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Assessing the environmental impact of tofu production: a systematic review for a sustainable industry

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ABSTRACT

The tofu industry provides communities with affordable protein sources. As protein sources, the environmental impact of tofu production was compared to other protein sources. Further, the tofu industry also produces waste and by-products affecting the environment. Some previous studies learned the environmental impact of tofu production. In this study, we aim to get information on which stages of the process in the tofu industry impact the environment and what type of strategy is applied to reduce the environmental impacts. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) approach was then chosen to filter the most recent research publications published in international peer-reviewed journals. We found that most articles calculated the environmental impact based on GHG, which contributed mainly from imported soybeans and electricity used during production. This research can act as a foundation for further studies related to the tofu industries, enabling treatment, better strategies, and solutions for waste to be developed.

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INTRODUCTION

Started in China, tofu is well-known for its healthy and cheap protein resources. Globally, tofu is famous for supporting vegan and healthy lifestyles. Based on Shurtleff and Aoyagi (2022), the earliest tofu company in San Fransisco was Wo Sing Co. Then, at the beginning of the 20th century, most of the tofu shops in the United States were owned by Japanese ancestors.

On the other hand, it also becomes an essential ingredient in local daily meals for Indonesians. In Indonesia, the weekly average per capita consumption of soybean-based food in 2022 was 0.148 kg or 2.707 kg/capita/year (Mas'ud. and Wahyuningsih 2022). Tofu resulted from Chinese influence who lived in or only visited Java. The technology is adopted and then locally produced since it is perishable and impossible to import. Now, the tofu industry can be found in almost every region in Indonesia, as stated by Faisal et al. (2016). The tofu industry in Indonesia is classified as a small and home industry.

There are two main steps to produce regular tofu: soymilk preparation and soymilk coagulation. Firstly, it starts with soybeans screening, soaking, grinding, filtering, boiling, coagulating, pressing, preserving, and packaging. By processing soybeans into tofu, the anti-nutrient can be removed from soybeans while also increasing the digestibility of soybeans. Guan et al. (2021) described producing tofu starts with making soymilk by soaking, pulping, and filtering the soybeans. Soymilk is cooked, a coagulant is added, and the soybean pulp, or okara in *Japanese*, is the main by-product. Several types of coagulants are used in the tofu industry, classified into salts, acids, and enzymes (Rekha and Vijayalakshmi 2011). The coagulated curd is then squeezed to produce tofu.

In our presumption, imported soybeans and untreated wastewater are the main contributors to environmental impacts. Soybeans used in the Indonesian tofu industry are mainly imported, causing a significant greenhouse effect. About 1.27 tons of soybeans were imported in the first half of 2020, as counted by the Central Bureau of Statistics (BPS) (Cindyara 2021). The amounts of local soybeans cannot meet the industry's demand. It is also a result that farmers consider not growing soybeans since soybeans have a low yield and are unfeasible farm-gate prices, as noted by Sayaka et al. (2021). Thus, only 0.63 million local soybeans were available in the local market, while the rest, 3.28 million, imported soybeans in 2020, as stated by Harsono et al. (2022). The environmental impact of importing soybeans, especially on greenhouse gas emissions or global warming, is higher than those of local sources.

Next, solid and liquid waste from the tofu industry is widely assumed to have impacted the environment badly. Tofu production heavily utilizes water to process soybeans into tofu. As stated by PKPT (2021) *in* Lubis et al. (2021), about 80% of water is used in processing soybeans into tofu, including washing, soaking, and boiling for making soybean milk. Furthermore, according to Kurniawati et al. (2019), most tofu industries are small industries with low energy efficiency and high pollution levels. Workers in the tofu industry cannot treat wastewater. Untreated waste pollutes the environment, especially the body of water, and causes pollution due to odors. Organic components in wastewater from the tofu industry cause an unpleasant smell, water contamination, and reduced water quality, as stated by Lubis et al. (2021).

Mejia et al. (2017) stated that tofu is technically an engineered food product. In addition, with the current trend in the agro-industry, tofu should be produced in an environmentally friendly manner by the agricultural sector that applies technology. We can find the improvement point by observing and calculating the environmental impact of each process in tofu production.

We aim to get information on which stages of the process in the tofu industry impact the environment, particularly global warming. In addition, we would like to see what type of strategy is applied or offered scenario to the industry to reduce the environmental implications of the tofu industry.

MATERIALS AND METHODS

This review used the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) statement to gather and screen the related articles. The PRISMA flow and the number of articles gathered during the process are depicted in Fig 1.

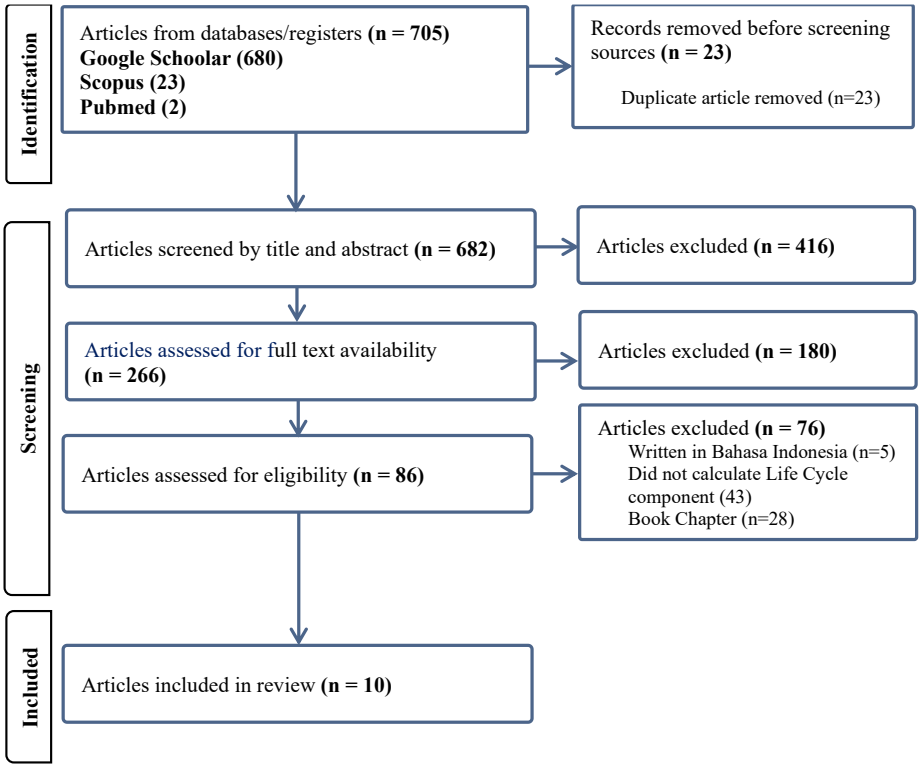

Figure 1 The PRISMA 2020 flow diagram

Search strategy

This search on Pubmed, Scopus, and Google Scholar began in August 2023. The search phrases for the life cycle of the tofu industry.

["LCA" OR "life cycle analysis" OR "environmental study" OR "environmental impact"]

AND ["tahu" OR "tofu" OR "soybean custard"]

The search was limited to publications from the last 5 years (2018-2023). However, only articles published in English were considered.

The PRISMA 2020 flow diagram, depicted in Figure 1, revealed 706 database entries, each with a title and an abstract. Articles with similar titles, authors, and release dates were removed and counted as one, while others were duplicates. A review paper or a book was not included. The collected papers were validated based on their title, abstract, and full text through Covidence.

Inclusion and exclusion criteria and assessment paper

We used Covidence to include requirements such as a study on the environmental impact of activities in the tofu industry. Studies on the life cycle assessment component and at least one of the environmental impacts, such as global warming or greenhouse gases (GHGs), are included in this review. Studies on the tofu industry that did not discuss global warming or GHG values were removed. As a result, only ten relevant papers in English were chosen and published in journals such as IOP Conference: Earth and Environmental Science (4 papers), 1 article respectively from Asia-Pacific Journal of Science and Technology, MDPI Environments, EPI International Journal of Engineering, East Asian Journal of Multidisciplinary Research (EAJMR), and some local Indonesian journals but written in English: Jurnal Teknologi Lingkungan, Serambi Engineering.

RESULTS AND DISCUSSION

Current status of environmental impact on tofu industries

The search resulted in 705 papers, of which 23 were duplications, 416 were excluded based on abstract and title, and 180 were unavailable for online full-text. After excluding 695 articles, five articles from Google Scholar and five from Scopus were used for discussion. The extraction of data from those articles is in Appendix 1.

Most of the articles in this study came from Indonesia, where tofu is produced by micro, small,

and medium enterprises (SME), and tofu is the leading and only product from those agro-industry. The SME industry is owned individually, with limited workers and assets value, limited technology, and dependent on human labor (Maksum et al. 2020; Lolo et al. 2023). One study was conducted by Colimoro et al. (2023) in Swiss.

Eight out of ten studies counted life cycle analysis using software (SimaPro or OpenLCA), and two studies manually calculated the global warming impact of tofu production. The boundary used in the life cycle analysis was the gate-to-gate system boundary by Kurniawati et al. (2019), Hartini et al. (2021), Rahmalia et al. (2021), and Rahmawati et al. (2022).

Life cycle analysis is limited only to process production. The imported soybean impact and wastewater were calculated by studies used cradle-to-gate applied by Colimoro et al. (2023), Herdiansyah et al. (2021), Lolo et al. (2023), Putri and Waluyo (2022), Sari et al. (2021), Yusuf and Agustina (2022).

Environmental impact assessment

Most studies on tofu production discussed global warming potential (GWP) or greenhouse gas emissions (GHGs) to convey the impact of tofu production activities on the environment. GWP notates as kg CO_2 equivalent. The higher the GWP, the more heated the gas traps and the more harmful to the climate (Rahmawati et al. 2022).

Further, there are similarities in the characteristics of the tofu industry in Indonesia: small enterprise, no treatment for wastewater, while one study is located in Switzerland. Although all studies discussed the tofu industry, the scale and final product differ slightly. In addition, there are several types of tofu sold in Indonesian market as stated by ASYX (ASYX, 2022), tahu putih or regular tofu, tahu pong, tahu sutera, tahu kuning or tahu takwa, tahu coklat, and tahu sumedang. However, most of the articles discussed only regular tofu production. Some industries packaged their products in plastic, as Putri and Waluyo (2022) and Colimoro et al. (2023) discussed. One article studied fried tofu by Hartini et al. (2021), while the rest of the studies were only counted until regular tofu.

Several articles used cradle-to-gate as a system boundary by calculating soybean plantation and transportation. Colimoro et al. (2023) counted the impact of organic soybean plantation, including fertilizer and machinery.

At the same time, other studies calculated global warming by getting soybeans from overseas. Tofu production started with obtaining soybeans from the market (local or imported), followed by washing, soaking, and boiling them to make soybean milk. For the tofu industry in Indonesia, most soybeans are imported from the US, which requires fuel for transportation and has a high impact on the environment. In 2019, 2.67 million tons of soybean were imported for tempe and tofu industries in Indonesia. Based on Sari et al. (2021) observations, imported soybeans resulted in 0.882 kg CO_2-eq from 0.982 kg CO_2-eq of total GWP value of tofu production. Yusuf and Agustina (2022) proved that transportation generated more than half of the total emission from tofu production (0.49 kg CO_2-eq from 0.8 kg CO_2-eq total). The imported soybeans were calculated by Putri and Waluyo (2022) from the plantation area in the Midwest area to the shipping area in Mississippi Bay and the Pacific Northwest area through the railway, then shipped into a port in the Java area.

On the other hand, local soybeans could not meet the industry's demand. Yusuf and Agustina (2022) explained that the tofu industry in Merauke no longer uses local soybeans. However, there are studies like Hartini et al. (2021), Herdiansyah et al. (2021), Kurniawati et al. (2019), Rahmalia et al. (2021), Rahmawati et al. (2022) did not count the importing soybeans since they calculated the impact only from processing soybean into tofu (gate-to-gate).

Tofu Production

During production, some industries used fossil-fuel heaters to boil and petrol-based electricity to pump water and grind the soybeans. Tofu industries in Jakarta used fossil-based electricity, as described by Putri and Waluyo (2022). by Kurniawati et al. (2 observed industries in the Yogyakarta area019), used biomass for boiling soybeans and electric pumps for supplying water. Moreover, in SMEs, tofu industries use a lot of water. In Indonesia, where most of the tofu industries are located in this study, electricity is based on coal. Coal combustion for producing electricity also produces pollutants that harm living things (de Coning and Swinley 2019).

The following process is coagulation, an essential process for producing tofu. Tofu texture

depends on the solid component of soymilk and coagulation used in production, as Andarwulan et al. (2018) stated. Coagulation might come as an acid (Herdhiansyah et al., 2021) or a whey-containing lactic acid (Hartini et al., 2021). Industries use whey to coagulate the soymilk fermented from remaining water from the clotting process and left for 1-2 nights. Whey is obtained during the coagulation and tofu pressing process, as stated by Lubis et al. (2021). Some industries use lactic acid as a tofu coagulant (Guan et al. 2021). Acetic acid production from the carbonylation of methanol generates GWP as much as 1 kg CO_2 eq per 1 kg acetic acid, as explained in Budsberg et al. (2020). In addition, coagulating used CH_3COOH triggers CO_2 and CH_4 formation, as Rahmawati et al. (2022) stated. Since the amount of acid produced from coagulation is small, the GWP of the coagulation process is lower than that of soybean production, transportation for importing soybeans, or the electricity used during production.

The last source of GHG emissions or GWP is wastewater and solid waste. Solid waste in some articles called okara or soybean pulp was obtained after soaking and grounding soybeans collected after straining soybeans in a cloth bag. Okara was sold as a powder to reduce the use of wheat flour and increase dietary fiber and plant-based protein while reducing gluten content in Japan. Mejia et al. (2017) stated that okara is used for animal feed, while in Indonesia, this soybean left will be used for feeding or upcycled into a Tempe called gembus. Moreover, wastewater remains unsolved in Indonesia since the SME industry lacks capital and capability. Wastewater with anaerobic is possible to release methane that causes greenhouse gas, as stated by Herdhiansyah et al. (2021).

Scenario to Reduce Environmental Impact

Although the tofu industry is widespread and can be found in every region in Indonesia, local soybeans cannot supply enough of the industry. Yusuf and Agustina (2022) proved that imported soybeans contributed more than half of the total GHG emissions of tofu production. Thus, Yusuf and Agustina (2022) and Lolo et al. (2023) suggested using local soybeans. Based on several studies, the condition urges the government to release a supportive regulation to improve the quality and quantity of local soybeans. Those regulations can help farmers to increase yield and price. From an environmental viewpoint, there is no good in continuously importing soybeans.

The tofu production process also contributed to GHG emissions regarding biomass utilization. Some industries use firewood (Rahmawati et al., (2022); Kurniawati et al.; (2019); Herdhiansyah et al. (2021), husk, and corn cob to cook soymilk and form tofu (Hartini et al., 2021). Furthermore, Hartini et al. (2021) and Herdhiansyah et al. (2021) suggested changing the biomass to biogas to reduce environmental impact. In addition, Yusuf and Agustina (2022) noted that combustible material was utilized in their observations and suggested a steam boiler to reduce GHG emissions. Rahmalia et al. (2021) suggested some scenarios to reduce the environmental impact of tofu production, such as using biogas or LPG despite biomass to reduce the GHG emissions by 3.45-5.73%.

Using electricity to pump water, grind, or mill becomes another environmental burden. Since the electricity source is mainly coal, electricity usage generated a higher impact on GWP in the tofu industry, as observed by Lolo et al. (2023). To reduce the effect of electricity usage, Lolo et al. (2023) suggested optimizing water usage change to a more efficient water pump and grinder machine. Eliminating coal as an electricity resource in Indonesia, as planned in 2056 by PLN as the leading supplier, into renewable energy should decrease the impact of electricity usage on the environment (Fachri, et al. 2015). Another study by Rahmalia et al. (2021) suggested saving electricity for pumping water to reduce the GHG emission.

Faisal et al. (2016) state that waste becomes a problem in the tofu industry in many places. Using wastewater treatment plants (WWTP) for the tofu industry is burdening producers, as Qatrunada et al. (2023) explained. However, Rahmalia et al. (2021) tried to compare different wastewater treatments based on their LCA. The current industry study by Rahmalia et al. (2021) already uses wastewater treatment to reduce pollutants in the nearest water body. By adding a moving bed biofilm reactor (MBBR) to the tofu industry, this study stated that the GWP value was reduced to 0.722 kg CO_2 -eq.

Another point of view on the environmental impact of tofu production came from Colimoro et al. (2023). They compared the environmental impact of different protein production sources,

including tofu, meat, and snails (Colimoro et al. 2023). The GWP of 1.24 kg organic tofu was 6.61E-5, 1.62 kg snails were 6.07E-5, and one kg meat was 3.92E-3. In addition, Putri and Waluyo (2022) suggested that the government is required to apply the carbon tax to force industries to manage their waste.

CONCLUSION

From studying ten articles related to environmental studies, we found that the imported soybeans contributed to global warming potential (GWP) or greenhouse gases (GHG). This condition should be considered to improve local soybean production to fulfill soybeans' industrial needs. Using biomass and electricity during soybean processing also contributes to the GHG. Some studies recommended biogas from tofu waste because it is rich in protein composition. However, it should be followed by changes in plan and utilities production. Last, wastewater treatment is required to reduce the effect of tofu dregs. Future environmental studies on tofu production can conduct more than GHG impact only.

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Appendix 1. Data extraction of an environmental impact study on the tofu industry

Refs	Location/year of publication	Product	Goal and Scope	Functional Unit	System Boundary	Climate change and GWP results	Main findings	Recommendations
(Colimoro, et al. 2023)	Switzerland, 2023	Packaged organic tofu	Identify the phases that cause the main environmental burdens and propose alternative solutions to minimize the impacts.	1 kg organic tofu production	Cradle-to-gate	0.426 kg CO_2-eq	This study calculated LCA from cultivation of soybean until processing it into tofu, including fuel used in agro-machinery and use of low-density polyethylene (LDPE), and heavy contribution of electricity contributed to environmental impact. There is also a comparison of tofu production to other protein sources since tofu is widely known for meat substitution.	They suggested changing grid electricity to self-production photovoltaic electricity.
(Hartini, et al. 2021)	Sugihmani, Central Java; 2021	Fried tofu	Measuring environmental impacts and providing recommendations for improvements to the tofu	Batch production	Gate-to-gate	47.93 kg CO_2-eq per batch (5 kg) or 9.56 kg CO_2-eq	From tofu processing only, the environmental impact came from the cooking and frying process that used rice husks and corn cobs. Another impact is caused by electricity for	This study suggested to have wastewater treatment (WWTPs). They also suggested changing corn husks and corncobs to biodigester.

Refs	Location/year of publication	Product	Goal and Scope	Functional Unit	System Boundary	Climate change and GWP results	Main findings	Recommendations
			production process				water pumps since processing soybeans requires a large amount of water.	
(Herdhiansyah, et al. 2021)	South Konawe Regency, 2021	Regular tofu	To determine the environmental impact of tofu production	1 kg tofu product	Gate-to-gate	GHGs 1.343 kg CO_2-eq	Life cycle analysis was conducted only on global warming potential (GWP) impact points without using software. The GHGs resulted from transportation and tofu production.	Changing fuel oil to gas was recommended for reducing emissions. During the processing stage, it is better to use tofu liquid waste biogas, replace the furnace with a boiler, and reduce electricity for washing soybeans.
(Kurniawati, Supartono and Suyantohadi 2019)	Baturetno, Yogyakarta, 2019	Regular tofu	To evaluate the application of LCA in a small-scale tofu industry, to calculate life cycle cost, and to assess its contribution to global warming potential (GWP)	1 kg of soybean	Gate-to-gate	GWP gas 0.1766 kg CO_2-eq	This study did not point out which part of production impacts the environment. The industry used biomass for boiling, electricity for grinding and water pumps, and fuel for transportation and distribution.	No scenario was offered to reduce GWO since they argued that a particular industry has a low GWP related to the production size.

Refs	Location/year of publication	Product	Goal and Scope	Functional Unit	System Boundary	Climate change and GWP results	Main findings	Recommendations
(Yusuf and Agustina 2022)	Merauke, 2022	Regular tofu	They identified GHG hotspots and analyzed the flow of energy input-output across the life cycle of a tofu product at the ABC plant.	1 kg tofu product	Cradle-to-gate	Local: 0.337 kg CO_2-eq/ product Imported: 0.801 kg CO_2-eq/ product	This study compared mainly the environmental impact of using local and imported soybeans for tofu production. Tofu processing is the second emission generator, mainly from combustibles.	This study offered to use local soybeans, biogas from wastewater, solar water heaters, or steam boilers for processing to reduce impact. However, there is no further GHG calculation or comparison of those scenarios.
(Sari, Kuniawan and Sia 2021)	West Jakarta, 2021	Regular tofu	To analyze the life impact of tofu products	1 kg tofu	Cradle-to-gate	0.978 kg CO_2-eq	The highest contribution to global warming potential (GWP) is soybean transportation from the US. However, there is no additional discussion on acidification and eutrophication from wastewater.	No recommendations from this article, but they would like to conduct the subsequent research on several scenarios to reduce the GWP.
(Putri and Waluyo, Analysis of Potential GHG Emissions from Tofu Industry and	South Tangerang, Jakarta, and Tangerang city 2022	Regular and turmeric tofu in packaging	To inform the potential of GHG emissions of the tofu industry, including the production and transportation of	1 kg of tofu	Cradle-to-gate	In 3 industries (A = 0.515 kg CO_2-eq	Process contribution came mainly from untreated wastewater; thus, they suggest using wastewater for biogas, soybean cultivation, and transportation from farm	Considering the application of carbon tax to force industry to manage their waste to reduce the emission

Refs	Location/year of publication	Product	Goal and Scope	Functional Unit	System Boundary	Climate change and GWP results	Main findings	Recommendations
its mitigation in Indonesia 2022)			soybean and tofu production			B = 0.414 kg CO_2-eq C = 0.35 kg CO_2-eq)	to industry (imported soybean).	
(Lolo, et al. 2023)	Central Java, Indonesia	Regular tofu without packaging	Impact on the environment from tofu industries	1 batch production	Cradle-to-gate	GWP 16.1 kg CO_2-eq per 1 kg tofu	Energy during the tofu production process, electricity used for the water pump and grinder machine, soybean container, and transportation for importing soybeans from the US to Indonesia were calculated as the generator of GWP.	They suggested using water efficiently during the production process, making simple work instructions for efficient work, changing to a more efficient water pump and grinder machine, and considering using domestic soybeans to reduce the effect of imported soybeans.
(Rahmawati, et al. 2022)	Gresik, East Java 2022	Regular tofu without packaging	To analyze the global warming potential from the production process of one particular in	1 kg tofu	Gate-to-gate	2.95E8 kg CO_2-eq for GWP	Boiling, grinding, and clumping generated GWP in tofu production, related to the use of firewood for boiling, electricity in	They suggested that firewood boiling process should be substituted for gas (LPG).

Refs	Location/year of publication	Product	Goal and Scope	Functional Unit	System Boundary	Climate change and GWP results	Main findings	Recommendations
							grinding, and acid for coagulating	
(Rahmalia, et al. 2021)	Central Java	Regular tofu without packaging	Determine the environmental impact and update the tofu industry management with LCA	1 batch production of tofu	Gate-to-gate	GWP 27.628 kg CO_2-eq	This study calculated the environmental impact of tofu production with wastewater treatment. Wastewater and fossil fuels used during the process contributed most to environmental pollution.	Scenario 1: moving bed biofilm reactor (MBBR) can reduce GWP into 0.722 kg CO_2-eq Scenario 2: Sequencing Batch Reactor (SBR) can reduce GWP into 5.67 kg CO_2-eq Another recommendation is substituting diesel for biomass