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Carbon footprint in potato chips agro-industry supply chain: A case study in Garut, Indonesia

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Abstract

Supply chain activities in potato chips agro-industry contributed to carbon emissions, including transportation of potato from field to factory (scope 1), product processing in factory (scope 2) and delivery of product to retailers (scope 3). The objectives of this research were to establish carbon footprint model in potato chips agro-industry considering the environmental impacts, determine the highest emission contributor and suggest managerial improvement for reaching more sustainable supply chain. To reach these goals, Life Cycle Assessment (LCA) approach was applied. The results showed that carbon footprint in production of potato chips prepared in semi-mechanical processes reached 16.77 kgCO2-eq per 1 kg of potato chips. Furthermore, it was noteworthy that scope 3 obviously generated the greatest emission of 10.940 kgCO2-eq, regarded as the highest carbon footprint compared with other scopes. Therefore, strategic attempts to reduce carbon footprint were proposed in scope 3. This carbon footprint research was conducted to support the green supply chain in the traceability system in potato chips agro-industry.

Keywords

Carbon footprint, Green House Gases, Life Cycle Assessment, Potato Chips, Supply Chain

Introduction

The potato commodity and agro-industry product supply chain plays a pivotal role across numerous sectors, necessitating continuous refinement to optimize its performance [1]. Contemporary demands emphasize the integration of sustainable supply chain practices, focusing on current and future environmental and social considerations to mitigate adverse environmental impacts. Consequently, businesses undergoing development are increasingly encouraged to incorporate social, economic, and environmental dimensions into their operations. This proactive approach to managing and monitoring supply chain activities is crucial for bolstering sustainability performance [2].

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Climate change represents a paramount challenge within the sustainability discourse, manifested by escalating temperatures, rising sea levels, and increased drought occurrences, among other phenomena [3]. While "carbon" often serves as a shorthand for greenhouse gases (GHGs), given that carbon dioxide is the predominant GHG stemming from anthropogenic activities [4], the Intergovernmental Panel on Climate Change (IPCC) defines climate change as long-term shifts attributed to natural variability or human influence [5]. The scientific consensus is robust, indicating undeniable climate shifts [6], largely driven by accumulating GHGs in the atmosphere, partly a consequence of human endeavors. Recent industrialization, coupled with changes in agriculture and land use, has exacerbated GHG emissions [4]. For instance, carbon dioxide is a byproduct of fossil fuel combustion (e.g., coal, oil, gas), while methane emissions are substantially influenced by agriculture, livestock farming, and land utilization. Therefore, efforts to quantify GHG emissions are frequently termed carbon footprint assessments.

A carbon footprint can encompass various scopes: manufacturing, the value chain, or the product itself [7]. A production carbon footprint quantifies emissions from all manufacturing operations, including energy generation, production processes, and transportation vehicles. The value chain's carbon footprint extends to emissions from sources beyond the manufacturer's direct control, such as those from suppliers and consumers, as well as emissions during product use and end-of-life disposal [8]. Finally, a product's carbon footprint accounts for emissions throughout the entire life cycle of a product or service unit, from raw material extraction and manufacturing to its use, reuse, recycling, or final disposal [9]. Encouraging or compelling enterprises to adopt more sustainable behaviors—including minimizing material and labor waste, along with reducing emissions in distribution and transportation within the supply chain—is critical [10]. For example, potato chip companies within the agro-industry should actively strive to reduce emissions and GHG-related costs by optimizing their fleets, acknowledging their carbon footprint. Data suggest that, across industries, direct emissions from enterprises typically contribute to approximately 14% of their supply chain emissions before product use and disposal [11]. Hence, integrating supply chain considerations into sustainability metrics is imperative for effectively reducing emissions and environmental impacts. Notably, pollution, a direct consequence of human activity, manifests in various forms, including air, water, and land contamination [12]. Humanity's endeavor to restore natural equilibrium involves mitigating these direct, human-induced environmental perturbations [13].

Life Cycle Assessment (LCA) offers a comprehensive "cradle-to-grave" analytical framework to evaluate the energy consumption, costs, and environmental impacts associated with a product's entire life cycle—from raw material acquisition to the consumer's final use [14]. By quantifying environmental loads based on resource consumption (e.g., energy, water, fuel), LCA can pinpoint the environmental implications at each stage of potato chip production. Furthermore, to alleviate any identified environmental repercussions, it is essential to re-evaluate and implement diverse solutions aimed at minimizing environmental impact. Ultimately, LCA serves as a crucial tool for substantiating claims of a product's environmental friendliness, providing quantitative evidence of its green credentials and overall sustainability [15].

Based on the above elaboration, the objectives of this research were to develop a carbon footprint model in potato agro-industry using life cycle assessment approach for identifying environmental impacts, to determine the highest area emissions and interpretation improvement in the supply chain of potato chip agro-industry. This model's design is designed to increase efficiency while reducing the environmental impact of potato chip manufacture. Furthermore, the findings of this study can be utilized as a standard for investigating the carbon footprint of chip products, as well as offering benefits for industry players in terms of environmental management and the implementation of sustainable and environmentally friendly enterprises.

Method

Based on ISO 14040, stages of LCA included (1) goals and scope, (2) inventory analysis, (3) impact analysis and (3) result interpretation [16]. Setting the goals and scope was important for determination of data required, in which the data were collected from industry studied. Inventory analysis was performed using flow charts, mass balance, and energy balance to determine the usage of any material that produces an impact on the environment. Impact analysis was carried out to calculate the emissions produced by the formula, then classified the emissions according to predetermined impact. Proposed improvements were sought using literature study in various researches discussing the impact analysis.

Research stages

Life Cycle Assessment (LCA) serves as a comprehensive methodology for quantifying the environmental repercussions of a product or service across its entire supply chain [7]. In this particular investigation, the scope of environmental impact for potato chip products was narrowed to global warming potential, which was subsequently evaluated through the metric of carbon footprint [18, 19]. The measurement of carbon footprint has recently gained prominence as a crucial indicator for gauging environmental preservation efforts. Fundamentally, the carbon footprint represents the aggregate quantity of greenhouse gas emissions directly and indirectly attributable to all activities occurring within a defined system boundary [20].

This study's primary objective was to quantify the carbon footprint and ascertain the global warming impact associated with potato chips produced via a medium-scale semi-mechanical method in potato chip manufacturing facilities. The impact assessment strictly adhered to the guidelines outlined in the ISO 14040/44 standard for calculating the carbon footprint of products, employing the LCA methodology as per the IPCC 2007 framework.

Functional unit and LCA scope

In this investigation, the carbon footprint was quantified based on a meticulously defined functional unit: 1 kg of potato. This functional unit serves as the foundational reference against which all relevant inventory data for the study's system function are benchmarked. The scope of the product life cycle considered was comprehensive, encompassing all stages from the initial supplier and production processes, through the meticulous handling of raw materials, the entire production process, and ultimately, delivery to the retailer ("gate to gate"), as visually represented in Figure 1.

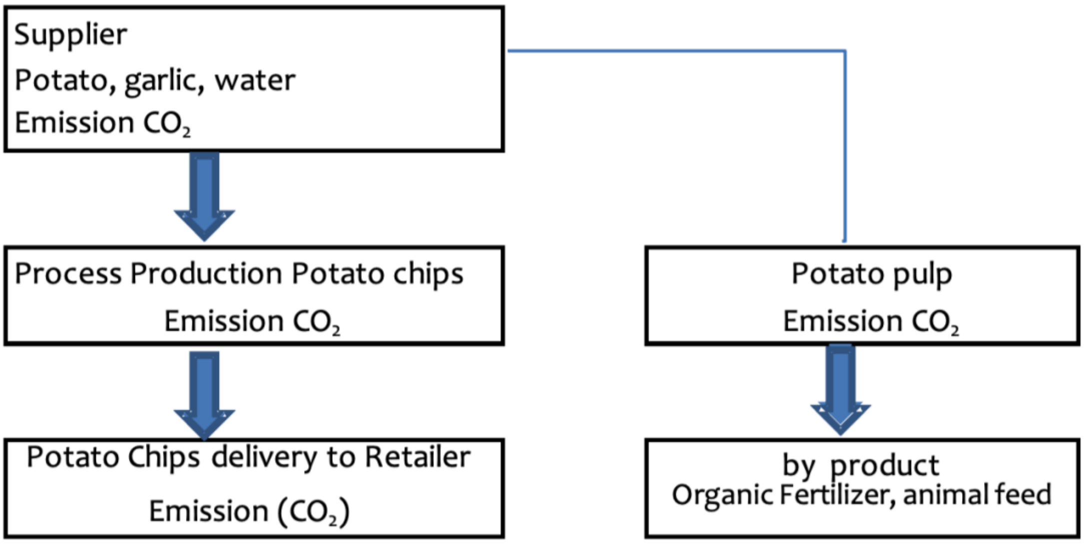

Figure 1. Scope of LCA study in potato chips agro-industry

Data collection

For the life cycle inventory, comprehensive data pertaining to both material and energy flows into and out of the defined system boundaries were systematically gathered. The inventory specifically focused on three key stages: post-harvest and raw material handling, transportation, and the production process. Data for these stages were acquired through a combination of direct interviews with relevant personnel and on-site measurements.

Table 1. Data source for life cycle inventory

Life Cycle Stage	Data	Data Source and Collecting Method
Postharvest and Handling (Farmer Group)	Material and wastes Diesel fuel Potato/kg	Measured Interview
Transportation (Retailer)	Type of vehicle and distance Diesel fuel	Measured Factory manager, interview
Production	Raw Material (Potato, Garlic, Salt), Fuel Oil, Diesel fuel, Cooking oil, Electricity	Measured Factory manager, interview

It is important to note that the characterization of effluent streams was exclusively conducted at PT Champ. For the purpose of this study, an assumption was made that other facilities or mills within the scope of the analysis exhibited comparable effluent characteristics. A detailed overview of the types of data collected and the methodologies employed for the life cycle inventory is provided in Table 1.

Data processing and analysis

Life cycle inventory analysis

Inventory analysis constituted a part of the LCA component comprised of material input and output information, raw material, energy, waste, and by-products in a life cycle of product [21]. Stages inventory analysis was carried out using LCA approach in the form of balance sheet flow analysis energy, mass balance, and emissions based on the provisions of ISO 14040 [22], as depicted in Figure 1. We used secondary data collected from company's documents and research publication, while data were also obtained from calculations considering assumptions and primary data. This stage accounted for calculation the quantity of raw material, energy, and emissions generated in production of 1 kg of potato chips.

Greenhouse Gas Effect (GHG)

The use of fossil fuels in potato chips agroindustry linked to generation of greenhouse gas emissions and thus participated in the occurrence of global warming. Three major greenhouse gases, i.e. CO_2, CH_4, and N_2O are generated from fossil fuel burning, production activities, catching and breeding activities, waste handling and treatments. Calculation of GHG emission referred to Intergovernmental Panel on Climate Change (IPCC), as presented in Eq. (1). Greenhouse effect due to CO_2 sourced from LPG, diesel and electricity.

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

Information: QF as Fuel consumption (l); NK as Net calorific value (kcal / l); and FE as Emission factor (Kg CO_2 / TJ)

Net calorific values and emission factors showed different values depending on the type of fuel used. The CO_2 emission generated from electricity usage was obtained using Eq. (2).

$$CO_2 \text{ emissions (power)} = QL \times FE \tag{2}$$

Information: QL as Electricity consumption (kWh); and FE as Emission factor (0.485 tCO_2 / MWh).

Furthermore, CH_4 emission came from wastewater and diesel usage. Calculation of CH_4 emissions derived from liquid waste was performed in accordance with the amount of COD produced. The emission followed IPCC [5] as seen in Eq. (3).

$$CH_4 \text{ emissions (watewater)} = VLC \times C \times FE \tag{3}$$

Information: VLC as Volume of liquid waste (l); C as COD value (mg / l); and FE as Emission factor (0.21 Kg CH4 / Kg COD).

Meanwhile, calculation of CH_4 emission derived from the use of fuel followed Eq. (4).

$$CH_4 \text{ (diesel)emissions} = QF \times NK \times FE \tag{4}$$

Information: QF as Fuel consumption (l); NK as Net calorific value (9 063 kcal / l); and FE as Emission factor (10 Kg CH_4 / TJ).

The calculation of nitrous oxide emission (N_2O) based on diesel usage was based on the amount of nitrogen present in raw material, while the emission factor referred to standard of IPCC [4]. In this case, N_2O emission was carried out using Eq. (5) [5].

$$N_2O\ \text{(diesel)emissions} = QF\ \times NK\ \times FE \tag{5}$$

Information: QF as Fuel consumption (l); NK as Net calorific value (9 063 kcal / l); and FE as Emission factor (0.6 Kg N_2O / TJ).

According to [5], GWP (Global Warming Potential) of CH_4 and N_2O was defined as 25 and 298, respectively. It was relatively equal to CO_2 using conversion base as follows: 1 Kg CH_4 = 25 Kg CO_{2eq} and 1 Kg N_2O = 298 Kg CO_{2eq}.

Results and Discussion

LCA goal and scope definition

As depicted in Figure 2, the existing supply chain of potato chips produced by PT Champ Garut contained farmer, farmer group, production process, retailer and consumer. Briefly, after harvested, potato was gathered in farmer group for quality checking, sortation and grading, packing and storage. Potato was sorted and graded according to standard of agro-industries. Subsequently, the sorted and graded potato was transported into food processing company, converting potato tubers into chips as a final product. The products were then distributed to retailers and marketed to consumers.

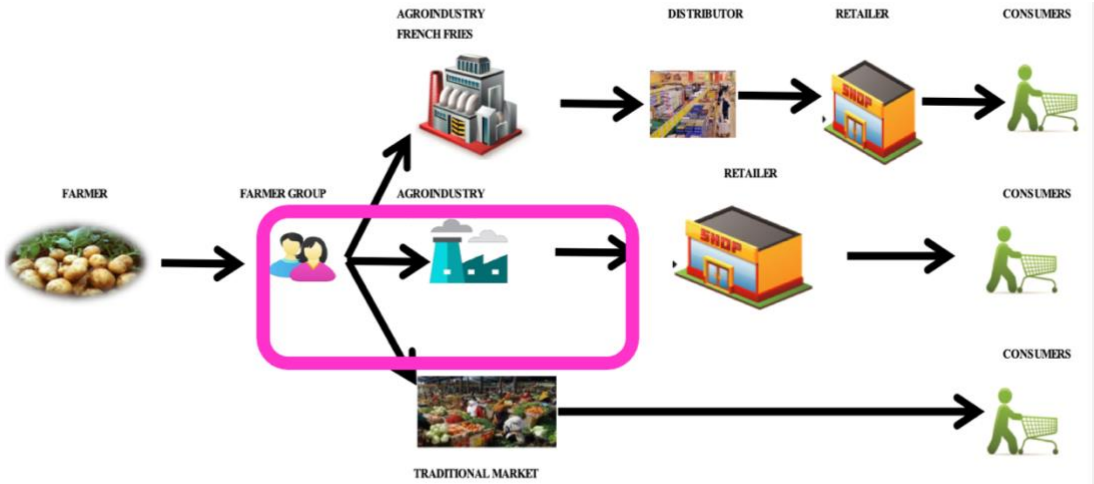

Figure 2. Supply chain in potato chips agroindustry

The information on supply chain is essential for describing the scope of emission, as exhibited in Figure 1. The scope starts with supply activities using the vehicles that transport potato from farmer group to mills, defined as scope 1. Processing in the potato chips agro-industry was considered as scope 2. The transportation using vehicles also occurred in distribution of end products to retailers, defined as scope 3.

Inventory data description

Activities in potato chips processing generated wastes, including liquid and solid (Table 2). Solid waste sourced from the pulp, reaching up to 2 kg, while liquid waste referred to wastewater and used cooking oil, reaching up to 218.51 kg. The waste generated from product processing activities could be upgraded as by-products, leading to waste reduction and energy efficiency.

Table 2. Waste generated in the production process of potato chips

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

Carbon footprint on supply chain of potato chips agro-industry

The carbon footprint calculation contained following stages: direct measurement, input-output LCA, energy-based calculation and activity-based calculation.

Direct measurement

Measurement of the exhausting gases in gate-to-gate scope discussed gases released from following routes: suppliers to potato, within product processing and producers to retailers. Greenhouse gases are analyzed based on the content of CO_2, which is converted to $CO_{2\text{-eq}}$ generated from burning fossil fuels and product processing activities. Direct measurement for life cycle inventory of the input-output data refers to system boundaries. As mentioned before, the inventory analysis was based on data collected from potato chips agroindustry located in Garut, West Java province. The mills were selected because the potato as main ingredient was purchased directly from potato farmer groups, meanwhile the product was prepared using semi-mechanical process. The food manufacturing process was 25 days per month, with daily production capacity of 1600 kg potato that involves 5 employees. The selling price of potato chips in retail ranges from 200,000 IDR to 215,000 IDR per kg.

Input-Output Life Cycle Assessment (IO-LCA)

Input-Output LCA describes raw material, energy, products and emissions released from each activity in the agroindustry supply chain [18]. This stage enables to quantify carbon emissions released from raw materials, energy, machinery and labors. In short, it serves to know the total carbon emissions in the supply chain for the company [23]. Measurement of carbon emissions is very important to take decisions in terms of implications for improvements in the company, especially in reducing the amount of carbon; thus, waste reduction can be achieved [19]. The illustration of life cycle of IO LCA was depicted in Figure 3.

Emission serves as an important indicator to measure since it provides strong implications for the type of methods that can be applied. We noticed that scope 3 showed a small portion in total supply chain emissions for the company. Therefore, scope 1 and scope 2 should receive more intense consideration [24]. However, emission derived from scope 3 could be more considerable when representing a large carbon size of a company, as often found in most companies. Input materials included (1) ingredients such as potato, water, cooking oil, garlic and salt, (2) electricity as source of energy and (3) fuel for transportation such as diesel. Meanwhile, the resulting output included potato chips and waste such as CO_2 emission, CH_4, N_2O, potato pulp, residual water and cooking oil.

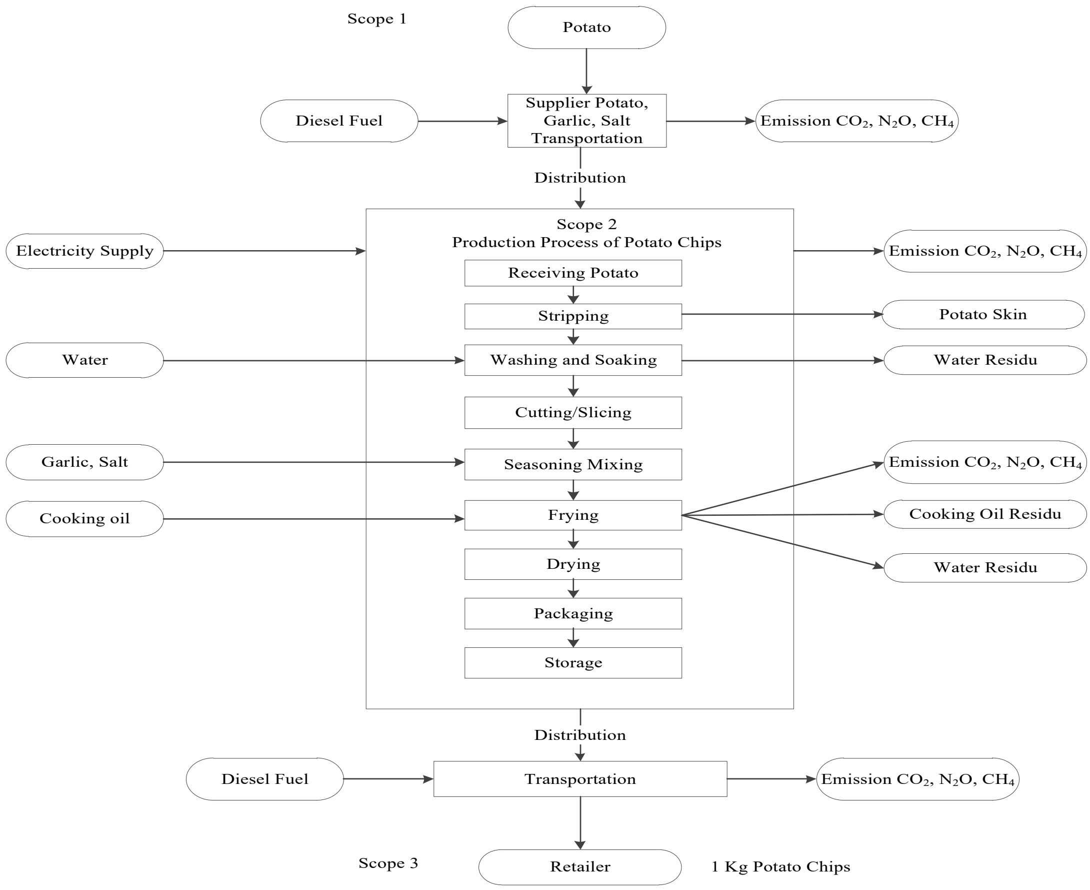

Figure 3. Input-Output LCA for Supply Chain in Potato Chips Agroindustry

Energy-based calculations

For life cycle inventory (LCI) assessments, the quantification of material and energy flows into and out of a system is paramount. Carbon emissions are frequently ascertained through energy-based calculations, which derive emission values based on either a specific mass balance or the theoretical combustion of constituent materials. This methodology proves particularly applicable to fuel consumption within both production sites and transportation operations. Given the inherent difficulty in directly monitoring precise fuel quantities, estimations often rely on extrapolation from general consumption data. Furthermore, the carbon content of a given fuel is commonly estimated using average figures. Energy-based calculations can also be extended to account for intermittent emissions stemming from electricity consumption, as many utility providers release the average rate of carbon emissions per unit of generated electricity [18].

In a practical application, specific processing activities yielded 70.89 kg of potato chips from an input of 100 kg of potatoes, simultaneously generating liquid, gaseous, and solid by-products. The liquid and gaseous waste streams present an opportunity for energy generation, thereby enhancing the overall energy efficiency of the process. Meanwhile, the solid waste, identified as potato pulp, was effectively converted into animal feed and organic fertilizer. Additionally, liquid waste produced during the potato washing process undergoes a dedicated purification treatment, making it suitable for other purposes. Analogously, the gaseous waste produced during the frying process can be transformed into an energy source, serving as a viable substitute for grid electricity.

Activity-based calculation

The activity-based calculation method is a widely adopted technique for quantifying carbon emissions, leveraging conversion factors to translate activity data into emission figures. These factors represent calculated ratios that link carbon emissions to specific proxy measures of activity associated with emission sources, often referred to as emission factors. This approach is particularly prevalent for its direct correlation between operational activities and environmental impact.

Table 3. Activity-based energy calculations

Activity	Use Energy (J) (A)	Energi (MJ/Year) (B)	Emission Factor (C)	GHG Emission(KgCO2eq /Year) (D)
	A	B	C	D = B x C
Scope 1 (Post harvest - Potato chips Agroindustry)				
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				1.055.655,300
Carbon Footprint kgCO2eq/kg potato				2,199
Scope 2 (Production potato chips)				
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				62.466,486
Carbon Footprint kgCO2eq/kg potato chips				2,937
Scope 3 (Potato Chips Agroindustry - Retailer)				
Emission transportation potato chips	33,333	708.900,000	0,328	232.660,980
Carbon Footprint kgCO2eq/kg potato chips				10,940
Carbon Footprint kgCO2eq/kg potato chips				**16,077**

Source: Data processing

For instance, within a reporting enterprise, activity-based calculations can be applied by converting metrics such as the weight of goods transported over a given distance, utilizing specific truck types, to estimate average carbon emissions. This is achieved through the application of relevant emission factors. Numerous initiatives now provide these standardized emission factors, particularly for key activities within a supply chain.

Furthermore, by extending this principle, the mass balance concept can be employed to determine the energy balance for various activities within, for example, the potato chips agro-industry supply chain. The specific activities considered for emission assessment should align with the defined scopes of emission relevant to the potato chips agro-industry supply chain.

As presented in Table 3, total carbon footprint showed a variability of emissions, i.e. 2.199 $kgCO_{2eq}$ (scope 1), 2.937 $kgCO_{2eq}$ (scope 2) and 10.940 $kgCO_{2eq}$ (scope 3). The total carbon footprint from postharvest to retailers reached 16.77 $kgCO_{2eq}$. Noticeably, scope contributed to the highest carbon footprint, thus improvement on scope 3 was needed to reduce the carbon footprint.

Impact Assessment

Impact assessment is the next step to determine the magnitude of the impact produced by potato chips. The impact was analyzed through GHG calculations along the supply chains of product using LCA approach. GHG emissions such as CO_2, CH_4, and N_2O will be presented as CO_2 equivalent (CO_2-eq). CO_2-eq can be interpreted as a depiction of some greenhouse gases in a common unit. The amount of CO_2-eq showed the total CO_2 emissions generated from a number or combination of GHGs which is added up with the equivalent level of impact on global warming [25]. The calculation of the impact of global warming using GWP 100 with the equivalent of greenhouse gases for CO_2, CH_4 and N_2O are 1, 25 and 298, respectively. The results of the total calculation of CO_2 emissions from the life cycle of potato chips are shown in Figure 4.

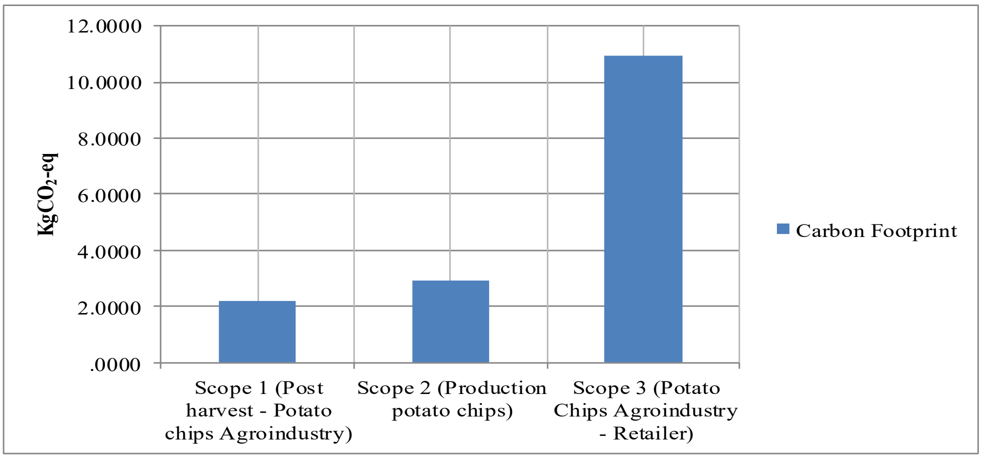

Figure 4. The carbon footprint result

Result interpretation

The total carbon footprint (Figure 4) revealed scope 1 as the lowest contributor. In this scope, potential gas emission came only from transportation of potato from supplier to potato chips processor using diesel vehicles. Furthermore, we also found that total emissions generated in scope 2 was lower than in scope 3. Similar to scope 1, the potential gas emission in scope 3 came from vehicles that account for transportation of end products to retailers. Considering the distance of retailers, fuel consumption in scope 3 was much higher than in scope. In addition, potential source of emission in scope 2 was the operating machinery that depends on electricity as energy source. In short, we noted that scope 3 was the highest contributor to the total emission in the system studied, as clearly evidenced in total carbon footprint reaching up to 10,940 kg CO_2-eq for each 1 kg of potato chips.

Research limitation

The scope of the selected product's life cycle included post-harvest activities, transportation of raw materials to industry, and delivery of potato chips to retailers. Determination of functional unit became one of critical stages since it fundamentally affected the following calculations. In this case, calculation of carbon footprint focused on CO_2, concerning that it is regarded as the most influential gas related to global warming [4]., while the input life cycle focused on energy use.

Managerial implication

This stage is the final step aiming to reduce the environmental impact caused by the production of potato chips. In this study the main focus is on reducing GHG emissions. Improvement scenarios to reduce GHGs that can be recommended in the potato chip life cycle include the shortage of retailer distance, being closer to the potato chip factory. Thus, the transportation consumes less energy, considering that transportation of end products from factory to retailers is responsible for the highest emission. Further scenario is the upgrading of by-products, attempted to increase their added value such as conversion of solid waste into animal feed and organic fertilizer.

Conclusion

Boundary system contained farmer group as suppliers which involved transportation activities form supplier to factory (scope 1), processing in the factory (scope 2) and product delivery to retailers (scope 3). Contribution of each scope to emission varied greatly, i.e. 2.199 kgCO2-eq, 2.937 kgCO2-eq and 10.940 kgCO2-eq, respectively. The carbon footprint in gate-to-gate scope for supply chain of potato chips agro-industry reached 16.77 kgCO2-eq per kg of potato chips. Major improvement was addressed to scope 3 as the greatest contributor to emission, designed to reduce the carbon footprint. To meet this challenge, the use of by-products (potato pulp) existing as solid waste for organic fertilizer or animal feed was proposed.

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