



## Assessing Global Warming, Acidification, and Eutrophication Impacts of Pempek Production Using Life Cycle Assessment: A Case Study in Palembang, Indonesia

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**ABSTRACT:** Traditional food production may generate environmental burdens through raw material sourcing, energy consumption, processing activities, packaging, distribution, and waste generation. This study assessed the environmental impacts of pempek production in a small-scale industry in Palembang, Indonesia, using the Life Cycle Assessment (LCA) approach. The assessment was conducted using the CML-IA Baseline method in SimaPro version 9.5.0.0, with a system boundary covering raw material procurement, dough preparation, resting, shaping, frying, packaging, distribution, and waste-related activities. Inventory data were collected based on one production cycle at Pempek X and included material inputs, energy use, water use, fuel consumption, packaging materials, and emission factors. The results showed that pempek production generated 311.96 kg CO<sub>2</sub>-eq for Global Warming Potential (GWP), 2.397 kg SO<sub>2</sub>-eq for Acidification Potential (AP), and 4.197 kg PO<sub>4</sub><sup>3-</sup>-eq for Eutrophication Potential (EP) per production cycle. The frying stage was the main contributor to GWP (32.1%) and EP (61.3%), mainly due to thermal energy use and cooking oil consumption. The packaging stage contributed the largest share to AP (approximately 27.0%) and also had a substantial contribution to GWP (25.2%). From the raw material perspective, wheat flour was the dominant contributor across several impact categories, followed by palm oil, demersal fish, tofu, and eggs. These impacts were mainly associated with upstream agricultural activities, energy use, and material production processes. The findings indicate that energy-intensive processing, raw material supply chains, and packaging materials are key environmental hotspots in pempek production. Improving frying efficiency, selecting lower-impact packaging, strengthening waste management, and sourcing more sustainable raw materials were recommended to reduce environmental burdens. This study demonstrates the usefulness of LCA for identifying improvement priorities in traditional food production systems.

**Keywords:** Acidification; Eutrophication; Global Warming Potential; Life Cycle Assessment (LCA); Pempek Production

### 1. INTRODUCTION

Pempek is a traditional food product from Palembang, Indonesia, that represents both

regional culinary identity and local economic activity. It is commonly prepared from ground fish, tapioca flour, wheat flour,

seasonings, and water, followed by a sequence of processing activities such as mixing, shaping, cooking or frying, packaging, and distribution. The growing demand for pempek has stimulated the development of small and medium-scale food enterprises in Palembang and South Sumatra, thereby contributing to employment generation, household income, and local food-based entrepreneurship (Syarifuddin et al., 2022; Wargadalem et al., 2023). However, the expansion of traditional food production also increases the use of raw materials, energy, water, and packaging materials, which may intensify environmental pressures when production systems are not managed efficiently.

Food production systems contribute to environmental impacts through several interconnected pathways. The procurement of agricultural, fishery, and auxiliary raw materials requires natural resources and may generate upstream emissions. Processing activities consume energy and water, while cooking or frying stages release combustion-related emissions and generate used cooking oil or wastewater. Packaging and distribution further add environmental burdens through material consumption, electricity use, fuel use, and waste generation. In small-scale food industries, these impacts may become more significant because resource management, energy efficiency, waste handling, and environmental monitoring are often limited (Thamir et al., 2019). Consequently, the environmental impacts of pempek production cannot be understood only from the final product but must be traced across the entire production chain.

The need to evaluate environmental burdens in food production is closely aligned with sustainable development priorities, particularly the Sustainable Development Goals (SDGs). Pempek production is relevant to SDG 12 on responsible consumption and production because it involves material efficiency, waste reduction, and cleaner production practices. It is also connected to SDG 13 on

climate action through greenhouse gas emissions from energy use and raw material supply chains, as well as SDG 6 on clean water and sanitation because food processing may generate wastewater and nutrient-related pollutants. As global concern about climate change, resource depletion, and ecosystem degradation continues to increase, systematic environmental assessment is required to support more sustainable production systems and evidence-based improvement strategies (Hapuwatte & Jawahir, 2021; Junianto et al., 2024).

Life Cycle Assessment (LCA) provides a comprehensive approach for evaluating the potential environmental impacts of a product system. According to the ISO 14040 and ISO 14044 frameworks, LCA assesses inputs, outputs, and potential environmental impacts from raw material acquisition to production, distribution, use, and end-of-life stages. In the food sector, LCA is widely used to identify environmental hotspots, compare process contributions, and formulate improvement strategies based on quantified evidence. Its application enables researchers and practitioners to determine which stages of production contribute most significantly to impact categories such as global warming potential, acidification potential, and eutrophication potential. Previous studies have demonstrated the usefulness of LCA in assessing environmental burdens and improvement opportunities in meat, fish, and processed food systems (Ichsan et al., 2025; Tian et al., 2021; van der Werf et al., 2020; Wiloso et al., 2022).

Environmental assessment studies have been conducted in several food processing sectors, including sugar, tofu, and fish processing. Sirait (2020) identified energy consumption as a major environmental issue in sugar production, while Harjanto et al. (2022) assessed tofu production using the ISO 14040 framework. Ar Rachmah et al. (2020) examined emissions associated with fish processing activities. In the context of pempek, existing research has mainly

focused on cleaner production practices for reducing waste in household-scale industries (Frisilla et al., 2024). Nevertheless, comprehensive and quantitative assessments of pempek production using a life-cycle perspective remain limited. This gap is important because pempek production involves multiple stages, including raw material procurement, dough preparation, shaping, frying, packaging, and distribution, each of which may contribute differently to environmental impacts.

Therefore, this study aimed to assess the environmental impacts of pempek production in a small-scale industry in Palembang, Indonesia, using the Life Cycle Assessment approach. Specifically, the study quantifies global warming potential, acidification potential, and eutrophication potential, and identifies the main process hotspots within the pempek production system. By providing quantitative evidence on the environmental burdens of traditional food production, this study is expected to support cleaner production strategies, improve resource efficiency, and contribute to more sustainable small-scale food industry practices.

## 2. MATERIALS AND METHODS

### 2.1. Study Area and Research Period

This study was conducted over an eight-month period, from December 2024 to July 2025, in a small-scale pempek production facility located in Palembang City, South Sumatra, Indonesia. The selected facility represents a conventional traditional pempek production system in which fish meat, tapioca flour, wheat flour, seasonings, and supporting ingredients are processed into various pempek products through semi-manual operations.

The assessment focused on the environmental impacts associated with pempek production using the Life Cycle Assessment (LCA) approach. The production system included raw material procurement, dough preparation, resting, shaping, frying, packaging, distribution, and waste generation. Inventory data were

collected based on one production cycle at the observed facility and were interpreted in relation to the total pempek output produced during that cycle. This unit was used to ensure that material and energy flows reflected the actual operational conditions of the small-scale production system.

### 2.2. Types and Sources of Data

This study used both primary and secondary data. Primary data were obtained through direct field observation, interviews with the owner and workers, and documentation of production activities. The primary data included information on production stages, raw material quantities, auxiliary materials, energy consumption, water use, equipment use, product output, and waste generation during pempek production.

Secondary data were obtained from production records, scientific literature, emission factor references, and relevant LCA databases. These data were used to support the estimation of emissions, the selection of inventory datasets, and the modelling of environmental impacts in the LCA software. The combination of primary and secondary data was intended to represent the actual production conditions while maintaining consistency with established LCA procedures.

### 2.3. Data Collection Methods

Data were collected through observation, interviews, and documentation. Direct observation was conducted to identify the sequence of production activities and to record input–output flows at each stage of pempek production. This method enabled the identification of material flows, energy requirements, water use, and waste outputs under actual production conditions.

Interviews were conducted with the owner and workers of the pempek production facility to obtain information on production procedures, raw material procurement, production frequency, equipment use, and waste handling practices. Documentation was used to verify

production records, purchase records, raw material quantities, packaging materials, water consumption, energy use, and other operational data relevant to the inventory analysis.

#### **2.4. Method for Assessing the Life Cycle**

The environmental impacts of pempek production were assessed using the Life Cycle Assessment method based on ISO 14040 and ISO 14044. The LCA framework consists of four main phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (Badan Standarisasi Nasional, 2016; Curran, 2012; Guinée et al., 2002; Hauschild et al., 2018; Kementerian Lingkungan Hidup dan Kehutanan, 2021; Sonnemann et al., 2019).

LCA modelling was performed using SimaPro version 9.5.0.0. The CML-IA Baseline method was applied to evaluate the potential environmental impacts of the pempek production system. This study focused on three impact categories: Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP). These categories were selected because they are closely related to energy consumption, combustion emissions, raw material production, wastewater generation, and nutrient-related environmental burdens in food production systems.

##### **2.4.1 Goals and Scope Definition**

The goal of this study was to assess the environmental impacts of pempek production and identify the main process hotspots contributing to environmental burdens. The assessment was designed to provide quantitative evidence that can support cleaner production strategies and more sustainable resource management in small-scale traditional food industries.

The system boundary followed a cradle-to-grave approach, covering raw material acquisition, production, packaging, distribution, and waste generated from production and consumption activities. In this study, the end-of-life stage was limited to waste associated with the observed

production context and product consumption within the defined system. The functional unit was defined as one production cycle of pempek at the selected facility, which served as the basis for compiling inventory data on materials, energy, water, packaging, emissions, and waste outputs.

##### **2.4.2 Life Cycle Inventory (LCI)**

The Life Cycle Inventory phase involved the identification and quantification of relevant input and output flows within the pempek production system. Inventory data were organized according to each production stage, including raw material procurement, dough preparation, resting, shaping, frying, packaging, distribution, and waste handling. Material inputs included fish, tapioca flour, wheat flour, salt, seasonings, tofu, eggs, cooking oil, water, and packaging materials. Energy inputs included fuel used for raw material transportation, liquefied petroleum gas used during frying, and electricity used for packaging equipment. Output flows included finished pempek products, used cooking oil, wastewater, solid waste, and emissions to air, water, or soil where applicable. The inventory data were entered into SimaPro version 9.5.0.0 using database entries that most closely represented the materials and processes used in the observed facility. When primary data were not available, secondary data from scientific literature, emission factor references, and LCA databases were used to complete the inventory model.

##### **2.4.3 Life Cycle Impact Assessment (LCIA)**

The Life Cycle Impact Assessment phase converted inventory data into potential environmental impacts using the CML-IA Baseline method. The assessment focused on Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP). Global Warming Potential represents greenhouse gas emissions associated with energy use, raw material supply, transportation, and

combustion processes. Acidification Potential reflects emissions that may contribute to acid deposition, such as sulfur oxides and nitrogen oxides. Eutrophication Potential represents nutrient-related emissions that may contribute to excessive nutrient enrichment in aquatic ecosystems. Three categories were selected because they are commonly used in environmental assessments of food production and are directly relevant to pempek production, particularly in relation to raw material sourcing, frying activities, wastewater generation, energy consumption, and packaging-related emissions.

#### 2.4.4 Interpretation

The interpretation phase involved evaluating the LCIA results to identify the dominant impact categories and the production stages contributing most significantly to environmental burdens. The interpretation focused on determining which processes acted as environmental hotspots within the pempek production system. The interpretation results were used to formulate improvement strategies for reducing environmental burdens. These strategies include improving energy efficiency, optimizing raw material use, reducing waste generation, improving wastewater handling, managing used cooking oil more effectively, and considering more sustainable packaging alternatives. The recommendations were developed to support cleaner production and more sustainable practices in small-scale traditional food industries.

### 3. RESULTS AND DISCUSSION

#### 3.1. Result

##### 3.1.1 General Description of the Study Object

Pempek Industry X is a small-scale food enterprise located in the 7 Ulu area of Palembang City, South Sumatra, Indonesia. The enterprise has operated since 2004 and employs 16 workers with different roles in procurement, processing, packaging, and sales. The products manufactured include pempek lenjer, pempek kulit, pempek adaan,

egg-filled pempek, papaya-filled pempek, pempek keriting, and tofu pempek. The production system is semi-manual and consists of several main stages: raw material procurement, dough preparation, resting, shaping, frying, packaging, and distribution. The dough is prepared by mixing ground fish, tapioca flour, wheat flour, seasonings, and water. After mixing, the dough is shaped into different pempek variants and rested for approximately 10–15 minutes before cooking or frying. The final products are then sold directly or packaged for distribution.

From an environmental perspective, the production process generates wastewater and solid waste. Wastewater from production activities is discharged into the surrounding drainage system, while solid waste is collected in designated containers before being transported to the municipal waste disposal site. The use of raw materials, energy, water, packaging materials, and waste handling practices indicates that pempek production has several environmental input–output flows that require systematic assessment.

The main raw materials used in pempek production are presented in Table 1. The quantities represent materials purchased in each procurement activity. Raw materials, particularly fish, are commonly purchased twice a week to maintain freshness and ensure production continuity.

**Table 1.** Raw materials purchased for pempek production

No	Material	Supplier	Quantity per Purchase
1	Tapioca Flour	7 Ulu Market	250 kg
2	Wheat Flour	7 Ulu Market	75 kg
3	Spanish mackerel (Scomberomorini)	Jakabaring Central Market	300 kg
4	Salt	7 Ulu Market	5 packs
5	Flavor Enhancer	7 Ulu Market	2 kg
6	Onion	Jakabaring Central Market	10 kg
7	Water	PDAM / Drinking Water Depot	As required

### 3.1.2 Goal, Scope, and System Boundary

The goal of the Life Cycle Assessment was to evaluate the environmental impacts of pempek production at Pempek Industry X and to identify the production stages that contribute most significantly to environmental burdens. The assessment was intended to provide quantitative evidence for improving the environmental performance of small-scale traditional food production.

The scope of the study followed a cradle-to-grave approach, covering raw material procurement, production, packaging, distribution, and waste generation. The system boundary included the acquisition of raw materials from suppliers, transportation to the production facility, processing activities, packaging, distribution to consumers, and waste generated within the observed production system. The end-of-life stage was limited to waste generated from production activities and direct product consumption within the defined system boundary.

The functional unit was one production cycle of pempek at the selected facility. This functional unit was used as the basis for compiling inventory data and calculating environmental impacts. The use of one production cycle reflects the operational characteristics of the small-scale production system and enables the input and output flows to be interpreted in relation to the total pempek output produced during that cycle.

### 3.1.3 Life Cycle Inventory (LCI)

The Life Cycle Inventory was organized according to the main stages of pempek production: raw material procurement, dough preparation, resting, shaping, frying, packaging, distribution, and waste handling. The inventory included material inputs, energy inputs, product outputs, by-products, waste, and emissions associated with each stage.

Material inputs consisted of fish, tapioca flour, wheat flour, salt, flavor enhancer, onion, tofu, eggs, cooking oil, water, and packaging materials. Energy inputs included gasoline and diesel for raw material

transportation, liquefied petroleum gas for frying, and electricity for packaging equipment. Output flows included semi-finished and finished pempek products, used cooking oil, wastewater, solid waste, and air emissions from fuel and energy use.

### Raw Material Procurement Stage

The raw material procurement stage represents the first stage of the pempek life-cycle system. Raw materials were obtained from two main supplier locations: Jakabaring Central Market and 7 Ulu Market. Transportation from these suppliers to the production facility required fossil fuel use and generated air emissions.

Jakabaring Central Market was located approximately 9 km from the production facility. Materials transported from this supplier included fish, tofu, chili, and onion. The operational vehicle had a fuel consumption rate of approximately 0.067 L/km, with a total transported load of approximately 320 kg per trip. Based on the travel distance and fuel consumption rate, the gasoline use for one procurement trip was approximately 0.6 L. The transportation activity generated emissions of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, CO, and NO<sub>x</sub>, as summarized in Table 2. The transportation capacity of the vehicle is calculated using the following equation:

$$\begin{aligned} VTC &= VLC \times TD \\ VTC &= 0.4 \text{ ton} \times 9 \text{ km} = 3.6 \text{ ton km (tkm)} \end{aligned} \quad (1)$$

The effective material transport capacity is calculated as:

$$\begin{aligned} MTC &= \frac{TMW}{VLC} \times VTC \\ MTC &= \frac{0.32 \text{ ton}}{0.4 \text{ ton}} \times 3.6 \text{ tkm} = 2.88 \text{ tkm} \end{aligned} \quad (2)$$

The gasoline consumption during transportation is calculated as:

$$\begin{aligned} FC &= FCR \times TD \\ FC &= 0.067 \frac{\text{L}}{\text{km}} \times 9 \text{ km} = 0.6 \text{ L} \\ FC &\approx 0.444 \text{ kg} \end{aligned} \quad (3)$$

where VTC are vehicle transport capacity (tkm), VLC are vehicle load capacity (ton), TD are travel distance (km), MTC are material transport capacity (tkm), TMW are transported material weight (ton), FC are fuel consumption (L), and FCR are fuel consumption rate (L/km).

The emissions from gasoline (RON 90) were determined using the emission factor method, utilizing data from the Ministry of Energy and Mineral Resources (Kementrian ESDM, 2023; Pusat Studi Transportasi dan Logistik UGM, 2017; Rusdiani, 2018; Tiarani et al., 2016). The emissions generated from fuel consumption during transportation were calculated using Equation (4).

$$\text{Emission} = \text{FC} \times \text{CF} \times \text{EF} \quad (4)$$

For CO emissions, the calculation also considers fuel density, as expressed in Equation (5).

$$\text{Emission CO} = \text{FC} \times \rho \times \text{CF} \times \text{EF} \quad (5)$$

where FC are fuel consumption (L), CV are net calorific value (TJ/Gg), EF are emission factor (ton/TJ), and  $\rho$  are fuel density ( $\text{kg/m}^3$ ).

The emission calculations include CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, NO<sub>x</sub>, and CO emissions. The calculation results for transportation activities are summarized in Table 2.

**Table 2.** Input–output inventory of the raw material procurement stage (Jakabaring Central Market)

Input		Output				
Material	Database	Qty	Unit	Material	Qty	Unit
Spanish mackerel	Demersal fish, fresh {GLO}   market for demersal fish, fresh   Cut-off, S	300	Kg	Spanish mackerel	300	Kg
Tofu	Tofu {GLO}   market for tofu   Cut-off, S	20	Kg	Tofu	20	Kg
Gasoline	Gasoline, at refinery/I/US	0.6	L	Carbon dioxide CO <sub>2</sub>	1.372	Kg
				Methane CH <sub>4</sub>	0.0000197	Kg
				Dinitrogen monoxide N <sub>2</sub> O	0.0001419	Kg
				Carbon monoxide CO	166.9	Kg
				Nitrogen oxide NO <sub>x</sub>	0.002944	Kg

The second supplier location was 7 Ulu Market, situated approximately 0.5 km from the production facility. Materials procured from this market included tapioca flour, wheat flour, salt, flavor enhancer, and eggs. These materials were transported using supplier vehicles with an estimated diesel

consumption rate of 0.125 L/km. One delivery trip transported approximately 798.8 kg of materials, resulting in an estimated diesel consumption of 0.0625 L. The inventory data for this procurement route are presented in Table 3.

**Table 3.** Input–output inventory of the raw material procurement stage from 7 Ulu Market

Input		Output				
Material	Database	Qty	Unit	Material	Qty	Unit
Tapioca flour	Cassava, at farm {TH}   Economic, S	250	kg	Tapioca flour	250	kg
Wheat flour	Wheat flour {RoW}   market for wheat flour   Cut-off, S	75	kg	Wheat flour	75	kg
Salt	Salt {GLO}   salt production from seawater, evaporation pond   Cut-off, S	10	kg	Salt	10	kg
Flavor enhancer	Chemical, organic {GLO}   market for chemical, organic   Cut-off, S	2	kg	Flavor enhancer	2	kg
Eggs	Consumption egg, at farm {RER}   Economic, S	50	kg	Eggs	50	kg
Diesel fuel	Diesel fuel   market for diesel   Cut-off, S	0.0625	L	Carbon dioxide (CO <sub>2</sub> )	0.1657	kg
				Methane (CH <sub>4</sub> )	0.00002237	kg
				Nitrous oxide (N <sub>2</sub> O)	0.000001342	kg

Input		Output				
Material	Database	Qty	Unit	Material	Qty	Unit
				Carbon monoxide (CO)	0.02681	kg
				Nitrogen oxides (NO <sub>x</sub> )	0.000002965	kg

### Production Stage

#### Dough Preparation

Dough preparation is the initial processing stage in pempek production. Ground spanish mackerel, tapioca flour,

wheat flour, salt, flavor enhancer, and water are mixed manually in a large container to form a homogeneous dough with the desired texture. The input–output inventory data are presented in Table 4.

**Table 4.** Input–output inventory of the dough preparation stage

Input		Output				
Material	Database	Qty	Unit	Material	Qty	Unit
Ground Spanish mackerel	Demersal fish, fresh {GLO}   market for demersal fish, fresh   off, S	10	kg	Dough	22.4	kg
Tapioca flour	Cassava, at farm {TH}   Economic, S	5	kg			
Wheat flour	Wheat flour {RoW}   market for wheat flour   Cut-off, S	2	kg			
Flavor enhancer	Chemical, organic {GLO}   market for chemical, organic   S	0.15	kg			
Salt	Salt {GLO}   salt production from seawater, evaporation pond   Cut-off, S	0.25	kg			
Water	Water, process, drinking	5	L			

### Resting Process

After mixing, the dough is rested for approximately one hour to stabilize its structure and improve its texture before shaping. This stage does not require

additional material or energy inputs because it consists only of a waiting period. The mass of the dough remains unchanged during the resting stage, as shown in Table 5.

**Table 5.** Input–output of the resting stage

Input		Output				
Material	Database	Qty	Unit	Material	Qty	Unit
Dough	Wheat flour mix {RoW}   batter wheat mix production   Cut-off, S	22.4	kg	Dough	22.4	kg

### Shaping Process

The rested dough is manually shaped into several pempek variants, including lenjer, kulit, adaan, egg-filled pempek, and tofu pempek. Additional ingredients, particularly

tofu and eggs, are incorporated depending on the product variant. This stage produces semi-finished pempek before the frying process. The input and output flows for this stage are summarized in Table 6.

**Table 6.** Input–output of the pempek shaping stage

Input		Output				
Material	Database	Qty	Unit	Material	Qty	Unit
Dough	Wheat flour mix {RoW}   batter wheat mix production   Cut-off, S	22.4	kg	Pempek	32.4	kg
Tofu	Tofu {GLO}   market for tofu   Cut-off, S	7	kg			
Eggs	Consumption egg, at farm {RER}   Economic, S	3	kg			

### Frying Process

The semi-finished pempek is fried using cooking oil as the heating medium and LPG as the energy source. The frying process changes the texture, color, and final mass of the product due to heat treatment and oil

absorption. This stage also generates used cooking oil and combustion emissions from LPG use.

LPG combustion in frying produces air emissions, including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and dinitrogen monoxide

(N<sub>2</sub>O). These emissions are the environmental burdens of the cooking stage in pempek production. Emissions from LPG use are calculated as shown in equation (4) (Rahmawati, 2022). The calculation results

of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions from the frying stage and he detailed input–output inventory for the frying stage used in the Life Cycle Inventory (LCI) analysis is presented in Table 7.

**Table 7.** Input–output of the frying stage

Input				Output		
Material	Database	Qty	Unit	Material	Qty	Unit
Pempek	Wheat flour mix {RoW}   batter wheat mix production   Cut-off, S	32.4	kg	Fried pempek	33.49	kg
Cooking oil	Palm oil, refined {GLO}   market for palm oil, refined   Cut-off, S	9	L	Used cooking oil	4.35	L
LPG gas	Liquefied petroleum gas {RoW}   market for liquefied petroleum gas   Cut-off, S	0.6	kg	Carbon dioxide (CO <sub>2</sub> )	1.789	kg
				Methane (CH <sub>4</sub> )	0.02838	kg
				Dinitrogen monoxide (N <sub>2</sub> O)	0.002838	kg

**Packaging Process**

After frying, the pempek is packaged using plastic packaging materials and vacuum-sealing equipment. Packaging aims to maintain product hygiene and extend product shelf life. Electricity consumption for the vacuum sealer was calculated at 0.75 kWh per production cycle based on a power requirement of 750 W and an operating time of one hour. Electricity use in this stage is associated with indirect emissions from the electricity supply system.

Electricity consumption during the packaging process is calculated using the following equation:

$$\text{Energy(kWh)} = \frac{\text{Power(Watt)} \times \text{Time(hours)}}{1000} \quad (5)$$

$$\text{Energy(kWh)} = \frac{750 \times 1}{1000} = 0.75 \text{ kWh}$$

**3.1.4 Life Cycle Impact Assessment Results**

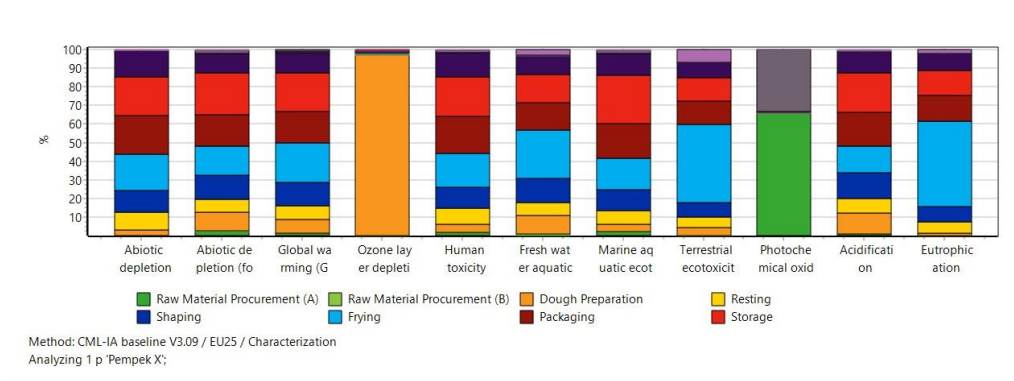
The Life Cycle Impact Assessment results were obtained by converting inventory flows into potential environmental impacts using the CML-IA Baseline method. The characterization results for 11

environmental impact categories are presented in Table 8.

**Table 8.** Characterization Results

Impact category	Unit	Total
Abiotic depletion	kg Sb eq	0.001587
Abiotic depletion (fossil fuels)	MJ	2285.173
Global warming (GWP100a)	kg CO <sub>2</sub> eq	311.9616
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000138
Human toxicity	kg 1,4-DB eq	188.8962
Fresh water aquatic ecotox.	kg 1,4-DB eq	178.8149
Marine aquatic ecotoxicity	kg 1,4-DB eq	202144.3
Terrestrial ecotoxicity	kg 1,4-DB eq	31.79867
Photochemical oxidation	kg C <sub>2</sub> H <sub>4</sub> eq	6.846749
Acidification	kg SO <sub>2</sub> eq	2.396789
Eutrophication	kg PO <sub>4</sub> <sup>3-</sup> eq	4.19736

The characterization results indicate that the pempek production system contributes to multiple environmental impact categories. As illustrated in Figure 1, marine aquatic ecotoxicity shows the largest absolute value, followed by abiotic depletion of fossil fuels, global warming potential, human toxicity, freshwater aquatic ecotoxicity, and terrestrial ecotoxicity. Since each impact category uses a different unit, direct comparison between categories should be supported by normalization.



**Figure 1.** Impact Assessment – Characterization

The graph shows the contribution of each stage of the pempek production process to various categories of environmental impact. The frying and storage processes appear to make a significant contribution to several impact categories, especially those related to energy consumption.

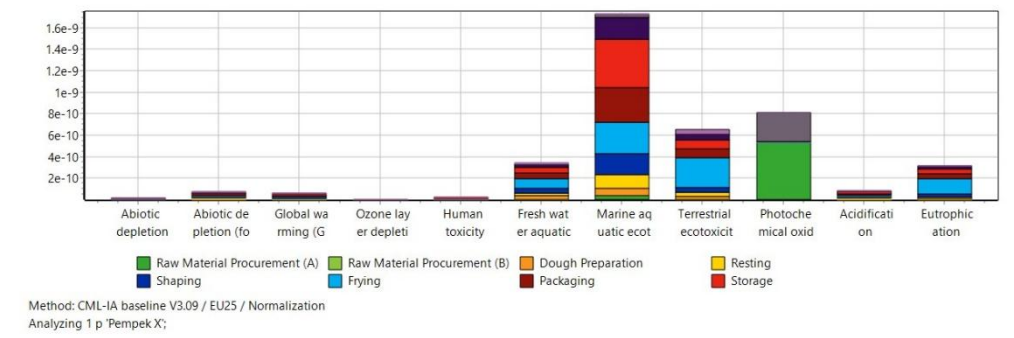
Normalization was conducted to compare the relative significance of different environmental impact categories on a standardized scale. The normalization results are presented in Table 9.

**Table 9.** Normalization Result

Impact category	Total
Abiotic depletion	1.8727E-11
Abiotic depletion (fossil fuels)	7.2669E-11
Global warming (GWP100a)	6.2080E-11
Ozone layer depletion (ODP)	1.5440E-12

Impact category	Total
Human toxicity	2.4368E-11
Fresh water aquatic ecotox.	3.4511E-10
Marine aquatic ecotoxicity	1.7324E-09
Terrestrial ecotoxicity	6.5505E-10
Photochemical oxidation	8.0792E-10
Acidification	8.5086E-11
Eutrophication	3.1816E-10

The normalized results show that marine aquatic ecotoxicity has the highest relative impact value, followed by photochemical oxidation, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, and eutrophication. As shown in Figure 2, ecotoxicity-related categories and atmospheric pollution categories are important environmental concerns in the assessed pempek production system.



**Figure 2.** Impact Assessment – Normalization

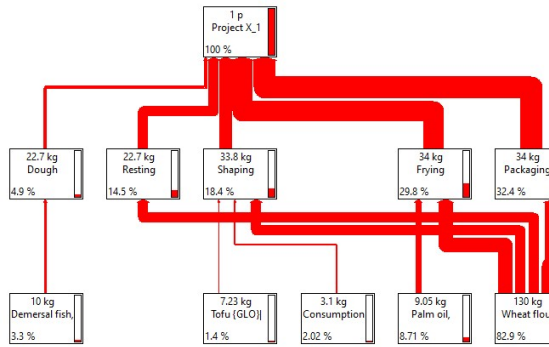
The normalization graph compares impact categories on a standardized scale. This process highlights the most significant categories, supporting LCA result interpretation.

### Environmental Impact Analysis on Each Impact Category

#### Abiotic Depletion

The total abiotic depletion impact of the pempek production system was 0.001587 kg Sb eq. As shown in Figure 3, the packaging stage contributed the largest share at 32.4%,

followed by frying at 29.8%, shaping at 18.4%, resting at 14.5%, and dough preparation at approximately 4.9%.

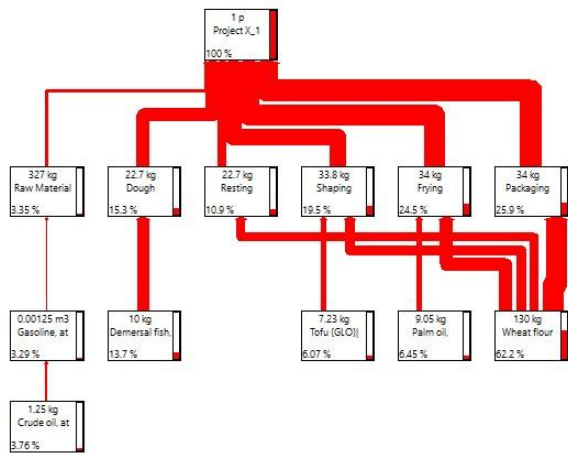


**Figure 3.** Contribution to the abiotic depletion impact category

From the raw material perspective, wheat flour was the dominant contributor, accounting for approximately 82.9% of the total contribution. Palm oil contributed 8.71%, while demersal fish contributed 3.3%. These results indicate that raw material consumption and processing-related energy use are the main contributors to abiotic resource depletion.

**Abiotic Depletion of Fossil Fuels**

The total abiotic depletion of fossil fuels was 2285.17 MJ. As illustrated in Figure 4, the packaging stage contributed the largest share at 25.9%, followed by frying at 24.5%, shaping at 19.5%, dough preparation at 15.3%, resting at 10.9%, and raw material acquisition at approximately 3.35%.

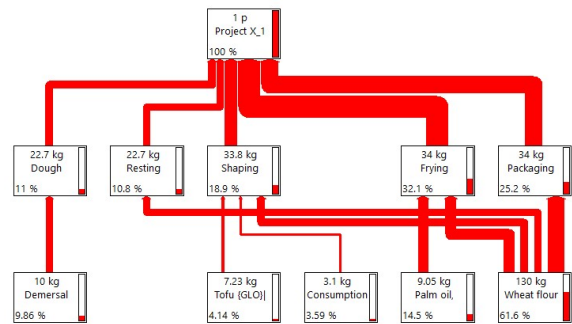


**Figure 4.** Contribution to the abiotic depletion (fossil fuels)

In terms of material contribution, wheat flour accounted for approximately 62.2%, followed by demersal fish at 13.7%, palm oil at 6.45%, and tofu at 6.07%. These findings indicate that fossil energy demand is strongly associated with raw material supply chains as well as energy-intensive processing and packaging stages.

**Global Warming Potential**

The total Global Warming Potential of the pempek production system was 311.96 kg CO<sub>2</sub> eq. As shown in Figure 5, the frying stage was the largest contributor at 32.1%, mainly due to LPG use during thermal processing. The packaging stage contributed 25.2%, followed by shaping at 18.9%, dough preparation at 11.0%, and resting at 10.8%.



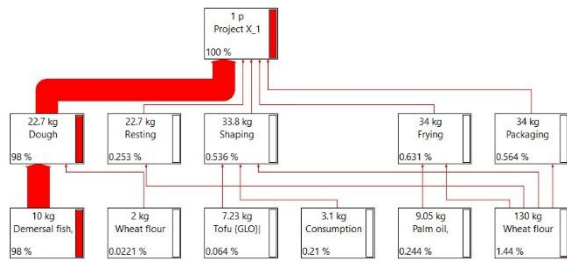
**Figure 1.** Contribution to the Global Warming Potential (GWP100a) impact category

From the raw material perspective, wheat flour contributed approximately 61.6% of the total GWP, followed by palm oil at 14.5%, demersal fish at 9.86%, tofu at 4.14%, and eggs at 3.59%. These results show that both energy use during frying and upstream raw material production are important contributors to greenhouse gas emissions.

**Ozone Layer Depletion**

The total Ozone Depletion Potential of the pempek production system was 0.000138 kg CFC-11 eq. As presented in Figure 6, dough preparation was the dominant contributing stage, accounting for nearly 98% of the total impact. Frying, packaging, shaping, and resting contributed

relatively small shares of 0.631%, 0.564%, 0.536%, and 0.253%, respectively.

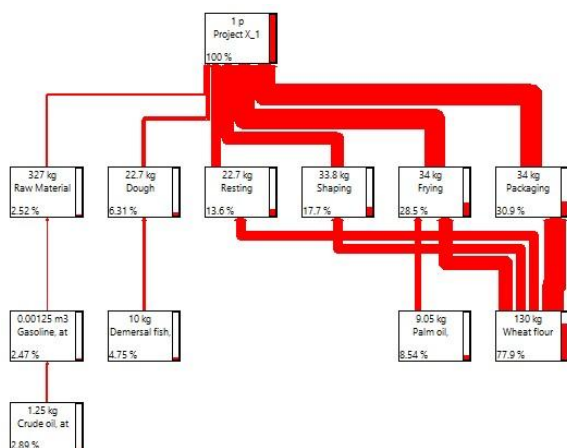


**Figure 6.** Contribution to the Ozone Layer Depletion Potential (ODP) effect category

Demersal fish was the dominant material contributor, representing approximately 98% of the total ODP contribution. Other contributors included wheat flour, palm oil, eggs, and tofu, each with substantially lower contributions. This result indicates that the supply chain of fish-based raw materials is the main factor associated with ozone depletion potential in the assessed system.

### Human Toxicity

The total human toxicity impact was 188.90 kg 1,4-DB eq. As shown in Figure 7, the packaging stage contributed the highest share at approximately 30.9%, followed by frying at 28.5%, shaping at 17.7%, resting at 13.6%, dough preparation at 6.31%, and raw material acquisition at 2.52%.



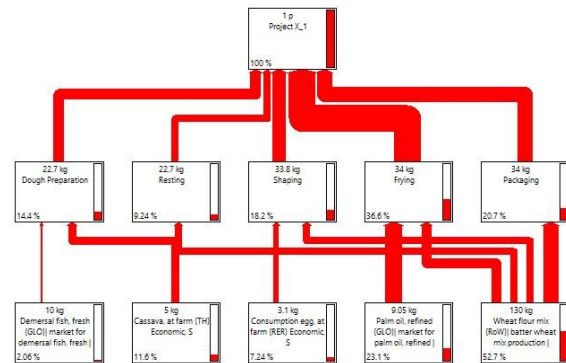
**Figure 7.** Contribution to the Human Toxicity effect category

Wheat flour was the dominant contributor from the material perspective, accounting

for approximately 77.9%. Palm oil contributed 8.54%, demersal fish 4.75%, crude oil 2.89%, and gasoline 2.4%. These results indicate that raw material production and energy-related processes are the main drivers of human toxicity impacts.

### Freshwater Aquatic Ecotoxicity

The total freshwater aquatic ecotoxicity impact was 178.81 kg 1,4-DB eq. As illustrated in Figure 8, the contribution pattern was similar to human toxicity, with packaging contributing the largest share at approximately 30.9%, followed by frying at 28.5%, shaping at 17.7%, resting at 13.6%, dough preparation at 6.31%, and raw material acquisition at 2.52%.

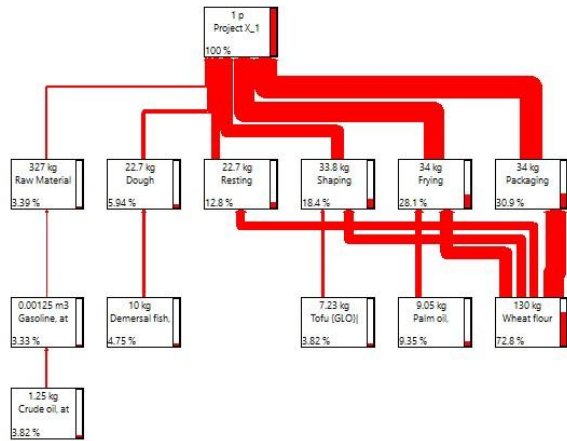


**Figure 8.** Contribution to the Fresh Water Aquatic Ecotoxicity category

Wheat flour contributed approximately 77.9% of the total impact, followed by palm oil at 8.54%, demersal fish at 4.75%, crude oil at 2.89%, and gasoline at 2.4%. These results suggest that upstream agricultural and processing activities contribute substantially to potential freshwater ecosystem impacts.

### Marine Aquatic Ecotoxicity

The total marine aquatic ecotoxicity impact was 202,144.28 kg 1,4-DB eq, which was the highest absolute value among the assessed impact categories. As shown in Figure 9, the packaging stage contributed the largest share at approximately 30.9%, followed by frying at 28.1%, shaping at 18.4%, resting at 12.8%, dough preparation at 5.98%, and raw material acquisition at 3.39%.

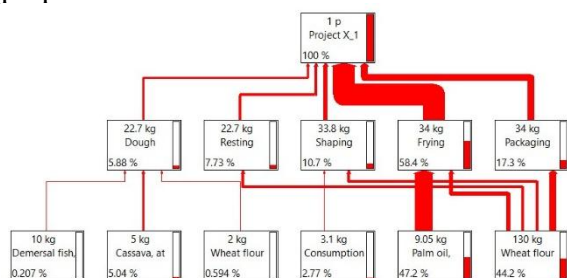


**Figure 9.** Contribution diagram of processes and materials to the Marine Aquatic Ecotoxicity impact category

Wheat flour was the largest material contributor at approximately 72.8%, followed by palm oil at 9.35%, demersal fish at 4.75%, crude oil at 3.82%, gasoline at 3.33%, and tofu at 3.82%. These results indicate that agricultural supply chains, energy use, and packaging-related processes are major contributors to marine ecotoxicity impacts.

### Terrestrial Ecotoxicity

The total terrestrial ecotoxicity impact was 31.80 kg 1,4-DB eq. As presented in Figure 10, the frying stage contributed the largest share at approximately 58.4%, followed by packaging at 17.3%, shaping at 10.7%, resting at 7.73%, and dough preparation at 5.88%.



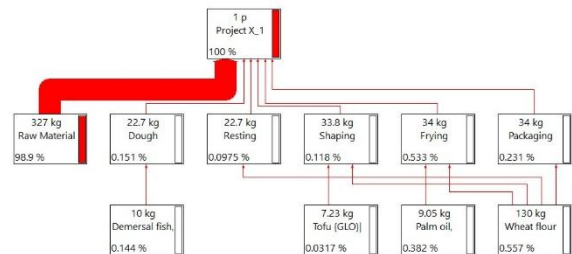
**Figure 10.** Contribution diagram of processes and materials to the Terrestrial Ecotoxicity impact category

Palm oil and wheat flour were the dominant material contributors, accounting for 47.2% and 44.2%, respectively. This result indicates that agricultural raw

materials and thermal processing activities are the main contributors to terrestrial ecotoxicity in the pempek production system.

### Photochemical Oxidation

The total photochemical oxidation impact was 6.847 kg C<sub>2</sub>H<sub>4</sub> eq. As shown in Figure 11, the raw material acquisition stage was the dominant contributor, accounting for approximately 98.9% of the total impact. This high contribution was mainly associated with fuel use during transportation, particularly gasoline combustion, which generates emissions related to photochemical oxidant formation.

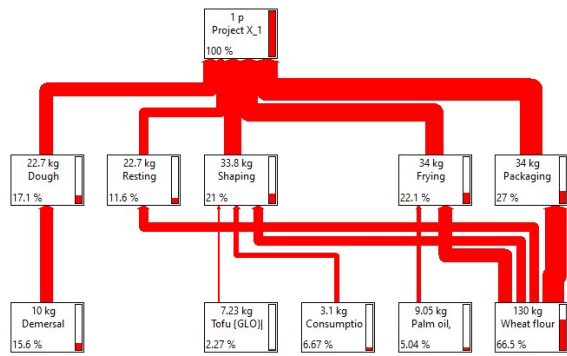


**Figure 11.** Diagram illustrating the process and material contributions to the Photochemical Oxidation impact category

These results show that transportation activities in the raw material supply chain are the primary source of photochemical oxidation impacts in the assessed system.

### Acidification

The total acidification impact was 2.397 kg SO<sub>2</sub> eq. As illustrated in Figure 12, the packaging stage contributed the largest share at approximately 27.0%, followed by frying at 22.1%, shaping at 21.0%, dough preparation at 17.1%, and resting at 11.6%.

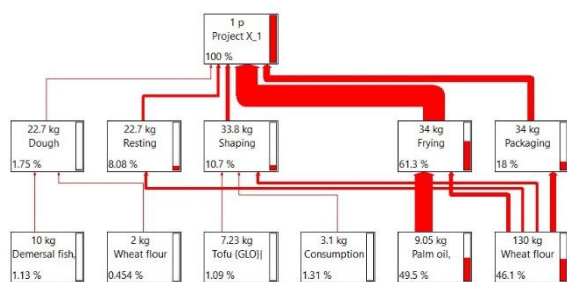


**Figure 12.** Contribution diagram illustrating the processes and materials affecting the Acidification impact category

Wheat flour was the main contributor from the material perspective, accounting for approximately 66.5% of the total contribution. Demersal fish contributed 15.6%, followed by eggs at 6.67%, palm oil at 5.04%, and tofu at 2.27%. These results indicate that raw material production and energy use across production stages contribute to acidification impacts.

### Eutrophication

The total eutrophication impact of the pempek production system was 4.197 kg PO<sub>4</sub><sup>3-</sup> eq. As shown in Figure 13, the frying stage was the dominant contributor at approximately 61.3%, followed by packaging at 18.0%, shaping at 10.7%, resting at 8.08%, and dough preparation at 1.75%.



**Figure 13.** Diagram of process and material contributions to the Eutrophication impact category

From the raw material perspective, palm oil and wheat flour were the primary contributors, accounting for 49.5% and 46.1%, respectively. These results indicate that agricultural raw material production and

energy-intensive frying activities are the main contributors to eutrophication potential in the pempek production system.

### 3.2. Discussion

#### 3.2.1 Global Warming Potential (GWP100a)

Global Warming Potential over a 100-year horizon (GWP100a) is an important impact category in Life Cycle Impact Assessment because it evaluates the contribution of a product system to climate change by converting greenhouse gas emissions into a common unit, namely kg CO<sub>2</sub>-equivalent (Pianjing & Wites, 2021). This indicator enables different greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, to be compared consistently across the production system.

The results of this study show that pempek production generated a total Global Warming Potential of 311.96 kg CO<sub>2</sub>-eq per production cycle. The frying stage was the largest contributor, accounting for 32.1% of the total impact, followed by packaging at 25.2%, shaping at 18.9%, dough preparation at 11.0%, and resting at 10.8%. The dominant contribution of frying indicates that thermal processing is a critical hotspot in the pempek production system. This result is consistent with previous food-related LCA studies showing that thermal processing often contributes substantially to carbon emissions because of direct fuel combustion and upstream energy production (Falciano et al., 2022).

The packaging stage also contributed substantially to GWP. This finding indicates that packaging materials and packaging-related energy use are important sources of greenhouse gas emissions in pempek production. The result is in line with previous studies reporting that the environmental performance of packaging is strongly influenced by material type, production process, and energy requirements during manufacturing (Brock & Williams, 2020). Therefore, packaging should not be considered only as a post-production

activity, but also as an important component of the product life cycle.

From the material perspective, wheat flour was the main contributor to GWP, accounting for 61.6% of the total material-related impact. Palm oil contributed 14.5%, followed by demersal fish at 9.86%, tofu at 4.14%, and eggs at 3.59%. The high contribution of wheat flour is associated with upstream agricultural activities, particularly fertilizer use, land preparation, crop processing, and transportation. This finding is consistent with previous literature indicating that wheat cultivation can generate substantial greenhouse gas emissions due to agricultural inputs and field-level emissions (Chiu, 2019). The contribution of demersal fish also reflects the energy-intensive characteristics of fishery supply chains, including fishing activities, storage, and transportation (Xing-Guo et al., 2023).

### 3.2.2 Acidification Potential (AP)

Acidification Potential measures the contribution of emissions such as sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), and ammonia (NH<sub>3</sub>) to environmental acidification. This impact category is commonly expressed in kg SO<sub>2</sub>-equivalent and is closely related to fossil fuel combustion, fertilizer use, and other emission-generating activities in agricultural and industrial systems (Setiawan et al., 2021).

The total Acidification Potential of the pempek production system was 2.397 kg SO<sub>2</sub>-eq per production cycle. The packaging stage was the largest contributor, representing 27.0% of the total impact. This was followed by frying at 22.1%, shaping at 21.0%, dough preparation at 17.1%, and resting at 11.6%. The relatively high contribution of packaging indicates that the production and supply of packaging materials generate acidifying emissions. This finding supports previous LCA studies in food and marine product systems, which have shown that packaging materials can contribute significantly to acidification

impacts through energy use and manufacturing-related emissions (Wiloso et al., 2022).

The frying stage also contributed substantially to acidification because it relies on fossil-based energy. Fuel combustion may release SO<sub>2</sub> and NO<sub>x</sub>, both of which are major precursors of acidification. This result confirms the strong relationship between energy consumption and acidifying emissions, particularly in food processing activities that require thermal energy (Omar & Muthusamy, 2022). Therefore, reducing energy intensity during frying can also help lower acidification impacts.

From the raw material perspective, wheat flour was the dominant contributor, accounting for 66.5% of the total material-related acidification impact. Demersal fish contributed 15.6%, followed by eggs at 6.67% and palm oil at 5.04%. The dominant contribution of wheat flour is mainly associated with agricultural emissions, particularly ammonia and nitrogen oxides from fertilizer application. These emissions are widely recognized as important drivers of acidification in crop-based supply chains (Svanes et al., 2020). The contribution of demersal fish indicates that animal-based raw materials and their supply chains also influence acidification through fuel use, processing, and transportation.

### 3.2.3 Eutrophication Potential (EP)

Eutrophication Potential evaluates the contribution of nutrient emissions, especially nitrogen and phosphorus, to the enrichment of aquatic ecosystems. Excessive nutrient input can trigger algal blooms, reduce dissolved oxygen, and disrupt aquatic biodiversity. This impact category is commonly expressed in kg PO<sub>4</sub><sup>3-</sup>-equivalent and is often associated with agricultural activities, wastewater, and emissions from energy systems (Sari et al., 2023).

The total Eutrophication Potential of pempek production was 4.197 kg PO<sub>4</sub><sup>3-</sup>-eq per production cycle. The frying stage was the dominant contributor, accounting for

61.3% of the total impact. This was followed by packaging at 18.0%, shaping at 10.7%, resting at 8.08%, and dough preparation at 1.75%. The dominance of frying suggests that energy-intensive processing can contribute indirectly to eutrophication through emissions generated during fuel combustion and upstream energy production. This finding is consistent with previous studies indicating that energy systems may contribute to nutrient-related environmental burdens through atmospheric emissions and associated deposition pathways (Duan et al., 2019).

From the raw material perspective, palm oil and wheat flour were the main contributors to eutrophication, accounting for 49.5% and 46.1%, respectively. These results indicate that agricultural supply chains play a major role in nutrient-related environmental impacts. Fertilizer application, agricultural runoff, and nutrient losses during crop cultivation are commonly identified as key contributors to eutrophication. The finding is consistent with previous studies showing that fertilizer use in agricultural production contributes significantly to nitrogen and phosphorus emissions, which are the main drivers of eutrophication (Kheiralipour et al., 2024)

Overall, the discussion of GWP, AP, and EP indicates that pempek production has environmental hotspots in processing and upstream raw material supply chains. Frying is the most important hotspot for GWP and EP, while packaging is the major contributor to AP. Meanwhile, wheat flour and palm oil are consistently important material contributors across the three impact categories. These findings suggest that environmental improvement strategies should not focus only on the production facility, but also consider raw material sourcing, packaging selection, and energy efficiency throughout the pempek production system.

#### 4. CONCLUSIONS AND RECOMMENDATIONS

This study assessed the environmental impacts of pempek production using the Life Cycle Assessment (LCA) approach with the CML-IA Baseline method. The results indicate that the pempek production system generated environmental impacts of 311.96 kg CO<sub>2</sub>-eq for Global Warming Potential (GWP), 2.397 kg SO<sub>2</sub>-eq for Acidification Potential (AP), and 4.197 kg PO<sub>4</sub><sup>3-</sup>-eq for Eutrophication Potential (EP) per production cycle. These findings confirm that traditional pempek production contributes to greenhouse gas emissions, acidifying emissions, and nutrient-related environmental burdens.

The contribution analysis identified the frying stage as the main environmental hotspot for GWP and EP, accounting for 32.1% and 61.3% of the total impacts, respectively. This dominance is mainly associated with thermal energy use and cooking oil consumption during processing. The packaging stage was the largest contributor to AP, with a contribution of approximately 27.0%, and also contributed substantially to GWP at 25.2%. These results indicate that both energy-intensive processing and packaging materials play important roles in determining the environmental performance of pempek production. Other stages, including shaping, dough preparation, and resting, contributed moderate impacts but should still be considered in improvement strategies.

From the raw material perspective, wheat flour was the dominant contributor to several impact categories, particularly GWP and AP, with contributions of approximately 61.6% and 66.5%, respectively. These impacts are mainly associated with upstream agricultural activities, including fertilizer use, crop production, processing, and transportation. Palm oil was the main contributor to EP, accounting for approximately 49.5%, and also contributed 14.5% to GWP. Demersal fish, eggs, and tofu showed lower contributions, but they remain relevant because they are part of the

overall material supply chain of pempek production.

Based on these findings, several improvement strategies are recommended. First, energy efficiency in the frying process should be improved through better frying equipment, optimized cooking time, and more controlled processing temperatures. Second, cleaner energy sources should be considered to reduce greenhouse gas emissions from thermal processing and electricity use. Third, packaging practices should be improved by reducing unnecessary plastic use, selecting recyclable or lower-impact packaging materials, and optimizing packaging design. Fourth, raw material sourcing should prioritize suppliers that apply more sustainable agricultural and fishery practices, particularly for wheat flour, palm oil, and fish. Finally, waste management should be strengthened through better wastewater handling, used cooking oil management, and systematic solid waste collection.

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