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Environmental Impact Evaluation of Tofu Production using Life Cycle Assessment

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ABSTRACT

Tofu is one of the products made from soybeans that a sizable portion of people in a larger society consume. There are several ways to make tofu, from conventional to modern. The conventional tofu production process generates a lot of waste. Many of the researchers have explored numerous strategies to handle tofu waste in a way that minimizes its harmful influence on the environment. However, in many cases, the environmental impact is simply transferred from one process to another during the treatment of tofu waste. As a result, the whole tofu-making process requires an evaluation of the effects. Among these approaches is life cycle assessment (LCA). The study discovered that energy use was the primary factor leading to environmental impacts. Burning firewood for energy resulted in 55.61 kg of carbon dioxide equivalent. The emission value has been reduced to 32 kg CO_2 eq and 28 kg CO_2 eq, respectively, according to the findings of simulations by utilizing biogas and natural gas as fuels.

***Keywords*: LCA, simulations, tofu, waste.**

1. INTRODUCTION

Tofu is one of the many byproducts made from plant-based ingredients. In Indonesia, tofu is one of the basic foods consumed by many people. Based on data provided by the Central Statistics Board (BPS) in 2023, consumption per capita of tofu reached 7,094 kg/person reflecting the growth rate of 0,027%. Compared with consumption per capita of beef and fish, this number is significantly greater. The average number of tofu industries in Indonesia is 84,000, containing a range of levels from household-scale operations with five to eight laborers to large-scale factories involving more than one hundred individuals [1]. Out of this total, the tofu sector generates million solid and liquid waste that have a direct effect to the environment such as eutrophication, ecotoxicity and carbon footprint which is all lead to global warming potential [2,3]. Solid waste is typically generated by the tofu industry, accounting for around 40% of total 100 kg soybean production capacity. For every 100-kilogram soybean used in production, it takes roughly 1.5 - 2 m^3 of water [1]. However, much of the solid waste generated during the tofu production process is used as animal feed rather than being disposed of directly in the environment. Waste water also generated throughout the processes of soaking, blending, and tofu molding [1]. Significant quantities of wastewater, averaging 7–10 kg per kilogram of soybeans processed, are produced as a result of tofu processing [4]. Because of the high levels of chemical oxygen demand (COD) and biochemical oxygen demand (BOD) that are present in waste water from tofu production, it is supposed not to be possible to discharge it directly into the environment [5]. Tofu production wastewater

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contains nutrients such as 0.59 g/L total nitrogen, 0.078 g/L ammonia nitrogen, 0.26 g/L nitrate, and metal ions, making it ideal for microorganism growth [6].

A small manufacturing center area was built on 9 ha of land in Balikpapan. There are approximately 107 tofu and tempeh manufacturers in the vicinity, each possessing a daily production capacity ranging from 50 to 350 kg. Every month, 350–400 tons of soybeans are required to meet this capacity of production . The majority of the soybeans utilized originate from the US, while a small percentage are imported from Indonesia [7]. Three distinct categories of waste are generated in the region: solid, liquid, and gas waste. The solid byproducts generated during the tofu processing phase will be delivered directly to neighboring farms for utilization as animal fodder. However, any liquid waste will be directed to a nearby integrated water treatment facility. The final issue is the unresolved gas waste that results from wood combustion. The large amounts of waste gas created by combustion are readily apparent. High levels of air pollution and low energy efficiency are shown by this situation. However, neither the local community nor policymakers have paid any attention to this issue since the environmental effects of wood combustion have never been objectively assessed.

Many programs have been created during a couple years to handle some of the environmental problems related to product derived from agriculture industry and forests [8]. Some of the previous programs had a domino effect to the environment impact, it’s caused by only considered solving issues from one output point. In order of reducing the limitation, there is one method that can fully comprehend the environmental impact of one product life cycle, it’s called Life Cycle Assestment (LCA). The life cycle assessment (LCA) looks at the environmental implications of a product system and material input from the perspective of its whole life cycle [9]. Using a standardized framework as outlined by ISO 14040, LCA improves our understanding of every step of the production process, from extracting raw materials to manufacturing, using, and disposing of the product [10]. This method calculating through the entire life cycle to pinpointing the hotspots and processes so that they can contribute to environmental impact like greenhouse gas (GHG), ozone depletion (ODP), photochemical oxidation, euthrophication, and etc (Alam et al., 2016). LCA also uses ISO 14040-based standardized measurements and Key performance indicators (KPIs) to help with things like finding environmental dangers, ranking improvements, comparing goods, and supporting decision-making [12]. Although there are difficulties in applying LCA in agriculture industry particullarly the industry that used the conventional method for producing product. The progress on collecting the data should be done independently like interviewing the owner , or you may get straight to the manufacturing process in order to obtain measurements for yourself. In order to completed the data, we have to use a lot of secondary data as a reference to get the primary data so that the midpoint emission can be calculated. On top of that, a significant number of studies have concentrated on life cycle applications in the agricultural industry, which are mostly concerned with evaluating the numerous varieties effects of tofu production. In the entire life cycle of tofu production, liquid waste is often be the main topic in evironmental impact. But, there are some research that revealed that energy consumption from tofu production give the portion of carbon footprint [12,13]. Greenhouse gas emission determined by CO_2 eq was revealed that throughout 1kg of tofu production produce 16% from soybean acquiring, 52% from tofu production, 23% from the packaging and 9% from the transportation of soybean [14].

However, none conventional methods-based study of the tofu life cycle has ever been done in Balikpapan's tofu manufacturing areas. Furthermore, a comprehensive LCA study, beginning with soybean purchase and ending with tofu packaging waste disposed to landfills, will serve as the foundation for evaluating the identification of hotspots throughout the tofu manufacturing process. Inventory data collection must be complete and transparent in order for the study evaluation to be regarded high-quality. As a result, using the input and output data collected during the investigation, we conducted a comparison simulation of the fuel utilized in the tofu making process. The goal of this simulation is to estimate the effectiveness of sustainable bioenergy that can be employed throughout the process while also reducing the impact of combustion emissions in the form of CO_2. And also, the growing demand for alternative energy resources has sparked renewed interest as a valuable renewable resource as a substitute to conventional fuel supplies [4].

2. RESEARCH METHODS

The systems have been modelled in OpenLCA 1.11.1 2022, and the Life Cycle Assessment (LCA) is carried out in accordance with the methods outlined in ISO 14040/14044 standards (ISO 2006a, 2006b). Midpoint impact from the whole process including energy consumption were determined using the CML IA Baseline and IPCC (Intergovernmental panel on climate chage report). There are 14 different types of midpoint effect environments. The present investigation focused on a mere three environmental effect categories. The selected categories exclusively comprise those that pertain to the environmental impacts caused by carbon emissions. The CML method was utilized in this study to evaluate the midpoint impact of the environment by considering the greenhouse gas effect, ozone depletion, and photochemical oxidation. Additionally, we employed the IPCC method to validate the results of the CML method in the context of global warming. The methodology and data used in order to estimation of environmental impact is presented in the following sub-sections. There are 4 stages used in LCA, including Goal and scope, inventory analysis, impact analysis and interpretation.

The process of making tofu in Somber, Balikpapan has two primary raw material which are soybean and water. Figure 1 shows the stages of tofu production from soaking, grinding up to product packing. There a slight difference in the process of making tofu with another industries. Usually they used additional coagulants like vinegar to mold the protein. But in this process, on the agglomeration process as a starter acid solution they used vinegar, but then for next batch they used to ferment the soybean boiled water over 1-2 nights. Fermentation process produces lactic acid which can coagulate protein [12]. Energy used throughout the process are diesel for grinding and firewood for cooking. For the purpose of minimizing operating costs, the tofu production unit constructs its own utility to support the production of the primary product. They generate steam by utilizing the residual fuel derived from wood scraps or discarded twigs. In the cooking process for soy juice, the steam generated will serve as a heating medium. The production of steam using wood fuel results in significant emissions. Consequently, we propose the substitution of energy sources such as natural gas and biogas to assess the potential reduction in emissions generated. The Ecoinvent V3.10 database on open LCA 1.11.0 provides data on the generation of natural gas and biogas. Besides producing the main product, tofu production process generates solid waste in form of soybean hulls and liquid waste from filtering and agglomeration process. The limitation of this LCA studies was conducted based on assumption that green house gasses (GHG) emission and energy demand in soybean farm is neglected.

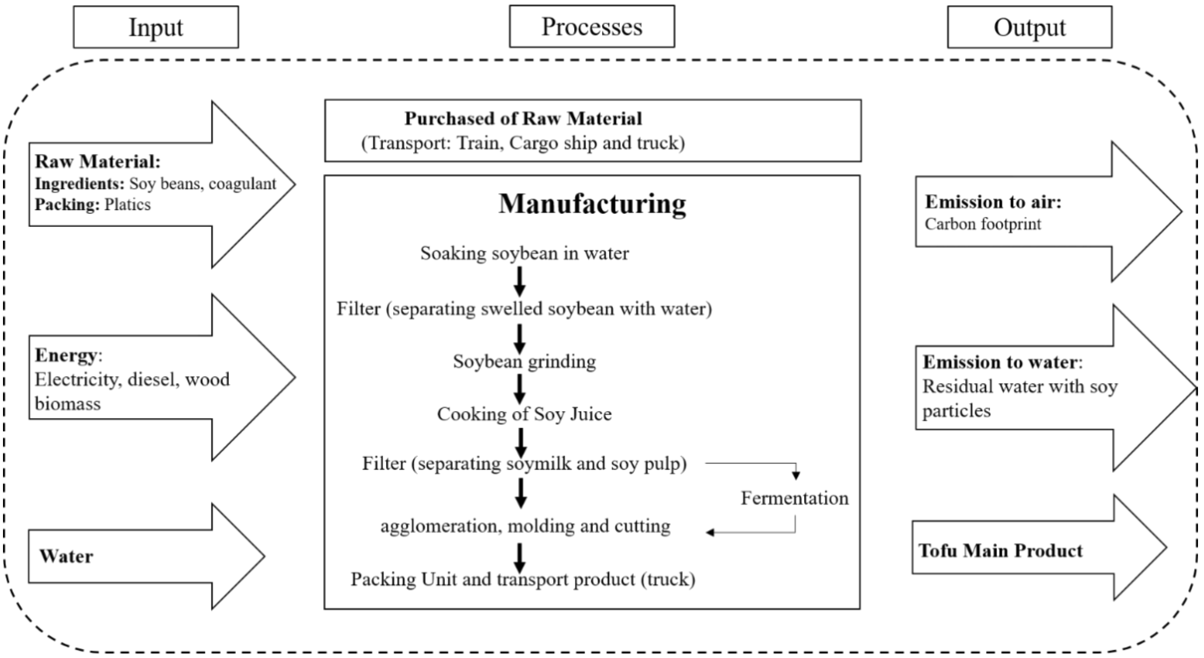

Figure 1. Boundary system of life cycle assesment on tofu production.

2.1. GOAL AND SCOPE

The objectives of this study is to measure the carbon footprint in the life cycle tofu production. The spesific objectives are:

- To quantify life cyle environmental impact of tofu production.
- Analyse the environmental hotspot in the tofu production to identify the opportunities for reducing environmental impact.
- To identify the most sustainable bionergy conversion pathways.

This research uses a single-process batch or something similar with 35 kg of tofu as the functional unit. The functional unit is utilized to formally characterize the product that is being investigated in accordance with its function. Additionally, it enables a unified analysis of many stages in accordance with a basis that is functionally equivalent [15]. The system boundary represents multiple stages, as you can see in Figure 1. The whole mass balance of these life cycles for producing 35 kg of tofu is then quantified in inventory analysis.

2.2. INVENTORY ANALYSIS

The data utilized in this research comprises primary and secondary sources. Primary data is gathered from on-site surveys, industry owner interviews, and direct measurement. On the other hand, secondary data is sourced from relevant scientific journals and openLCA databases like Agribalyse 3.1.1 and Ecoinvent V3.10. Agribalyse database is the agriculture and food sector database provide by ADEME, however Ecoinvent is the database contains international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, transport and etc. In the tofu production system, the subsystem processes included (a) raw material preparation, (b) process production, (c) usage, and the end-of-life stage. The details of the data inventory for all stages can be seen in Tables 1–3.

Table 1 presents the inventory of raw material preparations, including the origin of soybean and the transportation methods until soybean reaches the production unit. The carbon footprint from transport section were was calculated according to the LCA database. Different types of transportation, like cargo shipping, trains and trucks, were used to bring input from the soybean farm to production unit's gate. The amount of distance travelled was measured in kilograms-kilometres (kg*km). According to the owner's interview, the soybean they utilized was imported from the united states (US). So that, we used to input soybeans from the U.S from agribalyse database at life cycle inventory. These data eliminate the energy used from soybean farm.

Table 2 shows the entire process production of tofu. This part mostly relies on direct measurement for data collection. In order to compute the emission from the manufacture of tofu all the way up to the factory gate, the original data inventories that included all known inputs of materials, energy, soybeans, transportation, and manufacturing process were imported into the openLCA 1.11.0 program. Tranportation, energy consumption and residual water treatment for individual, and food disposal by the consumer are not included in this analysis.

Last part of providing the inventory analysis is reflect on the Table 3. It shows the transport of main product to the market and the last stopped is to landfill. The kind of transportation that we used is truck and provided by ecoinvent database. The input of amount of transportation to market and landfill using the same method as before.

Table 1. Inventory of raw material preparation.

Inventory of Raw Material Preparation			
Material/Process	**Input**	**unit**	**Source**
Ground Water	177.1	kg	Direct Measurement
Soybean	10	kg	Interview
Transport of Soybean (Train)	10*1739.7	kg*km	ecoinvent; Map estimated
Transport of Soybean (Ship)	10*20275.7	kg*km	ecoinvent; Map estimated
Transport of Soybean (Truck)	10*10.7	kg*km	ecoinvent; Map estimated
Transport of Plastics (Truck)	0.10388*10.7	kg*km	Direct Measurement; ecoinvent; Map estimated

Table 2. Inventory of process production.

Inventory of process production						
Process	**Input**	**Quantify**	**Output**	**Quantify**	**Unit**	**Source**
soaking	Dried soybean	10	swelled soybean	30	kg	Direct measurement
	water	25.5	water	5.2	kg	Direct measurement
Grinding	swelled soybean	30	Soy juice	36	kg	Direct measurement
	water	6				Direct measurement
	Diesel	0.14			kg	Ecoinvent; IPCC
Steam generator	Water	37.5	steam	37.5	kg	Direct measurement
	Firewood	31.25			kg	IPCC
Cooking	Soy Juice	36	Soy juice	156.24	kg	Direct measurement
	water	96.1				Direct measurement
	steam	37.5	steam	37.5	kg	Direct measurement
Filter	Soy Juice	156.24	Soy milk	130.64	kg	Direct measurement
			Soy pulp	25.6	kg	Direct measurement
Agglomeration , molding & cutting	Soy milk	130	Whey	90.55	kg	Direct measurement
	Acid Solution	57.4	Tofu	35	kg	Direct measurement
Packaging production	LDPE	0,14			kg	IPCC
	Electrical	0.0021			kJ	Ecoinvent; IPCC
Packing	Tofu	35	Packaged Tofu (40 unit)	47	kg	Direct measurement
	Water	12				Direct measurement
	Plastics	0.10388				Direct measurement

Table 3. Inventory of usage stage and end of life stage.

Inventory of usage stage and End of life stage			
Material/Process	**Input**	**unit**	**Source**
Transport product to market (Truck)	47*4.6	kg*km	ecoinvent; Map estimated
Transport packaging to landfill (Truck)	0.10388*20.2	kg*km	ecoinvent; Map estimated
Packaging to landfill	0.10388	kg	Direct Measurement

2.3. IMPACT ASSESMENT

Midpoint impact that will be analyse in this study are greenhouse gas (GHG), ozone depletion and photochemical oxidation. The carbon emissions from the tofu industry's gas waste led to the selection of those three groups, as indicated earlier. Greenhouse gas impact values are quantified across time horizons of 20-, 100-, and 500-year in order to facilitate policymakers in making informed decisions regarding climate change [11]. And ozone depletion and photochemical oxidation are the extension of GHG emission potential [16]. According to what was previously said that the aims of this study is to quantify and analyse the environmental impact and to identify the most sustainable bioenergy conversion pathways for reducing the carbon emission. The data of biofuel production process that used for another scene was got from ecoinvent database. Furthermore, IPCC is employed to estimated the GHG emission of energy consumption. The calculation of CO_2 emissions from the fuel usage can be peformed using the following equation [17]:

$$E_{CO_2} = DA\,.\,EF \qquad (1)$$

For diesel:

$$DA = F_{diesel}\ x\ \rho\ x\ NCV\ x\ 10^6 \qquad (2)$$

For firewood:

$$DA = F_{biomass}\ x\ NCV \qquad (3)$$

Where,

E_{CO_2}	: Total emission of CO_2
DA	: Activity data with energy unit
EF	: Emission Factor
F_{diesel}	: Diesel consumption
$F_{biomassa}$	: Biomass consumption
NCV	: Net calorific value
ρ	: Density

The emissions of particular greenhouse gases (CO_2, N_2O, CH_4) from each stage of production were transformed into carbon dioxide equivalents (CO_2-eq) using a predetermined conversion factor [18]. The total impact score of GHG emission and ozone depletion can be calculate using the following equation:

Greenhouse Gas:

$$IS_{GHG} = EF_{GHG}\ x\ Amt_{GHG} \qquad (4)$$

Ozone Depletion

$$(IS_{OD})_i = (EF_{ODP}\ x\ Amt_{ODP})_i \qquad (5)$$

Where:

IS_{GHG}	: Impact score for GHG
EF_{GHG}	: Equivalency factor for GHG
Amt_{GHG}	: Amount of inventory output of GHG chemical i released to air per functional unit
$(IS_{OD})_i$	: Impact score for ODP
$(EF_{ODP}$	: ODP Equivalency factor
Amt_{ODP}	: Amount of ODP chemical i released to air per functional unit

Impact score of ozone depletion was quantify into chlorofluorocarbon-11 equivalents (CFC-11 eq). The release of spesific ozone depletion emission are, CFCs (chlorofluorocarbon), all Halons and HCFCs (hydrochlorofluorocarbon). Meanwhile, the impact score of photochemical oxidation was determined into C_2H_4 eq.

2.3.1 OVERALL IMPACT ASSESMENT

The overall impact that is represented in the picture is based on a batch process of tofu production, which is equivalent to 35 kg of tofu. Figure 2 illustrate the environmental impact from the whole life cycle. The preparation of raw materials has the least impact, while the production process has the most. The raw material preparation section does not consider the environmental effects or the energy required during the process of acquiring soybeans on the farm. The effect shown is only from the transportation process. It is the same as the usage stage, which only considers the effects arising from transportation to the market and landfill. Percent of impact that shows in the graph was mostly on the contribution of energy consumption. In spite of the fact that the phases of raw material preparation, usage stage, and end-of-life stage have a significant amount of energy consumption for transportation, but the production process is still the one that has the most impact on energy consumption. It was contributing to more than 80% of the impact that the production process generates.

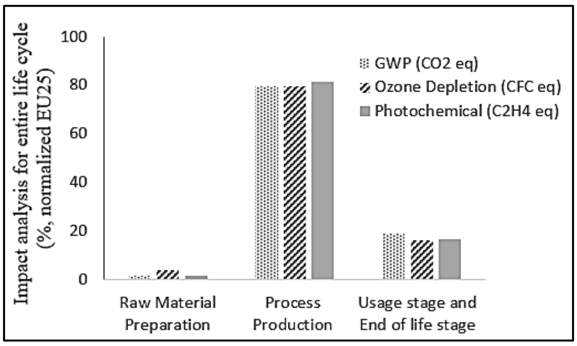

Figure 2. Environmental impact for whole life cyle.

2.3.2 PROCESS PRODUCTION IMPACT ASSESMENT

An analysis of the production process's impact is required in order to ascertain which aspect has the greatest influence. This analysis can help determine which conditions to modify to reduce emissions. Figure 3 presents the contribution to the environment for each process in the manufacturing section. The data revealed was normalized using EU 25. It shows that the processes of grinding and cooking were the most significant contributors to each impact. That was because both processes required energy input. The other stages of the process production didn't need any energy. The impact that was revealed by the other process was caused by the liquid waste that it generates and from water usage. Furthermore, due to the fact that every input data is computed utilizing a database, the consequence stems not solely from the manufacturing process but also from the procurement of the primary materials incorporated in the database. In addition to the CML IA baseline database, others calculations were performed using IPCC emission factors to determine the impact of using two types of fuel in the production process. It was discovered that the cooking process is the largest contributor to GHG emissions, followed by the grinding process. This is due to the cooking process using leftover wood or twigs as fuel to generate steam. In this procedure, 31.25 kg of wood yields 55.61 kg CO_2 eq. The unusually high emission value is due to wood or twigs having a low net calorific value (NCV) of 15.6 TJ/Gg. Meanwhile, the grinding process is the next biggest contributor to GHG emissions. In this method, the grinding machine runs on diesel fuel. Based on functional units, producing 35 kg of tofu requires 0.14kg of diesel. The usage of that much diesel fuel emits 0.4496 kg CO_2 equivalent. Diesel fuel has a greater NCV than wood; it is 43 TJ/Gg. Hence the combustion process works more efficiently and emits fewer pollutants.

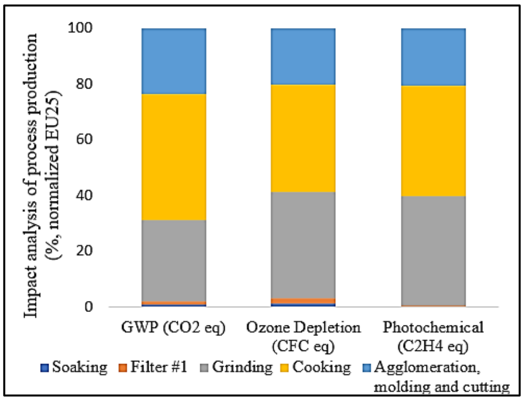

Figure 3. Environmental impact from process production.

3. INTERPRETATION

The interpretation step is the final level of the life cycle assessment. The process is divided into three stages: identifying relevant topics, sensitivity analysis, and conclusions. This study focuses on identifying hotspots in the life cycle of tofu production. There are three different types of impacts that are being investigated in this study: greenhouse gas emissions, ozone depletion, and photochemical oxidation. Based on the boundaries of the system, the cooking step contributed the highest effect number on greenhouse gas emissions, resulting in 55.61 kg CO_2 equivalent. This is because the energy that is being used has a calorific value that is relatively low. When fuel with a low calorific value is used, the combustion process is insufficient, leading to the production of a significant amount of carbon dioxide as a byproduct of the combustion reaction. Consequently, we carried out the simulations with a variety of fuels in order to ascertain the degree to which each alternative fuel was effective in reducing the amount of carbon dioxide (kg CO_2 eq) emissions.

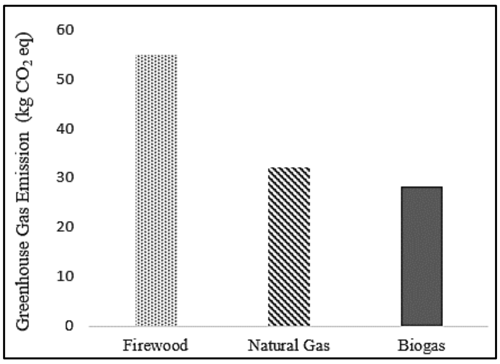

Figure 4. Energy substitution pathways.

Figure 4 illustrate the simulation results of comparing the use of biomass, natural gas and biogas fuels. Data source of natural gas and biogas provided by Ecoinvent V3.10 database. The substitution of biomass energy for the other two fuels resulted in fewer CO2 emissions. The usage of natural gas reduced CO2 production to 32 kilogram CO2 eq, whereas biogas produced an even lower quantity of 28 kg CO2 eq. Biogas fuel could be an alternative energy source in the future because the tofu production process generates a lot of organic liquid waste that has the potential to produce biogas.

3.1 SENSITIVITY ANALSYS

Most LCA studies that conducted a sensitivity analysis employed a straightforward, one-at-a-time (OAT) approach. An OAT approach involves selecting an input parameter, making a modification to it (for example, by 10%), and then quantifying the influence that this change has on the model output [19]. The modification in this study is not in the product input, but in the impact computation approach that utilizes the database. Database that we use as a comparison with CML IA baseline is ReCiPe 2016 H Midpoint. This database also estimated the environment impact on the midpoint section. Additionally, ReCiPe has the ability to transform life cycle inventory data into a sum of midpoint life cycle impact scores using globally representative characterization factors and the same equivalence units as the CML IA Baseline. Due to these factors, the ReCiPe 2016 H midpoint can be employed as a means of comparison in order to verify the accuracy of the preceding method. Based on interpretation that the GHG emission has the bigest impact to the environment than the other, so that the sensitivity analysis parts using the GHG emission as the reference parameter in Figure 5.

4. CONCLUSION

A cradle-to-gate LCA on the environmental impact contribution of tofu making reveals that the production process were the hotspots which needs to be improved with compared to two other processes which were raw material preparation and use/end of life stage. Within the manufacturing processes, grinding and cooking processes were the most significant contributors to the environment, mainly because both processes required energy input. Therefore, in order to reduce burden to the environment, biogas fuel selection could be an alternative energy source because tofu production process generates a lot of organic liquid waste that has the potential to produce biogas. This study could serve as a base case for comparison with other LCA work on tofu production utilizing other clean energy options in the future.

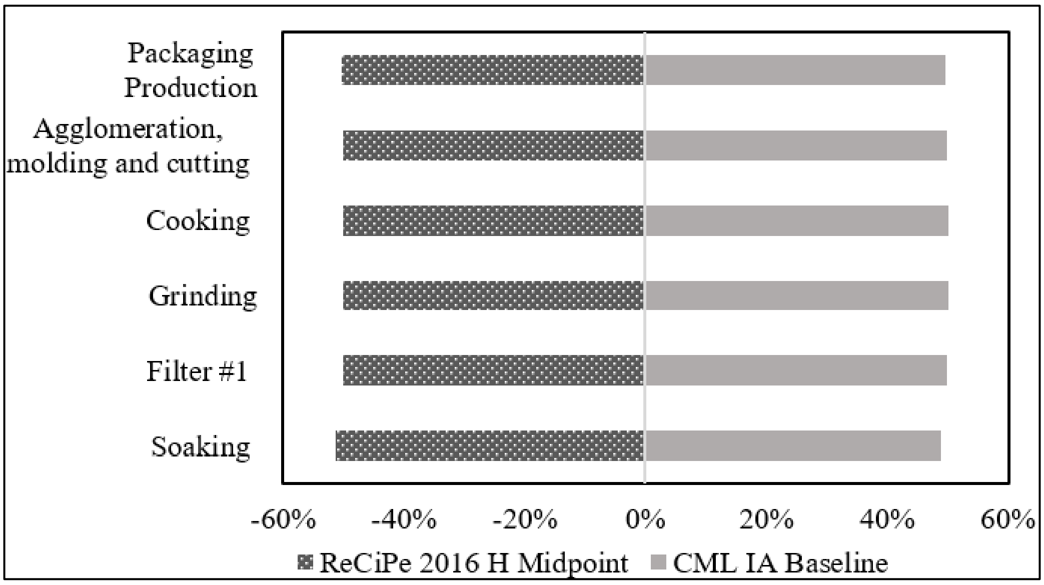

Figure 5. Sensitivity analysis of GHG emission from tofu production.

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