



## RESEARCH ARTICLE

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## ENVIRONMENTAL ASESMENT STUDY BASED ON THE LIFE CYCLE OF POTATO CHIPS PRODUCTS IN GARUT, WEST JAVA

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### ABSTRACT

The potato chip supply chain plays a strategic role in achieving both operational and sustainability objectives within the agro-industrial sector, making continuous performance improvement essential. Developing agricultural and agro-industrial supply chains requires careful consideration of multiple factors to ensure systems that are integrated, effective, efficient, responsive, fair, and sustainable. However, sustainability efforts are increasingly challenged by climate change, which contributes to rising temperatures, sea-level increases, droughts, and other environmental threats. These impacts are intensified by the ongoing growth of greenhouse gas (GHG) emissions, primarily driven by industrial activities, changes in agricultural practices, and land-use transformations. To address these challenges, this study applies a Life Cycle Assessment (LCA) approach to evaluate the entire life cycle of the potato chip supply chain with the aim of reducing its environmental impacts. An LCA-based model is developed specifically for the potato chip agro-industry to identify critical stages that significantly contribute to environmental burdens. This identification is conducted through a detailed analysis of the production process, providing insights that support the adoption of environmentally responsible and sustainable production practices.



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### I. INTRODUCTION

The supply chain of potato commodities in the potato chip agro-industry plays a strategic role across various operational aspects; therefore, its performance must be continuously enhanced. As a result, supply chains for agricultural commodities and agro-industrial products tend to exhibit higher levels of complexity, uncertainty, and dynamic behavior. A sustainable supply chain is characterized by its ability to recognize present and future environmental and social impacts and to implement effective mitigation strategies. Climate change is defined as long-term variations in climate patterns caused by natural processes or anthropogenic activities [1]. In recent years, greenhouse gas (GHG) emissions have increased significantly, largely driven by industrial expansion and changes in agricultural practices and land use. Potato chip agro-industry companies have the opportunity to reduce both GHG emissions and operational costs, for example, by installing auxiliary power units on transportation vehicles once carbon emissions are identified. However, organizations aiming to reduce emissions encounter major challenges. According to [2], across various industrial sectors, direct emissions account for only approximately 14% of total supply chain emissions prior to product use and disposal. Consequently, sustainability assessment must adopt a supply chain perspective to effectively control emissions and minimize environmental impacts. Efforts to reduce direct environmental impacts, such as pollution arising from human activities within the potato chip agro-industry supply chain, contribute to the restoration of ecological balance [3].

The consumption of material and energy inputs, including fuel, represents a significant source of pollution, particularly in the form of GHG emissions. The Indonesian government has demonstrated its commitment to mitigating GHG emissions by targeting a 26% reduction through domestic initiatives and up to 41% with international support, as stipulated in Presidential Regulation Number 61 of 2011 concerning the National Action Plan for Greenhouse Gas Emission Reduction. To systematically evaluate environmental impacts and support pollution reduction efforts, an appropriate analytical approach is required, namely life cycle assessment (LCA). Life cycle assessment is a cradle-to-grave methodology used to quantify energy consumption, costs, and environmental impacts throughout all stages of a product's life cycle, from raw material extraction to end-of-life consumption [4]. In the context of potato chip production, LCA enables the evaluation of environmental burdens associated with the utilization of resources, energy, water, fuel, and other inputs across each processing stage. Furthermore, to reduce potential environmental impacts, it is necessary to conduct reanalysis using various improvement alternatives to identify more sustainable production scenarios [5].

Based on this background, the research problems addressed in this study include identifying the inputs, outputs, and environmental impacts generated during potato chip production, quantifying CO<sub>2</sub> emissions throughout the production process, and evaluating improvement alternatives to optimize processes or products while minimizing environmental degradation. Previous LCA-related studies have been conducted on banana chips [3], sago starch [6], cane sugar [4], beef crackers [5], and broiler chicken [7]. However, research focusing on the environmental impacts of the potato chip agro-industry supply chain remains limited, despite the contribution of each processing stage to overall carbon emissions. Therefore, this study aims to design and develop a life cycle assessment model for the potato chip agro-industry to identify critical points with significant environmental impact potential. Hotspot identification is performed through the analysis of potato supplier distribution, transportation activities, and production processes. The findings are expected to support environmentally friendly production practices and provide benefits for industry stakeholders in environmental management, thereby promoting sustainable and eco-efficient industrial development in alignment with President Prabowo's ASTA CITA program.

## II. THEORETICAL REFERENCE

### II.1 LIFE CYCLE ASESSMENT

#### II.1.1 Research Design

Life Cycle Assessment (LCA) is a method used to evaluate the impact of a product on the environment. A product's life cycle focuses on collecting information and analyzing the environmental impacts of a product, which can consist of goods and services [8]. LCA encompasses a cycle that begins with raw material extraction, production, transportation, operations, and finally recycling [6]. LCA is generally a method for identifying and quantifying energy use, natural resource use, and environmental disposal, as well as evaluating and implementing potential environmental improvements. LCA is a method that can be used to fully understand the environmental impacts of the entire product and service lifecycle being evaluated collectively [5]. LCA is included in the implementation of ISO 14000, which is implemented using a systems approach. Therefore, the LCA method creates the foundation for operational environmental information systems and environmentally sound business operations [7]. Life Cycle Assessment is an objective process for assessing the environmental burden associated with a product, process, or other activity. The application of life cycle analysis is carried out by identifying and determining the quantity of material and energy use, the release of residual materials and energy into the environment, assessing the environmental impacts resulting from the use of materials and energy, and assessing and implementing opportunities to drive environmental improvement efforts. The core of life cycle assessment is the appropriate assessment of the technological, economic, and environmental implications of materials, processes, or products throughout their life from creation to waste or from one creation to a new creation in the same or another product type [7].

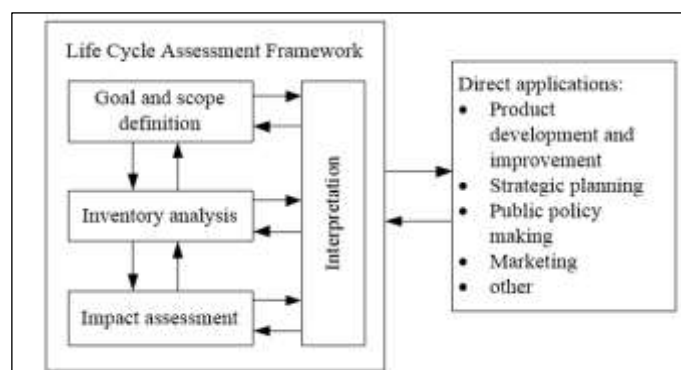


Figure 1: Life Cycle Assessment Scheme.

Source: [6].

Figure 1 shows the stages of an LCA and the relationships between them. A Life Cycle Inventory is a data-based, objective quantification process for energy and raw material requirements, emissions to air, liquid waste, solid waste, and other types of materials released into the environment over the life span of a product, process, or activity. A Life Cycle Impact Analysis is a technical, quantitative and/or qualitative process for characterizing and assessing the impact of environmental impacts identified in the inventory components. This assessment should include consideration of ecological and human health impacts, as well as other impacts, such as habitat alteration and noise. A Life Cycle Improvement Analysis is a systematic assessment of the need and opportunity to reduce environmental impacts associated with energy and material use and waste generation throughout the life cycle of a product, process, or activity. The analysis can include quantitative or qualitative measures of improvement [8].

### II.1.2 Stage LCA

The LCA consists of four stages: defining objectives and scope, inventory analysis, impact analysis, and interpretation

1. Determining the objectives and scope (Goal Definition and Scoping) The first stage of the LCA method is determining the parameters related to the analysis to be conducted. These parameters are:
  - a. Target, determining the objectives to be achieved
  - b. Constraints, considering alternative components and processes that can be used
  - c. Functional Units
2. Inventory Analysis (Life Cycle Inventory/LCI). In this stage, the data needed for the analysis is collected, including raw materials, energy, by-products, and contamination. The LCA method is used to explore sources that can be used to obtain the required data. The amount of data available is crucial to the success of an analysis. The Life Cycle Assessment considers five types of outputs: products, by-products, solid waste, liquid waste, and emissions. Each stage receives inputs of raw materials and energy that move towards the next stage and release environmental waste [4].
3. Impact Analysis (Life Cycle Impact Analysis/LCIA). Impact analysis aims to identify potential impacts that may occur during a product's life cycle. Impact estimation is intended as a careful and in-depth study of environmental quality, indicated by the magnitude of the impact and its level of importance. The magnitude of the impact is the difference between environmental quality without the project and the environmental quality conditions resulting from the project. Commonly used impact analysis methods include mathematical models, environmental quality standards, analogies, and expert assessments [9].
  - a. Mathematical models are formal methods commonly used to estimate the magnitude of the impact on environmental components resulting from project activities using mathematical formulas. This allows for quantitative determination and traceability of the impact behavior.
  - b. Environmental quality standards are used to estimate significant impacts through comparisons between field measurements or observations with applicable environmental quality standards.
  - c. Analogies are methods based on analogies or comparing environmental conditions and problems arising from similar activities in different locations.
  - d. Expert assessment is a method that can be used when data collection in the field is difficult. The impact estimates resulting from this method are highly dependent on the knowledge and experience of the assessor.

There are three stages in a risk impact analysis (LCIA): classification, characterization, and valuation [10].

- a. Classification. This stage involves the process of assigning and compiling LCI study data to homogeneous stressor groups (e.g., greenhouse gas pollutants or ozone-depleting compounds) within larger impact groups (e.g., human health, ecological health, and resource depletion).
- b. Characterization. Analysis and estimation of the magnitude of impacts on human health, ecological health, or resource depletion for each stressor group, derived from the application of specific impact assessment tools.
- c. Valuation. This stage involves weighting the results of each characterization stage so that the most significant environmental impact categories receive more attention than the least significant ones.
4. Interpretation (Interpretation/Life Cycle Improvement Analysis). This is the final step in conducting an LCA. It involves interpreting the results, evaluating them, and then analyzing what can be done to improve products, processes, or services related to reducing environmental impacts [11]. The results of the analysis conducted in the inventory and impact assessment stages are translated into actions that will benefit the industry and the environment [12].

## III. MATERIALS AND METHODS

### III.1 OBJECT AND SUBJECT OF THE STUDY

The study was conducted in the potato chips agro-industry at PT Champ Garut, West Java Indonesia. The study was conducted in June-November 2025. The calculation of carbon footprint is based on a functional unit, which is the measure of the system function that informs the reference unit related to the research inventory data. In this study, the functional unit was defined as 1 kg of potato. Scope of product life cycle covered whole aspects, including supplier and production process, from handling of raw materials, production process until delivery to storage “gate to gate”.

### III.2 THEORETICAL JUSTIFICATION OF LIFE CYCLE ASSESMENT

The carbon footprint concept can be classified into manufacturing, value chain, and product perspectives [13]. The manufacturing carbon footprint represents emissions generated from all production-related activities, including energy consumption, processing operations, and transportation vehicles. Meanwhile, the value chain carbon footprint encompasses emissions occurring beyond manufacturing boundaries, such as those originating from suppliers and end users, including emissions during product utilization and end-of-life stages [14]. Furthermore, the product carbon footprint accounts for emissions throughout the complete life cycle of a specific product or service unit, starting from raw material extraction and manufacturing processes to usage, reuse, recycling, and final disposal stages [15]. A range of strategies can be implemented to stimulate companies to adopt more sustainable operational practices, such as minimizing material and labor inefficiencies as well as reducing emissions arising from distribution and transportation activities within the supply chain [16].

In the potato chip agro-industry, greenhouse gas (GHG) emissions and operational expenses can be lowered by optimizing transportation systems, including the installation of auxiliary power units on delivery vehicles once carbon footprint levels have been identified. Previous studies report that, on average, direct emissions generated by companies across industrial sectors contribute only about 14% of total supply chain emissions before the stages of product use and end-of-life treatment [17]. Consequently, sustainability evaluation should be undertaken from an integrated supply chain perspective to effectively control emissions and mitigate broader environmental impacts. Environmental degradation is closely linked to human activities [18] and occurs in multiple forms, including air, water, and soil pollution. Reducing direct environmental pressures caused by anthropogenic actions reflects ongoing efforts to preserve and restore ecological balance [19]. Life cycle assessment (LCA) serves as a cradle-to-grave analytical framework for assessing energy consumption, economic costs, and environmental impacts throughout a product's life cycle, beginning with raw material extraction and ending with final consumption [20].

In the context of potato chip production, LCA facilitates the identification and quantification of environmental loads associated with the use of resources, energy, water, fuel, and other material inputs at each processing stage. Furthermore, potential environmental impacts can be further reduced through re-evaluation using alternative improvement scenarios to identify more sustainable production options [21]. LCA also provides a quantitative basis for determining the level of environmental performance and sustainability of products or services [22]. Based on these considerations, LCA-based research on the potato chip agro-industry supply chain requires the development of a carbon footprint model to systematically identify environmental impacts, determine emission hotspots across supply chain stages, and strengthen interpretative analysis. The proposed model is expected to enhance production efficiency while simultaneously reducing the environmental impacts associated with potato chip manufacturing. In addition, the results of this study may serve as a reference for carbon footprint assessments of snack products and provide valuable support for industry stakeholders in environmental management and the adoption of sustainable and environmentally responsible industrial practices.

### III.3 VARIABLES AND MEASUREMENT INSTRUMENT

Based on ISO 14040, the life cycle assessment (LCA) methodology is structured into four fundamental phases, namely: (1) formulation of objectives and system boundaries, (2) life cycle inventory compilation, (3) life cycle impact evaluation, and (4) result interpretation (ISO, 2006). The objective and scope definition phase is essential for specifying the required data and determining system boundaries, with data primarily obtained from the industrial system being analyzed. The life cycle inventory phase involves the use of process flow charts, mass balance, and energy balance analyses to quantify material and energy inputs and outputs, as well as to assess their potential environmental relevance. Subsequently, the impact assessment phase quantifies emissions using standardized calculation methods and classifies them into predetermined impact categories. Recommendations for improvement are then formulated through a comprehensive review of relevant studies addressing environmental impact evaluation and mitigation strategies. Life cycle assessment (LCA) offers a structured framework for evaluating the environmental impacts of products or services throughout their entire supply chains [23]. In this research, the environmental assessment of potato chip production is focused on the global warming impact category, which is examined through carbon footprint analysis [11]. Carbon footprint assessment has become widely accepted as an important indicator of environmental performance and is defined as the cumulative amount of greenhouse gas emissions, both direct and indirect, generated within defined system boundaries [18]. The carbon footprint model developed in this study is intended to quantify greenhouse gas emissions and assess the global warming potential associated with potato chips produced using a medium-scale, semi-mechanical processing system. The impact assessment follows the ISO 14040/44 standards for product carbon footprint calculation and applies the Intergovernmental Panel on Climate Change (IPCC) 2007 methodology.

### III.4 FUNCTIONAL UNIT AND LCA SCOPE

Carbon footprint calculations are based on a defined functional unit, which represents the quantified performance of the system and serves as a reference for all inventory data. In this study, the functional unit is specified as 100 kg of potatoes. The assessed product life cycle includes activities related to raw material supply and production processes, encompassing raw material handling, processing, and storage operations. The LCA scope applied in this research follows a gate-to-gate approach, as illustrated in Figure 2.

#### III.4.1 *Observational and Engineering Data Collection*

For the life cycle inventory, data related to materials and energy entering and leaving the system were collected. Inventory data related to supplier potato and raw material handling, transportation, and production processes were obtained through interviews and direct measurements. Characterization was conducted only at PT Champ. In this case, we assumed that other factories have similar waste characteristics. A summary of the types and methods of life cycle inventory data collection is presented in Table 1.

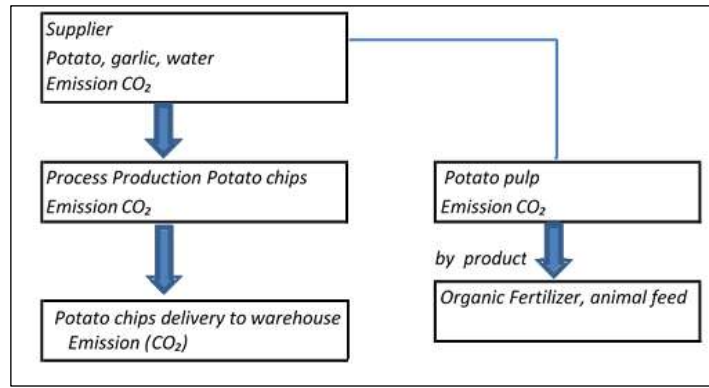


Figure 2: Scope of LCA study in potato chips agro-industry.

Source: Authors, (2026).

Table 1: Sources of life cycle inventory data.

| Life Cycle Stage | Data                                                                                 | Data Source and Collecting Method        |
|------------------|--------------------------------------------------------------------------------------|------------------------------------------|
| Supplier potato  | Material and wastes<br>Diesel fuel<br>Potato /kg                                     | Measured<br>Potato farmers;<br>Interview |
| Transportation   | Type of vehicle and distance<br>Diesel fuel                                          | Measured<br>Factory manager, interview   |
| Production       | Raw Material (Potato, Garlic, Salt), Fuel Oil, Diesel fuel, Cooking oil, Electricity | Measured<br>Factory manager, interview   |

Source: Authors, (2026).

### III.5 DATA ANALYSIS PROCEDURE

#### III.5.1 Life Cycle Inventory (LCI) Analysis

Life cycle inventory analysis represents a core component of the LCA framework, encompassing the identification and quantification of material and energy inputs and outputs, including raw materials, energy consumption, waste, and by-products generated throughout the product life cycle [24]. In this study, the inventory analysis was conducted using an LCA-based approach incorporating material flow analysis, energy balance calculations, and emission estimations in accordance with the ISO 14040 standard (ISO, 2006), as illustrated in Figure 1. Data utilized in this stage were obtained from secondary sources, such as company records and relevant scientific publications, as well as from calculated estimates derived from primary data and defined assumptions. The inventory analysis stage focused on quantifying the amounts of raw materials, energy use, and emissions generated during the production of 1 kg of potato chips.

#### III.5.2 Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment was conducted in accordance with the objectives and system boundaries established in this study. The environmental impact category examined was global warming potential, which was evaluated by quantifying greenhouse gas (GHG) emissions, namely CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, and expressing them as carbon dioxide equivalents (kg CO<sub>2</sub>-eq).

#### III.5.3 LCA Result Interpretation

Result interpretation was conducted through two main stages, namely key issue identification and evaluation. The initial stage involved examining the consistency between inventory inputs and outputs and the resulting environmental impact assessments. Subsequently, an evaluation process was undertaken to identify potential strategies for emission reduction. Supporting data for interpretation were obtained from field observations, direct interviews with factory personnel, company documentation, and relevant previous studies.

#### III.5.4 Greenhouse Gas (GHG) Emissions

The utilization of fossil fuels in the potato chip agro-industry contributes significantly to greenhouse gas emissions and, consequently, to global warming. The primary greenhouse gases generated from fossil fuel combustion, production activities, and waste management processes include carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). Greenhouse gas emissions were calculated in accordance with the guidelines provided by the Intergovernmental Panel on Climate Change (IPCC), as presented in Equation (1). In this study, CO<sub>2</sub> emissions originated mainly from the use of liquefied petroleum gas (LPG), diesel fuel, and electricity consumption.

$$CO_2 \text{ emissions (fuel)} = QF \times NK \times FE \quad (1)$$

Information:

QF = Fuel consumption (l)  
 NK = Net calorific value (kcal / l)  
 FE = Emission factor (Kg CO<sub>2</sub> / TJ)

Net calorific values and emission factors vary according to the type of fuel utilized. Carbon dioxide (CO<sub>2</sub>) emissions resulting from electricity consumption were calculated using Eq. (2):

$$\text{CO}_2 \text{ emissions (electricity)} = \text{QL} \times \text{FE} \quad (2)$$

Where QL represents electricity consumption (kWh) and FE denotes the emission factor (0.485 t CO<sub>2</sub>/MWh). In addition, methane (CH<sub>4</sub>) emissions originated from wastewater generation and diesel fuel usage. CH<sub>4</sub> emissions from liquid waste were estimated based on the chemical oxygen demand (COD) generated, following the IPCC guidelines [1], as expressed in Eq. (3):

$$\text{CH}_4 \text{ emissions} = \text{VLC} \times \text{C} \times \text{FE} \quad (3)$$

Where VLC is the volume of liquid waste (L), C is the COD concentration (mg/L), and FE is the emission factor (0.21 kg CH<sub>4</sub>/kg COD). Meanwhile, CH<sub>4</sub> emissions associated with diesel fuel consumption were calculated using Eq. (4):

$$\text{CH}_4 \text{ emissions (diesel)} = \text{QF} \times \text{NK} \times \text{FE} \quad (4)$$

Where QF denotes fuel consumption (L), NK is the net calorific value (9,063 kcal/L), and FE represents the emission factor (10 kg CH<sub>4</sub>/TJ). Nitrous oxide (N<sub>2</sub>O) emissions derived from diesel usage were calculated based on the nitrogen content in the raw materials, with emission factors referring to IPCC standards [6]. The estimation of N<sub>2</sub>O emissions was performed using Eq. (5) [1]:

$$\text{N}_2\text{O emissions (diesel)} = \text{QF} \times \text{NK} \times \text{FE} \quad (5)$$

Where QF is fuel consumption (L), NK is the net calorific value (9,063 kcal/L), and FE is the emission factor (0.6 kg N<sub>2</sub>O/TJ). According to [7], the Global Warming Potential (GWP) values for CH<sub>4</sub> and N<sub>2</sub>O are 25 and 298, respectively, which are expressed in terms of CO<sub>2</sub> equivalents. Accordingly, 1 kg of CH<sub>4</sub> is equivalent to 25 kg CO<sub>2</sub>-eq, while 1 kg of N<sub>2</sub>O corresponds to 298 kg CO<sub>2</sub>-eq. Energy efficiency in this study was evaluated using the Net Energy Value (NEV) and Net Energy Ratio (NER), as defined in Eq. (6) and Eq. (7):

$$\text{NEV} = \sum \text{En}_o - \sum \text{En}_i \quad (6)$$

$$\text{NER} = \sum \text{En}_o / \sum \text{En}_i \quad (7)$$

Where NEV denotes the Net Energy Value, NER represents the Net Energy Ratio,  $\sum \text{En}_o$  is the total energy output, and  $\sum \text{En}_i$  is the total energy input. The net energy performance is considered satisfactory when the NER value exceeds unity (>1).

## IV. RESULTS AND DISCUSSIONS

### IV.1 LCA GOAL AND SCOPE DEFINITION

The potato chip supply chain operated by PT Champ Garut involves several key actors, including potato farmers, farmer groups, processing facilities. After harvesting, potatoes are collected by farmer groups for quality inspection, sorting, grading, packaging, and temporary storage. The tubers are classified according to agro-industry quality standards before being transported to the food processing facility, where they are processed into potato chips as the final product. The finished products are subsequently distributed to storage potato chips. Supply chain information plays a crucial role in defining emission boundaries, as illustrated in Figure 3. The assessment scope begins with upstream supply activities, which include transportation of potatoes from farmer groups to the processing facility using vehicles and is categorized as Scope 1. Processing activities within the potato chip agro-industry are classified as Scope 2.

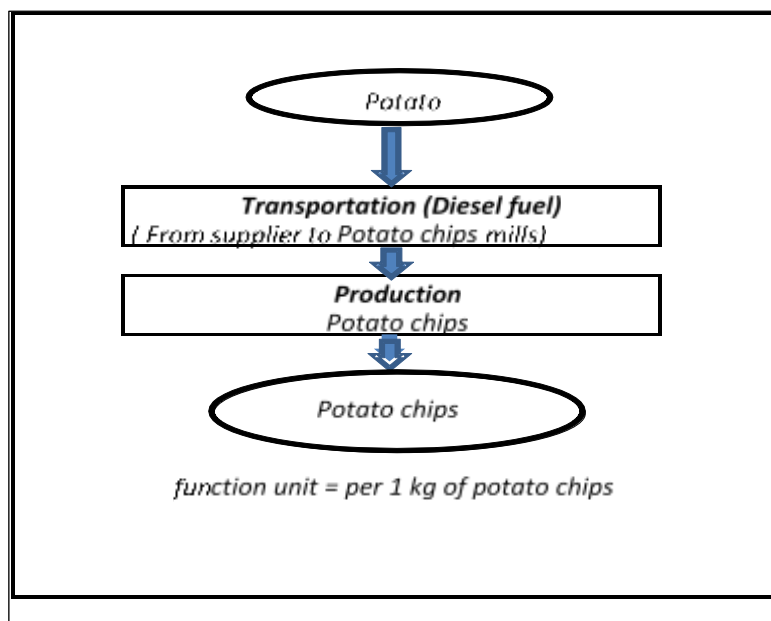


Figure 3: Scope of the emissions generated in supply chain of potato chips agroindustry.

Source: Authors, (2026).

## IV.2 INVENTORY DATA DESCRIPTION

### IV.2.1 Production Wastes Produced in Potato Chips Agro-Industry

Processing activities in potato chip production result in the generation of both solid and liquid wastes, as summarized in Table 2. Solid residues primarily consist of potato pulp, amounting to approximately 2 kg, whereas liquid waste includes wastewater and used cooking oil, with a total volume reaching about 219 kg. These wastes generated during the production process have the potential to be further utilized as by-products, thereby contributing to waste minimization and improved energy efficiency.

Table 2: Types and quantities of waste produced during the potato chip manufacturing process per 100 kg of raw potatoes.

| No | Process          | Waste                   | Total              |
|----|------------------|-------------------------|--------------------|
| 1  | Receiving        | -                       | -                  |
| 2  | Stripping        | Potato pulp             | 2 Kg               |
| 3  | Washing          | Water residue           | 98 L               |
| 4  | Mixing Seasoning | Water residue           | 47.11 Kg           |
| 5  | Frying           | Used cooking Oil, Water | 26.45 Kg, 43.56 Kg |
| 6  | Drying           | Used cooking oil        | 3.55 Kg            |

Source: Authors, (2026).

### IV.2.2 Carbon Footprint on Supply Chain of Potato Chips Agro-Industry

The carbon footprint assessment in this study was conducted through several stages, including direct measurement, input–output life cycle assessment, energy-based calculations, and activity-based calculations..

#### IV.2.2.1 Direct Measurement

Direct measurement, also referred to as direct observation, involves the continuous monitoring of pollutant emissions released into the atmosphere along the agro-industry supply chain [25]. In this study, observations covered various operational aspects, including transportation modes, fuel consumption, raw materials used in the assessed product, machinery, energy utilization during processing, workforce involvement, and waste generation throughout the production process. Within the gate-to-gate system boundary, exhaust gas measurements accounted for emissions generated from supplier-to-factory transportation, internal processing activities, and product distribution from producers to retailers. Greenhouse gas emissions were evaluated based on carbon dioxide (CO<sub>2</sub>) concentrations and subsequently converted into carbon dioxide equivalents (CO<sub>2</sub>-eq), representing emissions originating from fossil fuel combustion and processing operations. Primary data for the life cycle inventory were obtained through direct measurements within the established system boundaries. As outlined earlier, the inventory assessment utilized data collected from a potato chip agro-industry located in Garut, West Java Province. This production unit was chosen because raw potatoes were sourced directly from farmer groups and the processing activities employed a semi-mechanical system. The production process operated for approximately 25 working days each month, with a daily capacity of about 1,600 kg of potatoes and involving five workers.

#### IV.2.2.2 Input-Output Life Cycle Assessment (IO LCA)

Input–Output Life Cycle Assessment (IO-LCA) provides a comprehensive description of raw materials, energy inputs, products, and emissions generated from each activity within the agro-industry supply chain [21]. This stage facilitates the quantification of carbon emissions originating from material usage, energy consumption, machinery operation, and labor activities. Overall, IO-LCA enables the estimation of total carbon emissions produced across the company's supply chain [26]. The assessment of carbon emissions plays a crucial role in supporting decision-making processes related to operational improvements, particularly in efforts to reduce carbon intensity and minimize waste generation [22]. An illustration of the IO-LCA life cycle framework is presented in Figure 4. Emissions constitute a key indicator in environmental assessment, as they provide a critical basis for determining appropriate analytical and mitigation approaches. The results indicate that Scope 2 contributes a relatively small proportion of total supply chain emissions for the company under study. Consequently, greater emphasis should be placed on emissions originating from Scope 1 and Scope 2 activities [27]. Nevertheless, emissions associated with Scope 2 may become more significant in organizations with larger carbon footprints, a condition commonly observed across various industries. The input components considered in this assessment consisted of: (1) raw materials, including potatoes, water, cooking oil, garlic, and salt; (2) electricity as the primary energy source; and (3) transportation fuels, particularly diesel. The resulting outputs comprised the main product, namely potato chips, as well as various forms of waste, including greenhouse gas emissions (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O), potato residues, wastewater, and used cooking oil.

#### IV.2.2.3 Energy-Based Calculations

Energy-based calculation methods estimate carbon emissions by applying mass balance principles or theoretical combustion models to specific processes or facilities. This approach is particularly suitable for assessing emissions associated with fuel consumption in both production operations and transportation activities [17]. The level of analysis applied depends on the availability and quality of data. In practice, direct monitoring of fuel consumption is often challenging; therefore, emission estimates are commonly derived through extrapolation based on overall fuel usage data. Furthermore, the carbon content of fuels is generally represented by average values. Energy-based calculations may also be applied to emissions resulting from electricity consumption, as electricity providers typically publish average emission factors per unit of electricity generated [21]. In this study, energy-based calculations were supported by an assessment of the mass balance within the potato chip production process, as summarized in Table 3.

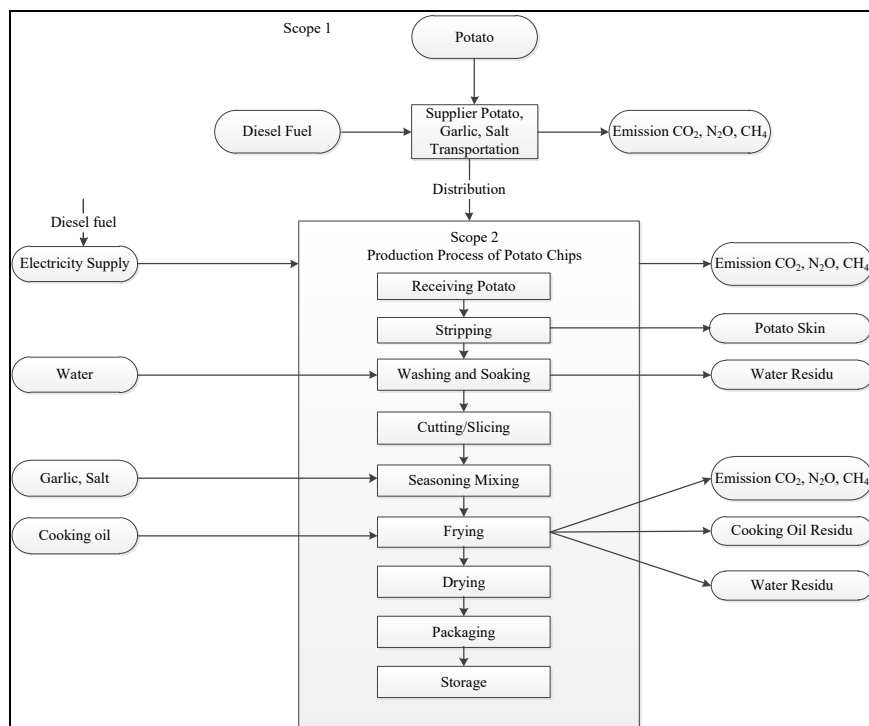


Figure 4: Input-Output LCA for Supply Chain in Potato Chips Agroindustry.  
Source: Authors, (2026).

Table 3: Mass Balance Potato Chips Production Process.

| Table 5.7: Mass Balance Potato Chips Production Process. |      |              |        |
|----------------------------------------------------------|------|--------------|--------|
| Process                                                  | Unit | Mass Balance |        |
|                                                          |      | Input        | Output |
| <b>Stripping + Cut</b>                                   |      |              |        |
| Potato                                                   | Kg   | 100          |        |
| Peeled potatoes sliced                                   | Kg   |              | 98     |
| Potato skin solids                                       | Kg   |              | 1.2    |
| Potato skin water                                        | Kg   |              | 0.8    |
|                                                          |      |              |        |
| <b>Washing</b>                                           |      |              |        |
| Peeled potatoes sliced                                   | Kg   | 98           |        |
| Water                                                    | L    | 100          |        |
| Clean sliced potatoes solids                             | Kg   |              | 58.8   |
| Clean sliced potatoes water                              | Kg   |              | 41.2   |
| Residual Water                                           | L    |              | 98     |
|                                                          |      |              |        |
| <b>Mixing</b>                                            |      |              |        |
| Clean sliced potatoes solids                             | Kg   | 58.8         |        |
| Clean sliced potatoes water                              | Kg   | 41.2         |        |
| Water                                                    | Kg   | 5            |        |
| Garlic                                                   | Kg   | 10           |        |
| Salt                                                     | Kg   | 3            |        |
| Potatoes sliced seasoning solids                         | Kg   |              | 70.89  |
| Potatoes sliced seasoning water                          | Kg   |              | 47.11  |
|                                                          |      |              |        |
| <b>Frying</b>                                            |      |              |        |
| Potatoes sliced seasoning solids                         | Kg   | 70.89        |        |
| Potatoes sliced seasoning water                          | Kg   | 47.11        |        |
| Cooking oil                                              | Kg   | 30           |        |
| Potato Chips                                             | Kg   |              | 70.89  |
| Potato Chips water                                       | Kg   |              | 3.55   |
| Potato Chips oil                                         | Kg   |              | 3.55   |
| Residual Cooking oil                                     | Kg   |              | 26.45  |
| Water                                                    | Kg   |              | 43.56  |
| <b>Drying</b>                                            |      |              |        |

|                     |           |       |              |
|---------------------|-----------|-------|--------------|
| Potato Chips        | Kg        | 70.89 |              |
| Potato Chips water  | Kg        | 3.55  |              |
| Potato Chips oil    | Kg        | 3.55  |              |
| Water               | Kg        |       | 3.55         |
| Cooking oil         | Kg        |       | 3.55         |
| <b>Potato Chips</b> | <b>Kg</b> |       | <b>70.89</b> |

Source: Authors, (2026).

As shown in Table 3, processing 100 kg of potatoes resulted in the production of 70.89 kg of potato chips, along with the generation of liquid, gaseous, and solid by-products. The liquid and gaseous wastes present potential for energy recovery, thereby contributing to improved energy efficiency. Meanwhile, potato pulp generated as solid waste was utilized as animal feed and organic fertilizer. Additionally, wastewater produced during the potato washing process was treated using appropriate purification methods, enabling its reuse for other purposes. Gaseous emissions generated during the frying process were also identified as having potential for conversion into alternative energy sources to partially substitute electricity consumption.

#### IV.2.2.4 Activity-Based Calculation

The activity-based calculation approach is designed to estimate carbon emissions based on activity-related data by applying appropriate conversion factors. These conversion factors, commonly referred to as emission factors, represent ratios that relate proxy measures of activities to their corresponding carbon emissions. Activity-based calculations are widely applied in carbon emission assessments due to their practicality and broad applicability [24]. The available activity-based methods vary in terms of data aggregation levels, with some approaches requiring more detailed activity information than others [23]. In the context of inbound transportation using trucks, it is assumed that transport services are outsourced to third-party logistics providers, resulting in emissions being categorized across three scopes. Detailed fuel consumption data, which are typically required for energy-based calculations, are generally unavailable from third-party logistics providers, as fuel use constitutes a significant component of transportation cost structures and is often treated as confidential information. Under such conditions, reporting organizations may employ activity-based calculations by estimating emissions through the conversion of transported mass, travel distance, and vehicle type into average carbon emissions using established emission factors. Several initiatives have developed emission factor databases applicable to key supply chain activities. Based on mass balance principles, these activity-based calculations can also be extended to estimate energy balances for supply chain activities within the potato chip agro-industry. The assessed activities correspond to the defined emission scopes within the potato chip supply chain. As presented in Table 4, total carbon footprint showed a variability of emissions, i.e 2.199 kgCO<sub>2eq</sub> (scope 1), 2.937 kgCO<sub>2eq</sub> (scope 2). The total carbon footprint from supplier to production process potato chips reached 5.137 kgCO<sub>2eq</sub>. Noticeably, scope contributed to the highest carbon footprint, thus improvement on scope 2 was needed to reduce the carbon footprint.

Table 4: Activity-Based Energy Calculations.

| Activity                                                   | Use Energy (A) | Energy (MJ/Year) (B) | Emission Factor (C) | GHG Emission(KgCO <sub>2eq</sub> /Year) (D) |
|------------------------------------------------------------|----------------|----------------------|---------------------|---------------------------------------------|
|                                                            | A              | B                    | C                   | D = B x C                                   |
| <b>Scope 1 (Supplier - Potato chips Agroindustry)</b>      |                |                      |                     |                                             |
| Potato                                                     | 6,667          | 3.200.000,000        | 0,328               | 1.050.240,000                               |
| Garlic                                                     | 4,000          | 12.000,000           | 0,328               | 3.938,400                                   |
| Salt                                                       | 5,000          | 4.500,000            | 0,328               | 1.476,900                                   |
| Total Emission Transportation                              |                | 3.216.500,000        | 0,328               | 1.055.655,300                               |
| <b>Carbon Footprint kgCO<sub>2eq</sub>/kg potato</b>       |                | 6,701                | 0,328               | <b>2,199</b>                                |
|                                                            |                |                      |                     |                                             |
| <b>Scope 2 (Production potato chips)</b>                   |                |                      |                     |                                             |
| Water supply                                               | 0,168          | 705,600              | 0,485               | 342,216                                     |
| stripping                                                  | 0,750          | 22.500,000           | 0,485               | 10.912,500                                  |
| washing and soaking                                        | 1,250          | 36.750,000           | 0,485               | 17.823,750                                  |
| Seasoning mixing                                           | 0,237          | 5.040,279            | 0,485               | 2.444,535                                   |
| frying                                                     | 1,500          | 31.900,500           | 0,485               | 15.471,743                                  |
| drying                                                     | 1,500          | 31.900,500           | 0,485               | 15.471,743                                  |
| Total Emission Production                                  |                | 128.796,879          | 0,485               | 62.466,486                                  |
| <b>Carbon Footprint kgCO<sub>2eq</sub>/kg potato chips</b> |                | 6,056                | 0,485               | <b>2,937</b>                                |
| Carbon Footprint kgCO <sub>2eq</sub> /kg potato chips      |                |                      |                     |                                             |
| <b>(From Supplier - Agroindustry) (scope 1 + scope 2)</b>  |                |                      |                     | <b>5,137</b>                                |

Source: Authors, (2026).

### IV.3 IMPACT ASSESSMENT

Impact assessment constitutes the subsequent stage for evaluating the magnitude of environmental impacts generated by potato chip production. In this study, the impact assessment was conducted through the calculation of greenhouse gas (GHG) emissions across the product supply chain using a life cycle assessment (LCA) framework. The GHG emissions considered, namely carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ), and nitrous oxide ( $\text{N}_2\text{O}$ ), were expressed in terms of carbon dioxide equivalents ( $\text{CO}_2\text{-eq}$ ). The  $\text{CO}_2\text{-eq}$  metric represents a standardized unit that allows different greenhouse gases to be compared based on their relative contributions to global warming. The total  $\text{CO}_2\text{-eq}$  value reflects the cumulative carbon emissions resulting from a combination of GHGs, adjusted according to their respective global warming potentials [27]. In this study, the global warming impact was calculated using a 100-year global warming potential (GWP100), with equivalency factors of 1 for  $\text{CO}_2$ , 25 for  $\text{CH}_4$ , and 298 for  $\text{N}_2\text{O}$ . The aggregated results of  $\text{CO}_2$  emissions across the life cycle of potato chips are presented in Figure 5.

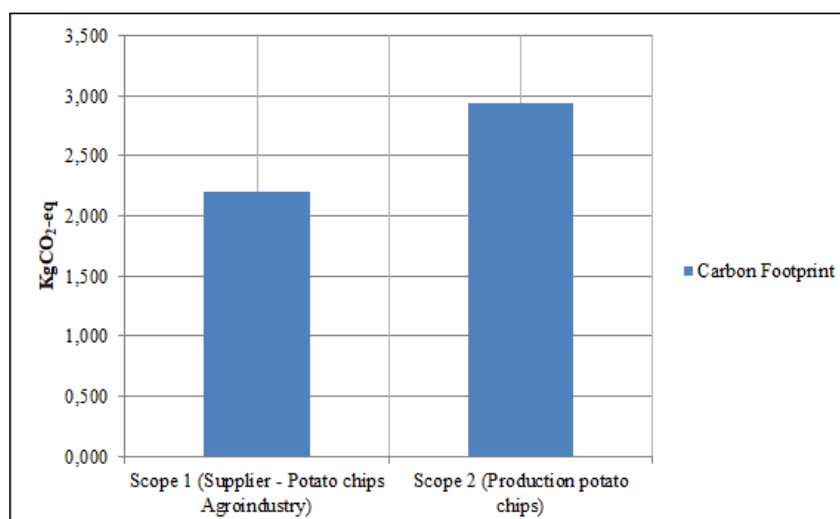


Figure 5: Carbon footprint results for each scope.  
Source: Authors, (2026).

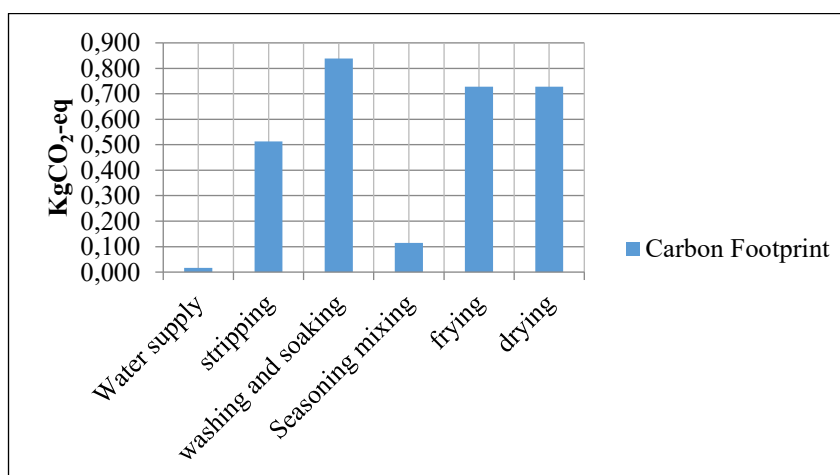


Figure 6: Carbon footprint results in the potato chips production process.  
Source: Authors, (2026).

### IV.4 INTERPRETATION OF RESULTS

The total carbon footprint analysis presented in Figure 5 indicates that Scope 1 contributes the smallest share of overall emissions. Within this scope, carbon emissions originate exclusively from the transportation of potatoes from suppliers to the processing facility using diesel-powered vehicles. In contrast, Scope 2 accounts for the largest proportion of total emissions. The dominant contribution in this scope is associated with the operation of production machinery that relies primarily on electricity as its energy source. Overall, Scope 2 represents the most significant contributor to total emissions within the assessed system, with the total carbon footprint reaching 5.137 kg  $\text{CO}_2\text{-eq}$  per kilogram of potato chips produced. As illustrated in Figure 6, the washing and soaking stages of the production process generate the highest carbon emissions, amounting to 0.84 kg  $\text{CO}_2\text{-eq}$ . These processes involve substantial water consumption and produce potato peel waste, resulting in liquid and solid residues that require treatment. The resulting potato peels have the potential to be reused as animal feed or organic fertilizer. A comparison with previous studies [24] conducted in agro-industrial systems shows that carbon footprint values in Brazil were reported at 1.09 kg  $\text{CO}_2\text{-eq}$ , which is considerably lower than the 2.937 kg  $\text{CO}_2\text{-eq}$  recorded in the potato chip agro-industry at PT Champ. This discrepancy indicates that there is significant potential for emission reduction in the Indonesian potato chip agro-industry through the implementation of energy efficiency improvements.

#### IV.5 ENERGY EFFICIENCY

Energy efficiency is evaluated based on the net energy associated with the life cycle of potato chips. Net energy refers to the total energy consumed and generated throughout the product life cycle and is expressed in units of MJ per kilogram of product [24]. In the potato chip life cycle, energy inputs consist of electricity used in the production process, diesel fuel consumed for transportation from potato suppliers to the processing facility and from the facility to retailers, as well as electricity utilized for lighting. Meanwhile, the output energy represents the total energy embodied in potato chips that is converted into thermal energy. Both input and output energy requirements are quantified in terms of heat energy (MJ), as summarized in Table 5.

Table 5: Life Cycle Energy of Potato chips.

| Activity                  | Input Energy | (MJ/Kg Potato chips) | Persentase (%) |
|---------------------------|--------------|----------------------|----------------|
| Supplier                  |              |                      |                |
| Transportation            | Diesel Fuel  | 6,701                | 52,53          |
| Potato chips Agroindustry |              |                      |                |
| Production process        | Electricity  | 6,056                | 47,47          |
| Total energy              |              | 12,757               | 100            |

Source: Authors, (2026).

Specifically, the energy value of potato chips is 12,757 MJ/kg of potato chips. Therefore, the NEV and NER can be estimated as presented in Table 6.

Table 6: Total energy input, energy output, NER, and NEV per kg of potato chips.

| Energi                | Agroindustri Potato chips |
|-----------------------|---------------------------|
| Input energy (MJ)     | 12,76                     |
| Output energy (MJ)    | 91,17                     |
| Net Energy Ratio      | 7,15                      |
| Net Energy Value (MJ) | 78,41                     |

Source: Authors, (2026).

Net Energy Ratio (NER) and Net Energy Value (NEV) serve as key indicators in assessing energy efficiency. Variations between energy inputs and outputs are primarily influenced by differences in transportation distances from suppliers to the agro-industry and from the agro-industry to retailers. As presented in Table 6, the energy input required for transporting raw materials from potato suppliers to the agro-industry amounts to 12.76 MJ per kilogram of potato chips produced. From an efficiency perspective, both NEV and NER demonstrate favorable performance, as indicated by a positive NEV value and an NER greater than one [25]. It should be emphasized that the production process accounts for a substantial portion of total energy consumption, given the agro-industry's dependence on electrically powered machinery, which contributes 47.47% of the overall energy demand. Improvements in energy efficiency can be achieved through the utilization of production by-products, such as potato peels, for conversion into organic fertilizer or animal feed. Additionally, enhancing the efficiency of machinery used in the potato chip production process can further reduce energy consumption and associated carbon emissions.

#### IV.6 RESEARCH LIMITATION

The life cycle boundaries of the evaluated product covered post-harvest activities, transportation of raw materials to the processing plant, and delivery of potato chips to retail outlets. The determination of the functional unit represented a crucial stage, as it significantly affected all subsequent calculations. In this research, the carbon footprint analysis was mainly focused on CO<sub>2</sub> emissions, considering that CO<sub>2</sub> is widely acknowledged as the most influential greenhouse gas in relation to global warming [1], while the life cycle input assessment primarily addressed energy utilization.

#### IV.7 MANAGERIAL IMPLICATION

This stage constitutes the final phase of the assessment, aimed at reducing the environmental impacts associated with potato chip manufacturing. The analysis primarily focuses on minimizing greenhouse gas (GHG) emissions. Several improvement alternatives can be recommended throughout the potato chip life cycle to lower GHG emissions, such as shortening distribution distances by selecting retail locations closer to the production facility. This strategy can reduce energy demand, considering that the transportation of finished products from the factory to retailers represents the dominant source of emissions. In addition, another improvement measure involves optimizing the use of by-products by increasing their value, for example by processing solid waste into animal feed or organic fertilizer.

### V. CONCLUSIONS

The system boundary included farmer groups as suppliers, encompassing transportation activities from suppliers to the processing facility (Scope 1) and processing operations within the factory (Scope 2). The contribution of each scope to total emissions differed substantially, amounting to 2.199 kg CO<sub>2</sub>-eq for Scope 1 and 2.937 kg CO<sub>2</sub>-eq for Scope 2. Overall, the carbon footprint within the gate-to-gate scope of the potato chip agro-industry supply chain reached 5.137 kg CO<sub>2</sub>-eq per kilogram of potato chips produced. Emission reduction efforts were primarily directed toward Scope 2, as it represented the largest source of emissions. This dominance is closely related to the factory's machinery system, which relies heavily on electricity and accounts for 47.47% of the total energy consumption. Consequently, improvements in energy efficiency, as reflected by Net Energy Value (NEV) and Net Energy Ratio (NER), are required.

To address this issue, the utilization of production by-products, particularly potato pulp generated as solid waste, was proposed for conversion into organic fertilizer or animal feed. This carbon footprint study was conducted to support the implementation of a green supply chain within the traceability system of the potato chip agro-industry by integrating circular economy principles. The application of a circular economy encourages the optimization of resource use through waste reduction, by-product valorization, and energy efficiency across the supply chain. Consequently, the results of this study are expected to promote more informed consumer choices by emphasizing not only food safety and health considerations, but also environmental sustainability and resource circularity, thereby contributing to the development of a more sustainable and resilient agro-industrial system.

## VI. AUTHOR'S CONTRIBUTION

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