International Journal of Scientific Engineering and Science
Volume 10, Issue 5, pp. 74-83, 2026. ISSN (Online): 2456-7361

Environmental Impact Reduction Strategies for the Cayenne Pepper Supply Chain: An Integrated Life Cycle Assessment and Multi-Criteria Decision-Making Approach

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***Abstract*— *One focus of developing the Sustainability Development Goals (SDGs) concept is developed in the environmental sector. One indicator of the SDGs is Food Loss and Food Waste (FLFW). Food Loss and Food Waste (FLFW) have a negative impact on the environmental sector. FLFW occurs in the food supply chain, especially in the agricultural production section. The issue of Food Loss and Food Waste (FLFW) is growing with its relation to environmental issues. Food waste contributes 40% of greenhouse emissions. The complexity of the supply chain generates waste that occurs in all processes along the supply chain. Global annual production phase emissions associated with food waste increased from 680 million tons of CO2e to 2.2 Gt CO2e or an average of 2.4% per year. So that efforts and strategies are needed to reduce the environmental impact of all processes in the agricultural supply chain, this study aims to examine the environmental impact of the cayenne pepper supply chain using an integrated life cycle assessment (LCA) and Multi-Criteria Decision Making (MCDM) approach. In this study, LCA is used to identify and analyze waste in the supply chain using Simapro software. While the MCDM approach in this study, namely AHP, was used to select alternative strategies for reducing the impact of waste by using expert choice software. This research contributes to realizing the sustainability of the food supply chain. The results of this study are an analysis of the environmental impact on the cayenne pepper supply chain and policy recommendations to reduce this environmental impact*

***Keywords*— *Analytical Hierarchy Process: Life Cycle Assessment: supply chain: Sustainability:Waste*

I. INTRODUCTION

The concept of sustainability is essential in the agricultural industry because production systems are interdependent, and a holistic or overall view of a supply chain system is needed to obtain optimal results from every improvement made [1]. The supply chain encompasses all activities involved in the flow and transformation of materials from raw inputs to end consumers, including information and capital flows. Sustainable supply chain management (SSCM) is defined as the integrated management of material, information, and capital flows across supply chain partners to achieve the triple bottom line of economic, environmental, and social sustainability [2].

Agriculture-based food supply chains have specific characteristics and are more challenging than other supply chains. The characteristics of an agriculture-based supply chain are that the production process is characterized by frequent adjustments, highly dependent on time, season, and production sequence. Another characteristic is the limited shelf life due to expiration issues and requires special techniques. Short processing times require traceability, monitoring, and quality system technology to ensure food quality, authenticity, and safety [3].

The potential risk in the food supply chain is that perishable food products increase food loss and food waste along the supply chain. FLFW also impacts the environment, one of which is a contributor to carbon emissions. Carbon emissions can be reduced by reducing FLFW levels in the supply chain [3, 4]. Carbon emissions in 2018 were reported to have increased by 2.7% [5]. The issue of Food Loss and Food Waste (FLFW) is growing with its relation to environmental issues. Food waste accounts for 40% of greenhouse emissions [6]. According to Porter and Reay [7], global annual production-phase emissions associated with food waste increased from 680 million tons of CO_2e to 2.2 Gt CO_2e—an average increase of 2.4% per year with the highest increases observed in South, Southeast, and East Asia. GHG emissions are generated across all nodes of the food supply chain, from upstream agricultural production through downstream retail and consumption [8].

The food supply chain involves stakeholders from upstream to downstream (farmers/breeders, traders, transportation, manufacturers, retail/food services, and consumers). Each chain has a different process and inputs and outputs, but each chain produces waste from each process. Waste in the form of carbon emissions is generated in each chain and in each process from upstream to downstream (9). In his research, Muth, Birney described the flow of GHG emission waste generated along the supply chain. It was found that the most carbon emissions occurred along the supply chain.

Indonesia ranks as the third-largest cayenne peppers-producing country in the world, with a production volume of approximately 7.16 million tons of cayenne pepper in 2017 [9]. Cayenne pepper is among the most perishable agricultural commodities, characterized by a complex multi-actor supply chain and high susceptibility to FLFW. Based on data from Porter and Reay[7], cayenne pepper ranks second among vegetables as a carbon emitter in Southeast Asia, highlighting

International Journal of Scientific Engineering and Science
Volume 10, Issue 5, pp. 74-83, 2026. ISSN (Online): 2456-7361

the urgency of environmental impact assessment in this commodity's supply chain.

The waste generated in each process can be studied using the Life cycle assessment (LCA) approach[10]. Life Cycle Assessment (LCA) is an instrument that can evaluate the environmental burden of a product, process, or activity throughout its life cycle. The food industry, one of the world's largest industrial sectors, is the largest energy user. Food production, preservation, and distribution activities consume much energy and contribute to total CO2 emissions. The great use of energy has resulted in global warming [11].

After knowing all the emissions generated in all process activities, a process is chosen that generates the most significant emissions in the LCA [10]. From this process selection activity, an alternative will be carried out in one process to reduce the impact [12, 13]. It aims to find the best treatment to reduce greenhouse gases. In getting the best alternative, many criteria must be considered that are included in the green supply chain concept. In parallel, Multi-Criteria Decision Making (MCDM) methods, such as the Analytic Hierarchy Process (AHP), provide a structured framework for selecting among competing improvement strategies based on multiple qualitative and quantitative criteria [14].

Considering the waste generated along the cayenne pepper supply chain and its impact on the environment, it is essential to conduct an environmental impact analysis study for the cayenne pepper supply chain. This study aims to analyze and measure the environmental impact of the cayenne pepper supply chain using a Life Cycle Assessment. In addition, this study also aims to determine alternative strategies for overcoming these problems by using a multi-criteria decision-making approach, namely AHP. The integrated LCA-AHP approach provides both a diagnostic tool for identifying emission hotspots and a decision support framework for selecting the most appropriate and feasible improvement strategies.

II. Literature Review

A. Page Layout

Agricultural tends to have high environmental impacts since they interact directly with land use. LCA is a widely accepted tool and methodology to measure this impact. Several Life Cycle Assessment studies in the agricultural product sector include the discussion of the use of LCA in fruits and vegetabl [12], production systems for roasted coffee, lemon juice, olive oil, and red wine[13], endive[15], tomato production[16], fruits and vegetables, meat, dairy and eggs, and fish[17], edible oil, protected crops (tomatoes, cherry tomatoes, peppers, melon, and zucchinis)[18], and rice, sugar beets, potatoes and tomatoes [19].

The focus of these studies is related to the use of simplified LCA and full LCA in several case studies[13], the examination of the environmental impact of organic farming and integrated agriculture[10, 15], the assessment of the environmental impact on GHG emissions at each hot spot along the supply chain[16], and the examination of the environmental impact of alternative use of shipping containers[20].

The LCA study in the cayenne pepper supply chain, covers the examination of the environmental impact with the scope of cradle to grave the examination of the environmental impact (energy and GHG emissions) on production by traditional means compared to technique methods in Ecuador with the scope of cradle to gate[21], the assessment of environmental performance on cayenne pepper production using monoculture and agroforestry methods in Indonesia with the scope of cradle to gate[22], the calculation of the environmental impact on the scope of gate to get starting from the arrival of raw materials in the company which include the transportation stage to the packaging of cayenne pepper products in Italy[4].

The cayenne pepper supply chain is characterized by a long chain involving many actors[4]. Figure 1 displays a general supply chain consisting of farmers, traders, processors, manufacturers, retailers, and consumers. The distribution of raw materials and products is carried out using trucks, cars, and ships. Meanwhile, an overview of the supply chain for the agricultural industry in Indonesia can be observed, where on the trader side, it involves many actors, including local collectors on the village level and district level, big buyers, and domestic buyers. Cayenne peppers do not directly transact with the manufacturer and Retailer, and they are connected with local collectors on village and district levels and big buyers.

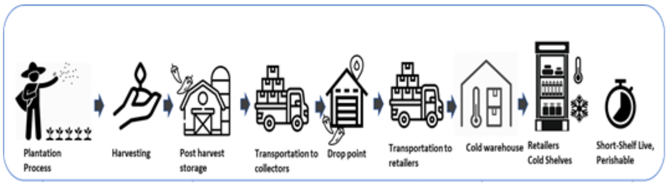

Fig. 1. Cayenne pepper Supply Chain [4]

For the supply chain of cayenne pepper in Indonesia, focusing on local markets with the best quality and premium prices. Retailer did not actively collaborate with farmers to get quality raw materials[4, 22].

III. Research Methodology And Data Collection

This study employs an integrated methodology combining Life Cycle Assessment (LCA) and Analytic Hierarchy Process (AHP). The LCA component follows ISO 14040:2006 and ISO 14044:2006 standards [11, 23], encompassing four stages: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation. The AHP component is used subsequently to prioritize improvement strategies identified through LCA interpretation.

Primary data were collected through field observations and semi-structured interviews with supply chain actors during 2020–2021. Secondary data were sourced from published literature and the SimaPro Ecoinvent 3 Agri-footprint database. Environmental impact assessment was performed using SimaPro 9.1 software with the EDIP 2003 methodology, and AHP analysis was conducted using Expert Choice software.

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A. Goal and scope of the LCA study

The study boundary is defined as cradle-to-grave, encompassing all supply chain stages from cayenne pepper cultivation on farms in Gowa Regency, South Sulawesi, through transportation, storage, and retail sale in Makassar City. The functional unit (FU) is defined as the annual production and distribution of cayenne pepper across the defined supply chain.

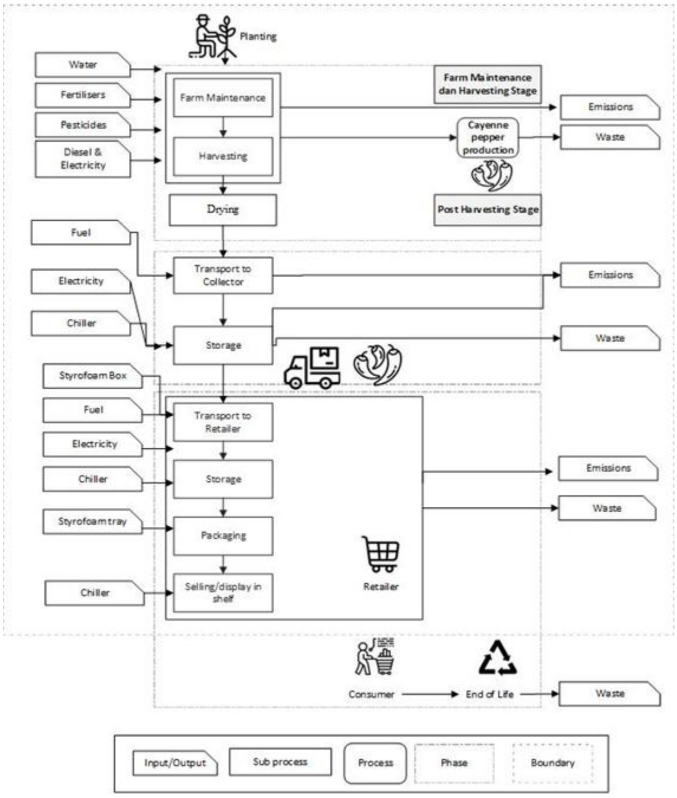

Fig. 2. Mapping Process and Boundary System

The supply chain is mapped to describe and identify the current flow of products and information for each process at all stages, as given in Table. 2. Seven processes are identified in the supply chain from Farmer to the retailer. 5M+I analysis (Man, Money, Method, Material, Machine, and Information) is performed to identify the variables and processes that affect the supply chain (in Figure 2). The impact categories assessed are: global warming potential (GWP 100a), ozone depletion potential (ODP), photochemical ozone formation, and human toxicity potential, consistent with the Environmental Product Declaration (EPD) indicator guidelines [24].

Process mapping is carried out to identify the inputs, processes, and outputs involved at each stage of the cayenne pepper supply chain. This mapping helps provide a clear overview of material flows, energy use, transportation activities, and waste generated throughout the production and distribution system. In addition, process mapping is used to define and strengthen the system boundaries of this research, as illustrated in Figure 1, ensuring that all relevant activities included in the study are clearly identified and systematically analyzed.

As part of the overall study, this Life Cycle Assessment (LCA) aims to identify and quantify the potential environmental impacts generated throughout the life cycle of cayenne pepper, starting from cultivation and post-harvest handling to transportation and downstream sales within the supply chain. Through this approach, the study provides a comprehensive understanding of the stages that contribute most significantly to environmental burdens and supports the development of more sustainable supply chain practices.

B. Life-Cycle Inventory

In this research, the primary data sources from observation and interviews to understand the process and characteristics during 2020-2021, secondary data are from the other literature and the SIMAPro application data of Ecoinvent 3 Agri-foot print.

1) Farm Maintenance and Harvesting Stage

In the production process at Farmers, we limit LCI to an area of 20 ha during the cayenne pepper planting season and 10 ha during the non-cayenne pepper planting season, with an average number of plants of 22,500 plants per hectare. For plant maintenance, farmers who still use inorganic fertilizers and insecticides are starting to be interested in using organic fertilizers. Farmers can make organic fertilizers from easily available materials, such as drum manure from farmers' livestock waste.

TABLE 1. Input and Output data for the Farm Maintenance and Harvesting Stage (referred to F.U.)

Input	Unit	Amount
Water		
Fertilizer		
Urea	Kg	300
Sp-36	Kg	250
KCI	Kg	250
ZA	Kg	650
Pupuk Kandang	Kg	25000
Pesticides		
Insektisida (Dimacide 400EC)	Kg	5
Fungsida (propineb 70%)	Kg	25
Energy		
Electricity	Kwh	38,976
Solar	kwh	6,6
Water Emission		
Nitrogen	Kg	0,072
Amonia	Kg	0,028
Chemical oxygen demand	Kg	0,000423
Soil Emission		
CH4	Kg	2571,519
Pestisida	Kg	0,014538
Energy for drying tools		
Electricity	Kwh	109,5

Farmers use water pumps to provide water during the dry season, ranging from February to October in Indonesia. The energy source that drives the water pump combines electricity and solar energy. Emissions to water come from fertilizers in the form of nitrate, ammonia, and chemical oxygen demand [19]while emissions to soil result from pesticides, according to papers [5]. As an organic waste, waste from the process of caring for cayenne pepper trees comes from leaves, and cayenne pepper that has fallen to the ground and has rotted. Furthermore, until the peak of the cayenne pepper harvest in September, the cayenne pepper is harvested and then stored in

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Volume 10, Issue 5, pp. 74-83, 2026. ISSN (Online): 2456-7361

gunny sacks. After the cayenne pepper is harvested, it is dried by aerating using a fan while the farmers carry out the grading and sorting process.

2) Transportation to Collector Stage

In this study, the transportation process from farmers to collectors in the cayenne pepper supply chain used pick-up vehicles. The fuel used is pertalite. Delivery from Farmers to Collectors is carried out 3-4 times weekly. Considering that the distance between Farmers and Collectors is quite far, fuel consumption is also high.

TABLE 2. Input data for the Transportation to Collector Stage (referred to F.U.)

Input	Unit	Amount
Transportation		
Fuel	Liter	2500

3) Storage in Collector Stage

When the cayenne pepper arrives at the collectors, the collectors carry out a sorting process to select cayenne pepper products that meet their quality standards. Then the cayenne pepper that passes the selection is stored in a warehouse that has a cold storage area. Cayenne pepper is stored in Styrofoam boxes when delivered to Retailers, as described below.

TABLE 3. Input and Output Data in Storing in Collector Processing

Input	**Unit**	**Amount**
Storage		
Electricity	Kwh	660,96
Air waste		
Kloroflorokarbon (CFC 11)		
CFC-12	Kg	8,64
Packaging		
Polistirena	Kg	592,8

4) Transportation to Retailer Stage

The transportation process from collectors to retailers in the cayenne pepper supply chain in this study also uses pick-up vehicles. The fuel used is pertalite. Delivery from collectors to retailers is carried out four times a week. Considering the relatively close distance between collectors and retailers, the fuel consumption is low, as described below.

TABLE 4. Input and Output Data in Transportation to Retailer Processing.

Input	**Unit**	**Amount**
Transportation		
Pertalite	Liter	180

5) Storage and Display in the Retailer Stage

Retailers have high-quality standards. It is known that the Retailer in this study is the most prominent modern supermarket in Makassar City. So that the quality standards applied are premium quality, whose market segmentation is the middle to the upper economy. So that the cayenne pepper goes through the sorting process again at the Retailer, cayenne pepper that does not meet quality standards is returned to the Collector. Retailers store cayenne pepper that has yet to be displayed in a window stored in a warehouse with refrigeration facilities. At the same time, the cayenne pepper that is being marketed is displayed in the store's chiller. Cayenne pepper is packed in Styrofoam trays and wrapped in clear polyethylene plastic. Input data for Retailers is shown in Table 5.

TABLE 5. Input and Output Data of Storing and Selling Processing in Retailer

Input	Unit	Amount
Storage		
Electricity	Kwh	660,96
Air waste		
Kloroflorokarbon (CFC 11)		
CFC-12	Kg	8,64
Pacakaging		
Polistirena	Kg	3146
clear polyethylene	Kg	314,6

C. Life Cycle Impact Assesment

In Processing environmental impact assessment data using SimaPro 9.1. Data processing by using this software, needs several steps, namely determining goals and scope, life cycle inventory, determining environmental impacts, and interpreting data. The scope of this research is limited to cradle-to-grave, starting from the planting of cayenne pepper to the sales process in the downstream part of the supply chain, namely at retailers. In the environmental impact determination stage, several stages are carried out, namely normalization and characterization. The data interpretation results will show the most significant impact of a process for further improvement efforts. This research aims to discover which processes contribute to environmental impacts, especially those related to air pollution and global warming. Each processing unit focuses on the materials used, energy (fuel/electricity), and the emissions released. As this study focuses on the agri-food industry, the recommended indicators limit the environmental impact of the EPD (Environmental Product Declaration) [25]. The method used in the Environmental Design of Industrial Products (EDIP) 2003 with the limitations of impact assessment in this research is global warming 100a, ozone depletion, ozone formation, and human toxicity. The measurements of environmental impact are carried out along the supply chain in 3 (three) stages in chronological order, 1) Farm Maintenance and Harvesting Stage, 2) Post Harvesting Stage, and 3) Storing and Selling Stage.

1) Calculating of the environmental impact on the cultivation process of cayenne pepper farming

After collecting data through a life cycle inventory, the identification process is carried out with goals and scope. After identification, input and output calculations from the product system in the life cycle inventory (LCI) are carried out.

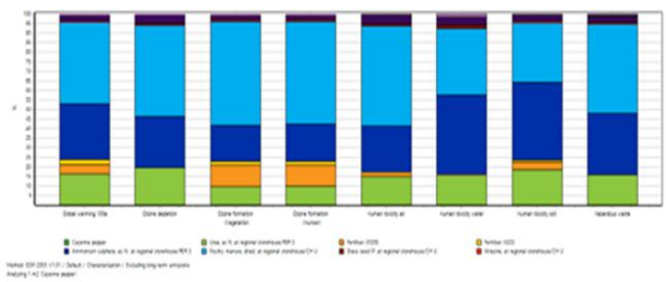

Figure 3. Environmental Impact on Cayenne Pepper Cultivation Process Using Categorization

The results of the LCI data processing produce a network that provides information on the relationship of each process that impacts the environment. On the network, we get a diagram that shows the interrelationships between processes connected by red lines. In addition, the thickness of the red line indicates the emission burden incurred by activities. The thicker the line, the greater the emission as shown in Figure 3.

2) Enviromental Impact on Drying Process of Cayenne Pepper

In the drying process, farmers use fans to aerate cayenne pepper after harvesting. The peppers are spread on tarpaulins and continuously exposed to airflow to reduce moisture content and maintain product quality. Although the use of electricity increases operational costs, farmers prefer this method because it makes the drying process easier to monitor and helps prevent spoilage.

Figure 4 shows the environmental impact of the cayenne pepper drying process. The green bar represents the environmental impact carried over from the previous process. Compared to cultivation and harvesting, the drying stage produces relatively low environmental impacts, as indicated by the large gap between the previous process and the drying process itself. However, the use of electric fans still contributes to global warming potential through electricity consumption and also generates hazardous waste associated with energy production and equipment use.

Related to the environmental impact of global warming, The Electricity and low voltage have the most significant impact on global warming. Electricity and low voltage donate carbon dioxide and methane fossils. So a strategy that involves stakeholders is needed to determine priority strategies for priority issues.

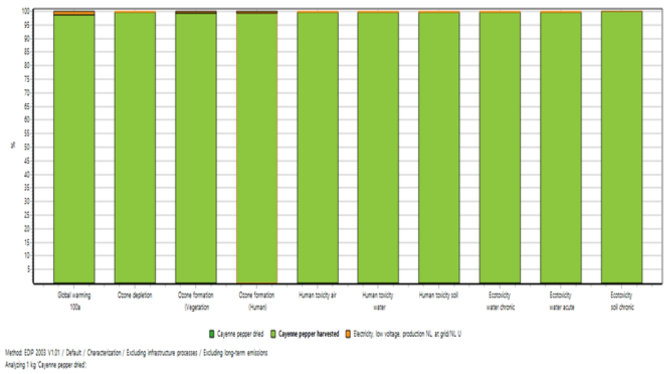

Figure 4. Environmental Impact on Cayenne Pepper Cultivation Process Using Categorization

3) Environmetal Impact on the Process of Sending Cayenne Pepper to Collectors

Sending cayenne pepper to collectors introduces an additional activity in the supply chain, namely transportation. At this stage, the peppers are packed in gunny sacks, similar to the previous handling process. Figure 5 illustrates an increase in environmental emissions, which is indicated by the thicker red lines across the supply chain activities. Among all stages, cultivation continues to be the dominant contributor to emissions due to the intensive use of agricultural inputs and field operations. However, transportation to collectors also contributes considerably to total emissions because the delivery process often involves long travel distances and high fuel consumption from lorry trucks. As a result, the overall emissions generated at this stage are higher than those produced during harvesting and drying activities. The environmental impacts presented in Figure 5 represent the total annual emissions generated throughout these processes.

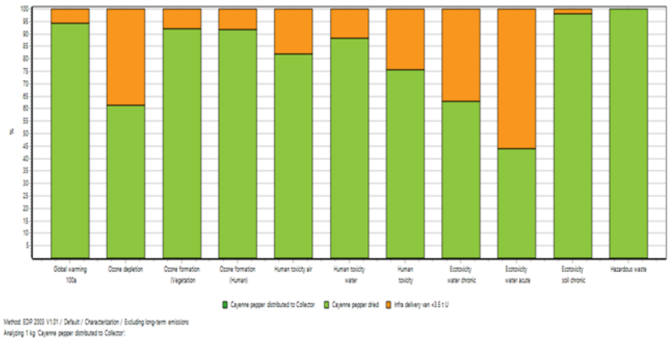

Figure 5. Environmental Impact on of Sending Cayenne Pepper to Collectors

4) Enviromental Impact on the Storage Process of Cayenne Pepper in Collectors

The storage of cayenne pepper at the Collector only has several additional processing activities involving refrigeration facilities and storage made of Styrofoam material. So the resulting impact is also quite significant. Figure 7 shows that more and more emissions are produced, indicated by the thicker red line connecting each process. The purple bar represents the waste generated. This waste is predominantly generated by the cooling facilities used to store cayenne pepper.

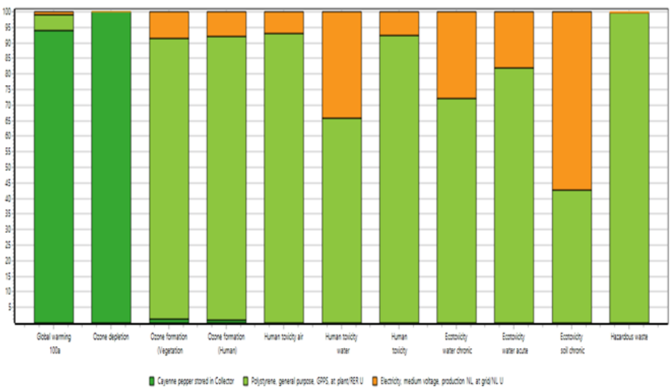

Figure 6. Environmental Impact on Storage Process of Cayenne Pepper in Collectors

Figure 6 shows the environmental impact of the cayenne pepper storage process at collectors. The dark green bars represent emissions generated through stored cayenne pepper. The bright green zinc is representative of the impact of emissions resulting from the use of Styrofoam boxes. It is known that Styrofoam boxes contain elements that have a terrible effect on the environment. In comparison, the yellow bar is the result of emissions resulting from the use of electricity in refrigeration facilities.

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5) Enviromental Impact on the Transportation Process to the Retailer

Delivery of cayenne pepper to Retailers has a few So the additional process activities involving transporting and storing Styrofoam materials. resulting impact is also quite significant. Figure 7 shows the environmental impact of sending cayenne pepper to retailers. The green bar shows the environmental impact of the previous process. The environmental impact of the previous process, namely the storage process at the Collector compared to the delivery process to the Collector, does not have too big a difference. It is because the storage usage in the previous and shipping processes are the same. So the emissions produced are almost the same. The resulting environmental impact is minimal in the delivery process to Retailers because the delivery distance is close. The location between collectors and retailers is close and is in the same city. The impact shown is the total emission for a year. The delivery process uses a lory car.

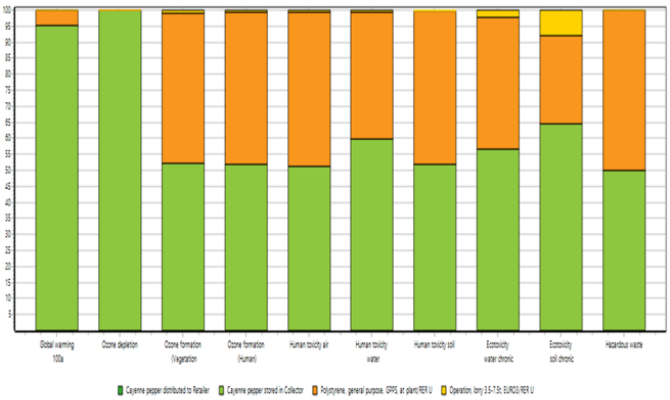

Figure 7. Environmental Impact on Transportation Process to the Retailer

6) Enviromental Impact on Storage and Sales Processes in Retailers

Storage at the retailer level adds several activities, mainly refrigeration and packaging using Styrofoam and polyethylene plastic to maintain product quality. These activities significantly increase environmental impacts, as shown by the thicker red lines in Figure 8. The purple bar represents waste generation, which mainly comes from refrigeration facilities and packaging residues.

The dark green bar shows emissions from storage and transportation from collectors to retailers, while the yellow bar represents emissions from Styrofoam and polyethylene packaging materials. These materials contribute substantially to environmental pollution because they are difficult to decompose and generate high emissions during production and disposal. The blue bar indicates emissions from electricity consumption used in refrigeration facilities.

Overall, refrigerated storage and packaging generate much higher emissions than previous supply chain processes, making retailer storage one of the most environmentally intensive stages in the cayenne pepper supply chain.

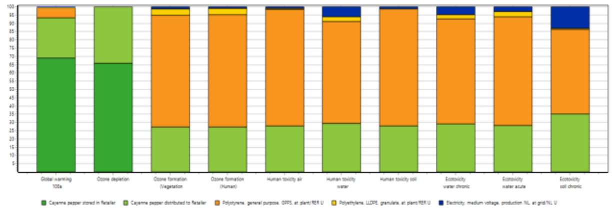

Figure 8. Environmental Impact of Cayenne Pepper Storage and Sales Process at Retailers using Categorization

D. Interpretation of results and Improvement Plans

Based on the results of environmental impact measurements obtained from the entire process along the supply chain, several alternative strategies have been found to address the high amounts of emissions produced. Table 6 shows the alternative strategies used in priority measurement in AHP. These strategies result from stakeholder interviews, exposure to the problems they face, and previous literature studies.

TABLE 6. The alternative strategies

Stages	Issue Solved	Alternative strategies
Cultivation	Emisi GRK	Organic fertilizer and zero waste technology
	Soil waste	
	Water waste	
	Soil waste	Farming planning
	Emisi GRK	
	land used	
	Soil waste	Biogas Technology Training
	Emisi GRK	
Post Harvesting	Emisi GRK	Natural drying
	Ecotoxicity soil	Use of environmentally friendly drying machines
Transportation	carbondioxide	Joint delivery
	carbondioxide	use of environmentally friendly vehicles
Storage	Emisi GRK	drop and pick up
	Ecotoxicity soil	environmentally friendly chiller
	ozone	Just in Time
Transportation	carbondioxide	Joint delivery
	Emisi GRK	use of environmentally friendly vehicles
	Ecotoxicity soil	Vegetable basket
	ozone	
Storage	carbondioxide	JIT
	Emisi GRK	environmentally friendly chiller
	Ecotoxicity soil	
Display	ozone	environmentally friendly packaging
	Human toxicity	display without chiller

In measuring alternative strategy for cultivation, three criteria are used: willingness to invest, environmental impact, and ease of implementation. Five stakeholders are representatives of farmer groups in Gowa Regency. Based on the results of measurements carried out with these three criteria, using organic fertilizers and pesticides is a priority choice compared to the other two strategies. This was chosen because of the low price and ease of implementation compared to other strategies. The other two strategies require quite a long adaptation time for Farmers, especially for Farmers who are aged.

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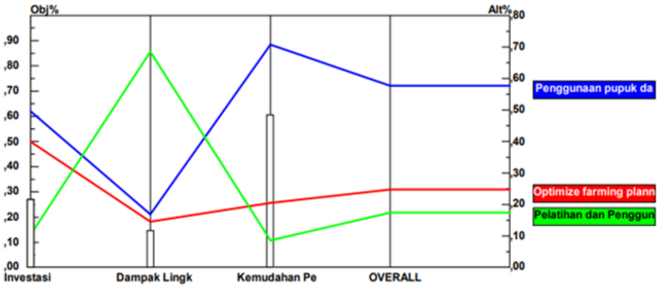

Figure 9. Performance Sensitivity for Alternative Cultivation Process Strategies

The measurement of alternative strategies for the cayenne drying process used the same three criteria as the previous process: investment willingness, environmental impact, and ease of implementation. Two alternative strategies were offered: natural drying, drying in the sun, and using an environmentally friendly fan. Based on the results of the three criteria, the two strategies had a slight difference as shown in figure 10. The highest score was obtained by drying using an environmentally friendly dryer. Although more expensive, the results are more optimal than drying in the sun. Natural drying carries the risk of drastically losing moisture in the cayenne peppers, thus decreasing their quality. In addition, monitoring and implementation using a fan is preferred because it is easier to implement.

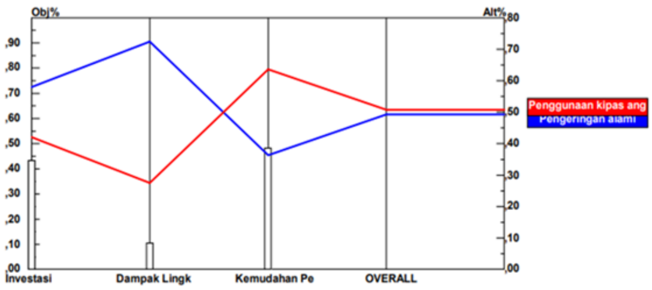

Figure 10. Performance Sensitivity for Alternative Drying Process Strategies

This alternative strategy assessment for process of sending cayenne peppers to Collectors used the same three criteria as the previous process: Investment Willingness, Environmental Impact, and Ease of Implementation. Two alternative strategies were offered: joint delivery and environmentally friendly vehicles, which are now widely used by the community and industry as shown in Figure 11. Based on the results of the three criteria, the two strategies had a significant difference in performance. The joint delivery program scored the highest compared to the environmentally friendly vehicles. The joint delivery program not only reduces environmental impact but also reduces shipping costs by optimizing vehicle capacity. Cayenne peppers are shipped together with other vegetables, thus reducing the frequency of deliveries for the total agricultural product. However, using environmentally friendly vehicles is still unfamiliar to farmers, and the costs are also quite high.

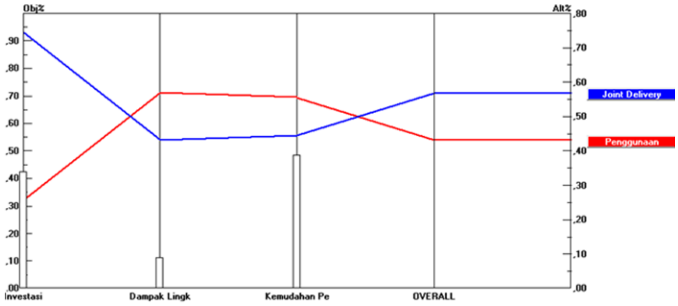

Figure 11. Performance Sensitivity for Alternative Strategies for the Process of Sending Cayenne Peppers to Collectors

The measurement of the process of storing cayenne pepper at the collector alternative strategy uses the same three criteria as in the previous process: Willingness to invest, Environmental Impact, and Ease of Implementation. Two stakeholders, Mr. John Frans and Mr. Alvin, representing collectors, were selected. Three alternative strategies were offered: Just in Time, a drop and delivery program, and the use of environmentally friendly chillers, which are now widely used in the community and industry. Based on the results of the measurements conducted using these three criteria, the two JIT strategies and the drop and delivery program have slight differences as shown in Figure 12. The drop and delivery program obtained the highest score compared to the other two strategies. The drop and delivery program not only reduces environmental impact but also reduces storage costs by optimizing communication with retailers. Furthermore, sales and marketing must be carried out optimally. Cayenne peppers are shipped simultaneously when they arrive at the collector's warehouse, thus shortening the storage period and reducing storage costs. These considerations are a primary focus for collectors. The JIT strategy is also quite popular, but its implementation is still difficult due to fluctuations in demand. Meanwhile, if using environmentally friendly chillers, collectors are not interested in this system because of the relatively high costs.

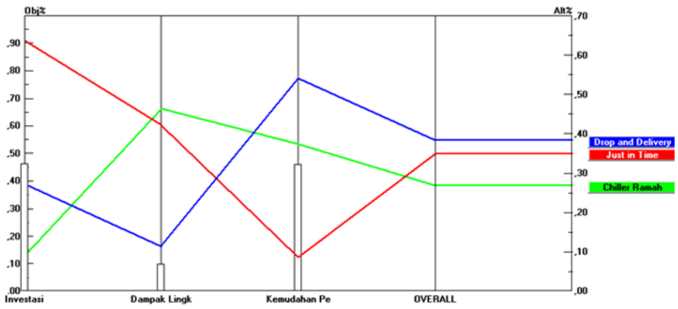

Figure 12. Performance Sensitivity for Alternative Strategies for Cayenne peppers Storage Processes at Collectors

The alternative strategy assessment used the same three criteria as the previous process: Investment Willingness, Environmental Impact, and Ease of Implementation. Two stakeholders represented the collectors. Two alternative strategies were proposed: delivery using food-grade vegetable boxes and the use of environmentally friendly vehicles, which are increasingly being adopted in communities and industries.

International Journal of Scientific Engineering and Science
Volume 10, Issue 5, pp. 74-83, 2026. ISSN (Online): 2456-7361

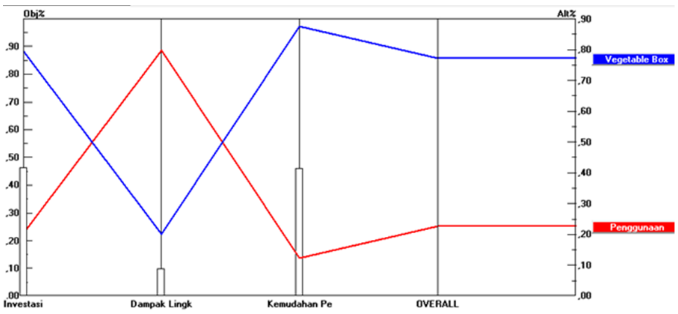

Figure 13. Performance Sensitivity for Alternative Strategies for Cayenne Pepper Delivery Process to Retailers

Based on the evaluation results using the three criteria, the two strategies showed significant differences. The use of vegetable boxes received the highest score compared to environmentally friendly vehicles as shown in Figure 13. This strategy can reduce environmental impacts while requiring lower investment costs. In addition, cayenne peppers are transported together with other vegetables, thereby reducing the overall frequency of agricultural product deliveries. However, the use of environmentally friendly vehicles is still relatively unfamiliar to collectors.

The alternative strategy assessment for the process of storing and selling cayenne peppers at retailers used the same three criteria as the previous process: Investment Willingness, Environmental Impact, and Ease of Implementation. Three stakeholders represented Supermarkets, all of whom were supervisors in the fresh product department. Two alternative strategies were proposed: the use of eco-friendly packaging and the elimination of chillers as shown in Figure 14, considering the short product display period of only three days.

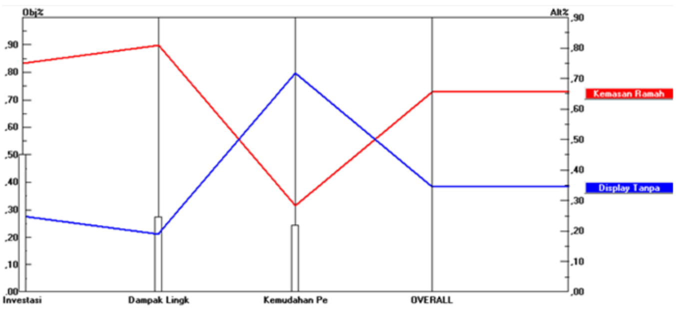

Figure 14. Performance Sensitivity for Alternative Strategies for Storage and Sales of Cayenne Peppers at Retailers (

The highest score was achieved by the use of eco-friendly packaging, which addresses one of the major environmental challenges in retail operations. Retailers preferred this strategy because they prioritize product quality and freshness, making the option of not using chillers the less favorable alternative.

The results indicate that environmental improvement strategies cannot rely on a single intervention, but instead require an integrated approach involving cultivation, post-harvest handling, transportation, storage, and retail activities. Each stage contributes differently to environmental impacts; therefore, the selected strategies must consider not only emission reduction potential but also economic feasibility and ease of implementation for stakeholders. In general, stakeholders tended to prioritize strategies that provide direct operational benefits while requiring relatively low investment costs. This finding shows that economic considerations remain an important factor in encouraging the adoption of sustainable practices within agricultural supply chains.

In the cultivation stage, the preference for organic fertilizer and zero-waste technology demonstrates that farmers are more likely to adopt strategies that are practical, affordable, and aligned with existing farming practices. Besides reducing greenhouse gas emissions, the use of organic fertilizers can improve soil quality and reduce chemical residues that may negatively affect the environment. However, the lower preference for farming planning and biogas technology indicates that technological adaptation and knowledge limitations remain major challenges, particularly among older farmers. This finding highlights the importance of extension programs and continuous technical assistance to improve farmers' readiness to adopt more advanced sustainable technologies.

For the post-harvest stage, environmentally friendly drying machines achieved the highest priority despite requiring higher investment costs. Stakeholders considered product quality and process efficiency to be more important than relying solely on natural drying methods. This result suggests that sustainability strategies are more acceptable when they simultaneously improve product quality and reduce post-harvest losses. In agricultural supply chains, quality deterioration directly affects product value; therefore, technologies that maintain product quality are perceived as beneficial not only environmentally but also economically.

TABLE 7. The best strategy

Stages	Issue Solved	Selected Strategy
Cultivation	Emisi GRK	Organic fertilizer and zero-waste technology
	Soil waste	
	Water waste	
Post Harvesting	Emisi GRK	Use of environmentally friendly drying machines
	Ecotoxicity soil	
Transportation	carbondioxide	Joint delivery
	carbondioxide	
Storage	Emisi GRK	drop and pick up
	Ecotoxicity soil	
	ozone	
Transportation	carbondioxide	Vegetable basket
	Emisi GRK	
	Ecotoxicity soil	
	ozone	
Storage	carbondioxide	JIT
	Emisi GRK	
	Ecotoxicity soil	
Display	ozone	Environmentally friendly packaging
	Human toxicity	

In transportation activities, joint delivery emerged as the preferred strategy because it optimizes vehicle capacity and reduces transportation frequency. This strategy demonstrates that collaborative logistics can significantly reduce carbon emissions while lowering operational costs. Similar conditions were also found in transportation from collectors to retailers, where the use of vegetable baskets was preferred due to lower costs and easier implementation. These findings indicate that stakeholders are more willing to adopt environmentally friendly strategies when they can also improve logistical efficiency and reduce distribution expenses.

At the storage stage, the drop-and-delivery strategy became the main priority because it shortens storage time and minimizes unnecessary inventory accumulation. This strategy reflects the importance of coordination and information sharing among supply chain actors to reduce waste and storage-related emissions. Meanwhile, the relatively low preference for environmentally friendly chillers indicates that investment cost remains a significant barrier, even though the technology offers environmental benefits. This condition suggests that financial support or incentives may be needed to encourage wider adoption of green technologies in storage operations.

At the retail stage, eco-friendly packaging was selected as the most preferred strategy because it addresses environmental concerns without compromising product freshness and quality. Retailers considered product appearance and consumer satisfaction as important factors influencing purchasing decisions. Therefore, eliminating chillers was viewed as less favorable despite its potential to reduce energy consumption. This finding illustrates the balance that retailers must maintain between environmental sustainability and product quality standards in modern retail systems.

Overall, the study demonstrates that strategies with lower implementation complexity, lower investment requirements, and direct operational benefits tend to receive higher acceptance among stakeholders. The results also show that improving environmental sustainability in the cayenne pepper supply chain requires collaboration among farmers, collectors, distributors, and retailers. By integrating environmentally friendly practices across all supply chain stages, greenhouse gas emissions and other environmental impacts can be reduced while maintaining product quality and operational efficiency.

IV. Conclusion

Based on emission measurements, it was found that the process that has the most impact on the environment is the process upstream of the supply chain, namely the cayenne pepper cultivation process. While the process that has the least environmental impact is the harvesting process because it is done manually.

The environmental impact assessment and AHP analysis show that improving sustainability in the cayenne pepper supply chain requires integrated strategies across all stages, from cultivation to retail. Stakeholders tended to prioritize strategies that are environmentally beneficial, cost-effective, and easy to implement. The selected strategies include organic fertilizer and zero-waste technology, environmentally friendly drying machines, joint delivery systems, vegetable baskets, drop-and-delivery and JIT systems, and eco-friendly packaging. These strategies help reduce emissions, improve operational efficiency, minimize waste, and maintain product quality. However, high investment costs and limited technological familiarity remain challenges in implementing advanced green technologies.

For future research, it is recommended to expand the scope of the study by involving more supply chain actors and different research locations to obtain more representative results. Future studies may also conduct quantitative analyses of the implementation costs and economic benefits of each environmentally friendly strategy to better evaluate their feasibility and effectiveness. In addition, further research can explore the application of more innovative green technologies, such as renewable energy, electric vehicles, and digital supply chain monitoring systems, to identify greater emission reduction potential. Longitudinal studies are also recommended to evaluate the long-term sustainability of these strategies and their impacts on product quality, operational efficiency, and the reduction of food loss and waste in the cayenne pepper supply chain.

Acknowledgment

The author would like thank to LP2S, Universitas Muslim Indonesia through the financing of Penelitian Unggul Program, 2022.

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