)	Volume	Total (USD)
A. Material Cost				
Soybean	kg	6.49×10^{-1}	5	3.25
Cooking oil	kg	1.08	0.90	9.74×10^{-1}
Fuel	Liter	4.97×10^{-1}	0.13	6.46×10^{-2}
Material Cost				4.29
B. Equipment and machine				
Grinding machine	Hour	4.03×10^{-3}	0.20	8.05×10^{-4}
Tofu mold	Hour	2.01×10^{-3}	0.07	1.41×10^{-4}
Chiffon fabric	Hour	6.38×10^{-3}	0.07	4.46×10^{-4}
Big bucket	Hour	2.22×10^{-4}	3.15	7.00×10^{-4}
Small bucket	Hour	9.68×10^{-5}	0.03	2.90×10^{-6}
Wok	Hour	1.29×10^{-3}	0.23	2.96×10^{-4}
Sieve iron	Hour	2.68×10^{-4}	0.05	1.34×10^{-5}
Tray	Hour	2.42×10^{-4}	0.05	1.21×10^{-5}
Knife	Hour	8.05×10^{-5}	0.03	2.42×10^{-6}
Frying pan	Hour	4.81×10^{-5}	0.03	1.44×10^{-6}
Well Column	Hour	1.07×10^{-3}	0.18	1.93×10^{-4}
Small skillet	Hour	2.42×10^{-4}	0.03	7.25×10^{-6}
Water barrel	Hour	1.37×10^{-3}	8.00	1.10×10^{-2}
Water hose	Hour	4.29×10^{-5}	0.07	3.00×10^{-6}
Equipment cost				1.36×10^{-2}
C. Labor				
Labor	Man	3.25×10^{-1}	2	6.49×10^{-1}
Labor cost				6.49×10^{-1}
D. Overhead				
Electricity	kWh	8.78×10^{-2}	0.21	1.84×10^{-2}
Tool depreciation				2.45×10^{-3}
Overhead cost				2.09×10^{-2}
E. Marketing				
Vehicles	Hour	1.61×10^{-1}	2.00	3.22×10^{-1}
Benzine	Liter	4.97×10^{-1}	0.22	1.09×10^{-1}
Depreciation				4.60×10^{-2}
Marketing cost				4.77×10^{-1}
Total cost (A+B+C+D+E)				5.45

In the tofu production process using biogas, a total production cost of USD 5.45 for each batch was obtained, while the market selling price was USD 7.14. The difference between the selling price and production costs is called the net value. Calculation of the benefit-cost of this tofu product produces a net value of USD 1.70 per batch. The most considerable production costs come from material costs at 80.05%; the second is labour costs at 11.17%, followed by marketing costs at 8.19%, overhead costs at 0.35%, and equipment costs at 0.23%. From these results, recommendations for improvement can be focused on reducing material costs from the tofu production process. One of the recommendations for improvement given by the researchers is the replacement of raw materials for combustion, which initially used rice husks and corncobs to switch to biogas.

Table 8. Comparison of EEI, EVR, and EER Before and After Improvement

Indicator	Before improvement	After improvement
Cost production	USD 5.82	USD 5.45
Price	USD 7.14	USD 7.14
Net value	USD 1.33	USD 1.70
Eco Cost	USD 10.76	USD 9.10
EEI	0.12	0.19
EVR	8.10	5.33
EER	-710.00	-433.00

For tofu products from Eko Budi's SME, an eco-efficiency index of 0.12 was obtained. This value belongs to the value category equal to or between 0-1, which means that the product is affordable but has yet to be included in the sustainable category. Unsustainable tofu products are caused by several things, such as liquid waste from tofu production being dumped directly into rivers, rice husk, corn cob piling up, cooking oil waste produced, using electric water pumps, and the emissions it generates. Disposal of waste into the environment can cause harmful impacts on the environment.

The eco-efficiency ratio rate is a calculation used to determine the ecological and economic efficiency of tofu products. The EER value is calculated by subtracting one from the EVR value and multiplying the result by 100%. The EER value in this study was -710%. This value indicates that the tofu production process harms the environment and the economy. It is not good because the product's net value is less than the environmental impact costs that should have been incurred. Tofu products' EER value can be increased by increasing their net value or lowering their cost factor, including production and environmental costs (eco-cost). The use of biogas can reduce eco costs from USD 10.76 to USD 9.10 while at the same time increasing the net value from USD 1.33 to USD 1.70. In the end, the use of biogas can increase the eco-efficiency index from 0.12 to 0.19.

4.5. Circular Economy Framework and Future Research Direction

Using biogas as a substitute for rice husk and corn cob tofu products increases the EEI value. Unfortunately, suppose the value does not surpass 1. In that case, the process is still stated as affordable but has yet to be sustainable. The researchers then developed a framework for a circular economy, depicted in Figure 2. Tofu waste, both solid and liquid, has the potential to be recycled into more valuable products. Solid waste in husks for the boiling and cooking processes can be used as organic fertilizer (Risnah et al., 2013). Tofu liquid waste contains high BOD, COD, TSS, and pH (Rajagukguk, 2020). These organic compounds' content can produce biogas when processed through an anaerobic process (Faisal et al., 2016).

Tofu liquid waste consists of approximately 65 per cent protein, with 25 per cent each of fat and carbohydrates, and a small percentage of potassium. As a result, liquid waste can still be utilized as a fibre-rich food that is suitable for consumption by the general public. The fermentation method, aided by Acetobacter Xylinum bacteria, can transform tofu liquid waste into nata de soya (Sukreni et al., 2022). Rice husks can be employed as a raw material for briquettes, serving as an alternative source of energy (Saeed et al., 2021). The number of roasted husks produced is approximately 1000 kg per day or 30 tons per month.

Experimentation involves the creation of derivative products from tofu waste, aiming to enhance added value, thereby reducing environmental impacts and increasing overall value. It is indeed true that both solid and liquid tofu waste holds the potential for recycling into valuable products. However, it is imperative to acknowledge that additional research is necessary to assess the feasibility and long-term sustainability of these recycling endeavours. This experiment holds promise for future study, as it will help determine the extent to which recycling initiatives can enhance the eco-efficiency index.

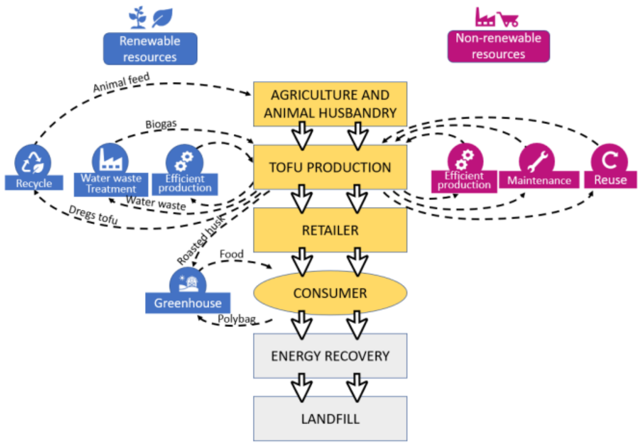

Fig. 2. Framework for a circular economy

Improving resource efficiency is essential for enhancing the sustainability of tofu production. The use of electric pumps for water consumption has been identified as one of the significant environmental impact hotspots (Hartini et al., 2021). Implementing a strategy that promotes low electricity and water consumption can reduce environmental impact while also lowering production costs. This, in turn, will increase the eco-efficiency index. The tree analysis diagram based on the life cycle assessment results can be seen in Figure 3.

The primary inhibiting factor for implementing biogas utilization from wastewater treatment is the need for funds and their availability. Insufficient training, expertise, and employee education also hinder the realization of a circular economy. The proposal suggests that collaboration among stakeholders can bolster Small and Medium-sized Enterprises (SMEs) in their pursuit of a circular economy. Partnership models, like the penta-helix approach, have demonstrated their effectiveness in boosting capabilities, particularly for SMEs with various constraints (Rosyadi et al., 2020). Moreover, these models have been found suitable for implementation in Indonesia (Irawati, 2006).

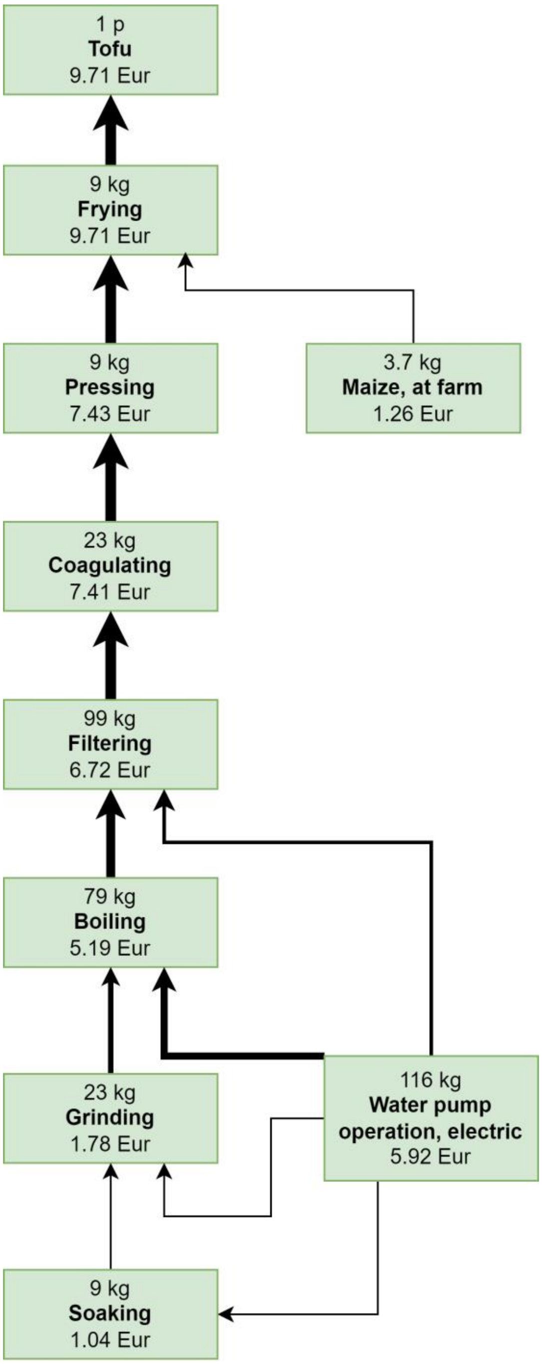

Fig. 3. Tree analysis diagram from the results of the life cycle assessment

Academics can address technological weaknesses, while governments can play a role in funding and regulation. Establishing mentorship programs with larger industries is crucial for bolstering SMEs. Mass media contributes to sharing knowledge and motivation, while the environmental community can serve as agents of change by monitoring environmental conservation efforts.

5. Summary and conclusion

The traditional tofu production process has an enormous waste potential and low production efficiency. Eco-efficiency analysis produces a value of 0.12. It means traditional tofu production is still economically profitable. However, the profit is too small to offset the environmental impact costs. If the liquid waste is processed into biogas, it is estimated to increase the EEI to 0.19. The level of eco-efficiency will increase, but it still needs to reach the sustainable category. The circular economy framework for traditional tofu production provides an opportunity to recycle all waste generated from traditional tofu production. Waste processed into products will increase value and, at the same time, reduce environmental impact. If producers, with the surrounding community's support, recycle tofu waste, eco-efficiency will increase. Because waste that turns into products will increase value and, at the same time, reduce environmental impact.

The main inhibiting factors are the lack of funds, technology, and expertise. The penta helix collaboration model is proposed to strengthen each other in the implementation of the circular economy for SMEs. Future research will be intriguing as it can conduct experiments to process waste into valuable products while studying the circular economy business model in tofu SMEs.

Acknowledgments

The Ministry of Research funds this research, Technology, and Higher Education Indonesia, under Matching Fund Kedaireka Program 2022, Number 177/E1/KS.06.02/2022 and 132/UN7.A/KS/2022.

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提高豆腐生产过程生态效率的框架：循环经济方法

關鍵詞
循环经济
对环境造成的影响
生态效率
生命周期评估
豆腐废水

摘要
本研究旨在提出改善 Sugih-manik 村豆腐生产工艺的建议。 30 多家豆腐中小企业产生固体废物和液体废物，污染了河流。 生态效率战略的实施始于确定豆腐生产过程。 采用生命周期评估（LCA）方法和 SimaPro 软件计算生态成本和生态效率水平。 据计算，每批次的生态成本值为 10.76 美元。 如果每天生产 30 批次，其中一家豆腐中小企业的生态成本值为 9.10 美元。 豆腐生产的生态效率指数 (EEI) 值为 0.12。 这个数值表明，豆腐产品只是实惠，但尚未实现可持续发展。 研究人员随后建议使用废水处理中的沼气来代替稻壳和玉米芯。 这项研究还开发了豆腐生产系统的循环经济框架。 该产量有望抑制水和固体废物的排放，提高未来豆腐生产过程的 EEI 值