Sustainability Efforts For Green Packaging As An Eco-Friendly Alternative Based On A Life Cycle Assessment Approach In The Food Product Supply Chain

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Abstract.
The increasing use of plastic packaging in food supply chains poses environmental concerns due to resource consumption and the potential generation of plastic waste. This study aims to evaluate the environmental impacts of plastic packaging using Life Cycle Assessment (LCA), identify critical impact hotspots, and develop a green packaging alternative based on starch bioplastic. The LCA was conducted using a cradle-to-gate system boundary with SimaPro and the Eco-costs 2024 V1 method across three packaging scenarios: polyethylene (PE), multilayer packaging, and polylactide (PLA). The bioplastic was developed using three formulations: F1 (glycerol), F2 (glycerol and CMC), and F3 (glycerol, CMC, and ginger extract), and was evaluated based on thickness, tensile strength, and elongation at break. The LCA results showed single score values of €14.6 for PE, €28.2 for PLA, and €65.9 for multilayer packaging, with carbon footprint identified as one of the major contributors to the environmental impact of the multilayer scenario. The bioplastic testing results showed thicknesses of 0.40, 0.50, and 0.40 mm for F1, F2, and F3, respectively, with tensile strength values of 4.28, 5.16, and 4.73 MPa and elongation at break values of 48.35%, 68.42%, and 57.26%, respectively. Among the three formulations, F2 demonstrated the best mechanical performance. The integration of LCA and mechanical testing indicates that the development of green packaging should consider a balance between material performance and environmental impacts. This approach supports Sustainable Development Goals (SDGs) 9 and 12 and provides a basis for developing more sustainable packaging systems toward a circular economy.
Keywords: *Green Packaging; Life Cycle Assessment; Bioplastic; Food Packaging and Circular Economy.*

I. INTRODUCTION

The issue of environmental pollution caused by plastic waste has become a pressing global concern that requires immediate resolution. Based on data from the National Waste Management Information System (Sistem Informasi Pengelolaan Sampah Nasional/SIPSN), the total waste generation in Indonesia in 2024 reached 33,437 tonnes, of which 19.59% consisted of plastic waste. Conventional plastics based on chemical polymers are notoriously difficult to decompose within a short period, thereby exerting a significant negative impact on ecosystems. The use of packaging for every food product remains a dominant practice due to its affordable price, wide availability, and ease of application. However, conventional plastic packaging based on thermoplastics such as PET, PP, PE, and PCl possesses characteristics that render it difficult to decompose, requiring hundreds of years for microbes to recycle such plastic waste, consequently causing pollution [1]. A considerable quantity of plastic is disposed of as waste or incinerated, which contaminates the air and soil, owing to the high costs associated with the collection, sorting, and recycling of plastic.

Indonesia, as an agrarian country rich in agricultural biodiversity, produces a wide variety of products including vegetables, fruits, and tubers such as cassava and similar crops [2]. Food products such as fruits and horticultural products possess distinctive characteristics, namely that they continue to undergo changes following the harvesting process, thereby affecting the quality attributes of these products. During the process of these characteristic changes, fruits and horticultural products undergo respiration, which ultimately leads to the degradation of nutrient content and may also cause damage to the products [3].

Concerns regarding such pollution have given rise to research seeking sustainable and environmentally friendly packaging alternatives. The concept of sustainable packaging has become a strategic approach to mitigating the environmental impact and carbon emissions generated by the packaging industry [4]. Green packaging is a sustainable packaging concept made from materials that are not harmful to the environment and can be recycled. Green packaging is typically made from starch and Poly Lactic Acid (PLA) [5]. Starch is obtained from plant-based materials with a high carbohydrate content, such as cassava, sweet potato, maize, and cereals [6]. Green packaging that is recyclable and reusable is expected to reduce the use of plastic in daily activities [5].

In the present study, the development of an alternative food packaging or coating made from renewable and environmentally friendly materials, namely edible film, will be conducted [7]. The material to be utilised contains starch, which is a natural polymer extracted from plants that can be used to produce biodegradable materials owing to its readily degradable nature, environmental friendliness, and easy availability [8]. Films are formed from carbohydrates, which may include starch, gums (alginate, pectin, and gum arabic), and chemically modified starch. The formation of protein-based films may utilise casein, soy protein, wheat gluten, and maize protein [9]. Hydrocolloid-based membranes are highly suitable as barriers to the transfer of oxygen, carbon dioxide, and lipids. This type of film possesses excellent mechanical properties, rendering it suitable for enhancing membrane structure to prevent disintegration [10]. Edible film is expected to provide protection for food products, for instance by maintaining moisture, reducing chemical and physical packaging damage, and extending the shelf life of food.

To achieve the SDGs, nations must be able to commit and cooperate comprehensively in addressing the environmental impact of plastic packaging [11]. Sustainable environmentally friendly packaging (green packaging) must be pursued in alignment with the realisation of the Sustainable Development Goals (SDGs), particularly in the aspect of responsible consumption and production [12]. The adoption of green packaging alternatives will be subjected to effectiveness testing regarding technical and economic feasibility, with the expectation of providing a tangible contribution to addressing the global challenge of plastic waste whilst simultaneously facilitating the transformation towards a sustainable circular economy.

II. METHODS

a. Definition of Goal and Scope Definition

The scope of this study is cradle to gate, from the raw material extraction process to the manufacturing process of molding packaging sheets. The distribution phase, consumption stage, and final disposal are excluded from the calculation (cut-off). This scenario compares current conditions regarding the use of plastic as food packaging, particularly among MSMEs.

Ø Scenario 1: PET/PE thermoplastic packaging used by food MSMEs. This packaging is widely used for food products due to its affordability, widespread availability, and transparency. However, this packaging does not degrade easily, making it the most dominant source of plastic waste in Indonesia.

Ø Scenario 2: Multilayer packaging. This packaging combines PET, aluminum foil, and high-density polyethylene (HDPE), providing better product protection and extending the shelf life of food products.

Ø Scenario 3: Biodegradable/bioplastic packaging. This packaging can extend a product’s shelf life by 6–12 months. However, its drawbacks include the inability to be recycled and its contribution to carbon emissions.

Furthermore, to ensure a fair and balanced comparison of these three packaging scenarios, a Functional Unit was established. The standardized basis for comparison is not the weight of the plastic itself, but rather the “packaging capacity”—that is, the packaging’s ability to contain and protect 100 grams of MSME potato chips. Since the material characteristics of each scenario differ, the function of “containing 100 grams of potato chips” will automatically result in varying weights of empty packaging. The weight of conventional plastic (PE) packaging to hold 100 grams of product is set at 5.0 grams. Meanwhile, in Scenario 2—which involves composite (multilayer) packaging—the weight is determined based on the dry goods packaging industry’s standard Product to Package ratio of 12.0%. Since it wraps 100 grams of product, its mass is precisely set at 12.0 grams per unit. Meanwhile, in Scenario 3, the use of bioplastic (PLA) requires a slightly greater mass—5.8 grams compared to 5 grams in Scenario 1— This is due to the difference in density between bioplastic and plant-based polymer materials; bioplastics have a higher density and therefore require a greater mass of material to achieve an equivalent level of mechanical strength in the product packaging process.

Once the functional equivalence of the packaging per unit was established, this calculation scale was then multiplied to align with actual operational conditions in the field. Based on an operational analysis of the SME, the Reference Flow was set at 3,920 packages per month; this reference flow calculation is based on an average daily production rate of 140 packages and 28 days of effective operational work. This total figure serves as the basis for the multiplier used to calculate the accumulated mass of material inputs (Life Cycle Inventory) and to assess the extent of the environmental impact generated by the SME over a one-month period.

b. Life Cycle Inventory (LCI)

In the Life Cycle Inventory (LCI) phase, this stage involves inventorying all material input requirements based on the established operational reference flow for the SME, namely 3,920 packaging units per month. In Scenario 1—which involves conventional PE plastic packaging—the empirical mass estimate is set at 5.0 grams per package. Based on the accumulation of this reference flow, the total mass amounts to 19,600 grams. These results are then entered into the SimaPro software using the Packaging film, low-density polyethylene {GLO} database.

Scenario 2 focuses on composite (multilayer) packaging, with the mass determined according to the industry's standard Product-to-Package ratio of 12.0 grams per unit. With the same total monthly production volume, the cumulative material mass reaches 47,040 grams. The structure of this multilayer packaging is assumed to consist of a combination of polyethylene terephthalate (PET) as the outer layer, aluminum foil as the primary barrier against gas and light, and polyethylene (PE) polymer as the sealant layer. Given the input parameters for the mass-based Life Cycle Assessment (LCA) software, the percentage distribution of materials is calculated using a basis weight approach, which involves converting the standard manufacturing layer thickness (microns) and multiplying it by the density of each material. Based on this mathematical approach, the total composite mass of 47,040 grams is proportionally distributed as follows: the PE layer accounts for 55% (25,872 grams), the PET layer for 25% (11,760 grams), and the aluminum foil for 20% (9,408 grams). In the life-cycle inventory modeling, the process parameter Extrusion, plastic film {GLO} was added with a load of 37,632 grams, representing the accumulated mass of the polymer layers—namely, PE and PET (25,872 + 11,760 grams). This value was used because the Extrusion, plastic film process in the database represents the formation of plastic film through an extrusion process that occurs only with polymer materials, whereas the aluminum foil layer does not undergo plastic extrusion and is therefore not included in the mass of that process.

Meanwhile, Scenario 3 evaluates the use of eco-friendly packaging made from bioplastic (Polylactide/PLA). In this scenario, the density of the plant-based polymer was adjusted to yield a packaging mass of 5.8 grams per unit. The total material mass required for this scenario was calculated to be 22,736 grams; this result was obtained by multiplying the total number of units used in the reference flow by the packaging mass, followed by data input using the polylactide, granulate {GLO} database. Scenario 3, which involves bioplastics, also includes the extrusion, plastic film {GLO} manufacturing process with an equivalent load of 22,736 grams to simulate the conversion of raw plastic pellets (granules) into packaging sheets.

c. Life Cycle Impact Assessment (LCIA)

The purpose of this life cycle assessment stage is to evaluate the extent of the environmental impact generated by the object under study. In this study, the life cycle impact assessment was conducted using SimaPro V 9.5.0.2 software by applying the Eco-costs 2024 V1 evaluation method.

d. Substitution of plastic packaging with edible film

Preparing the materials involves starch, plasticizer, distilled water, and acetic acid. The starch is then dissolved in distilled water at a concentration of 3%–5% and stirred until homogeneous using a magnetic hot-plate stirrer; next, a plasticizer is added at a concentration of 20–40% to enhance the film's flexibility. Next is the gelatinization process, in which the starch solution is heated to prevent starch granules from forming and to create a homogeneous gel. The degassing process—removing air bubbles—is performed by letting the starch solution stand or by brief sonication to eliminate air bubbles and prevent the film from becoming brittle. This is followed by the film casting process, where the film thickness is controlled by the volume of solution poured, and the surface is leveled to achieve uniform thickness. The drying process is carried out at room temperature, followed by characterization of the edible film to assess its suitability as green packaging.

e. Testing the effectiveness of the packaging Laboratory testing is conducted to determine the mechanical performance of the edible film as an environmentally friendly alternative for food packaging (green packaging). Tests for tensile strength and elongation at break are performed. The tensile strength test measures the film's resistance to tensile force before breaking, while the elongation at break test measures the film's flexibility or ability to stretch before failing [13].

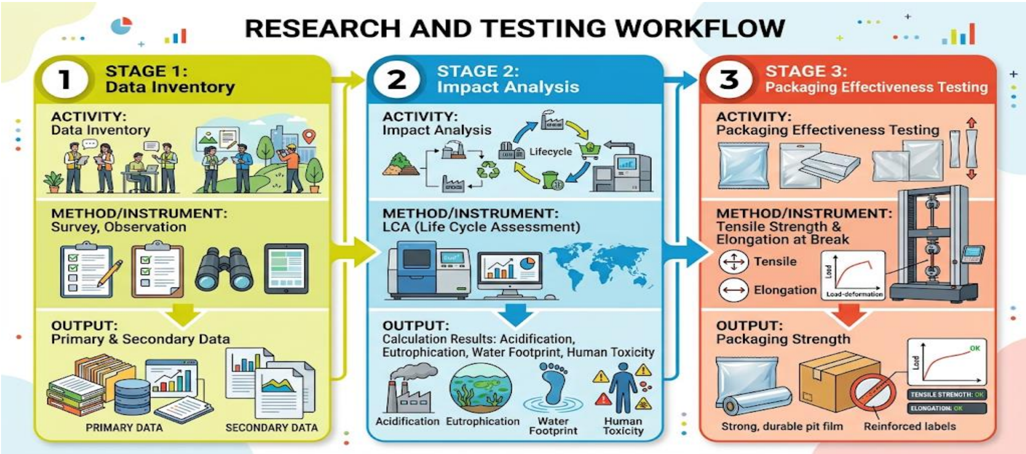


Fig. 1. Research Phases, Methods, and Achievement Indicators

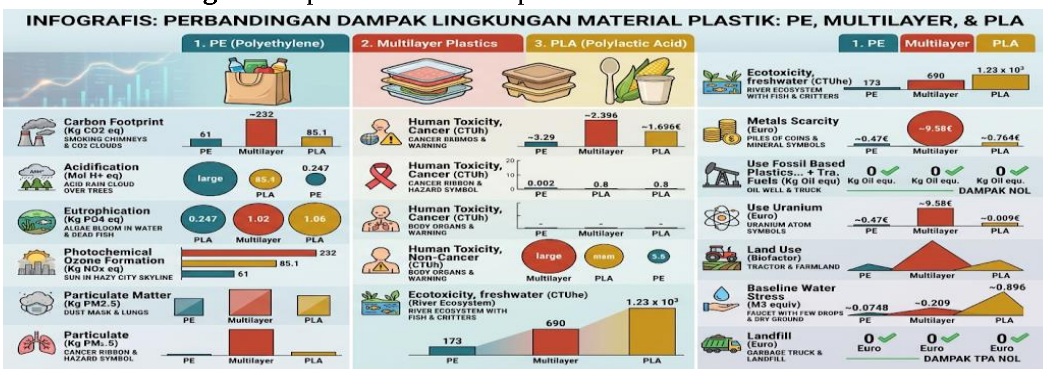
III. RESULT AND DISCUSSION

a. Life Cycle Impact Assessment (LCIA)

The LCIA stages in this study are divided into four: characterization, normalization, weighting, and single score.

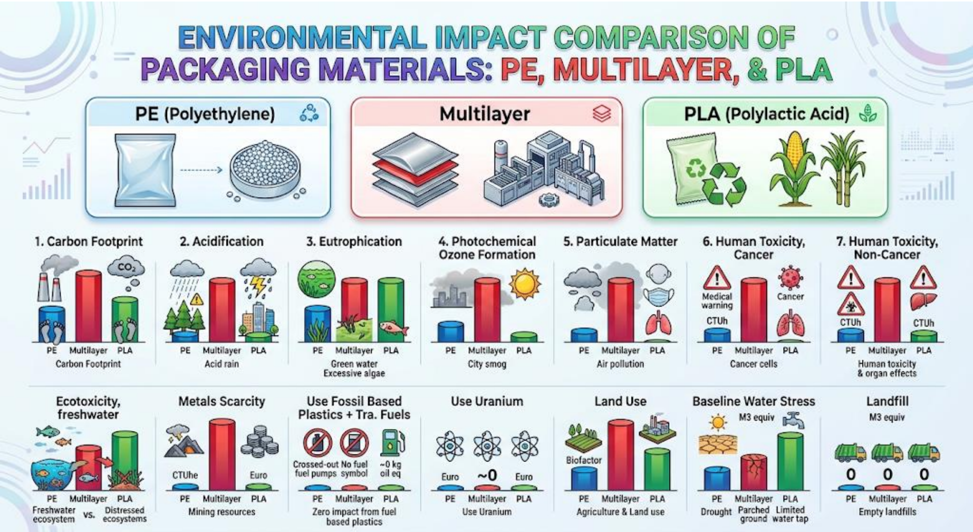
Characterization: Characterization is the measurement stage that identifies the magnitude of emissions in a substance and analyzes their impact on each environmental impact category. During characterization, the emission values from each packaging scenario are weighted to reflect their contribution to each midpoint category. Based on calculations from the SimaPro software, there are 15 environmental impact categories evaluated in the Eco-costs method. Each category results in a different level of pollution, depending on the type of packaging material used. The characterization values for the three packaging scenarios (PE, Multilayer, and PLA) are shown in Figure.

Fig. 2. Output from the Simapro Characterization Software



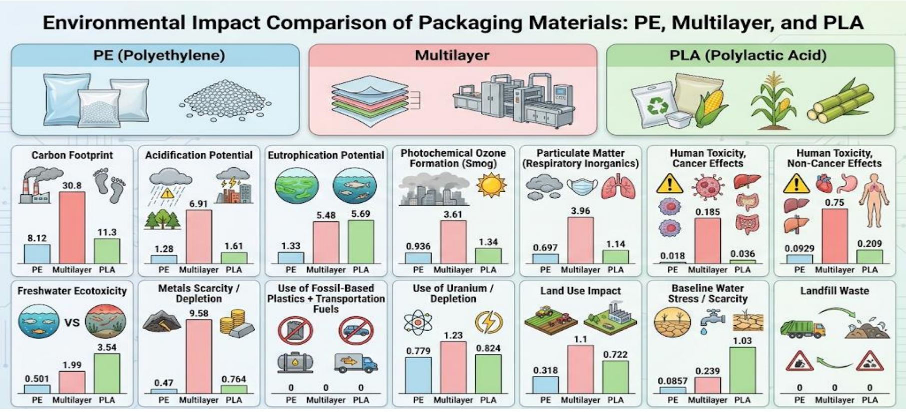
Normalization The next stage is the normalization stage, in which normalization factors are used to standardize the values of each impact category that was previously characterized. The primary objective of normalization is to convert all impact categories so that they have a uniform unit of measurement. Normalization values are obtained by multiplying the characterization values by the method's built-in normalization factor, thereby allowing all environmental impact indicators to be compared precisely on the same unit basis. The normalization factor values for each impact category from the three packaging models are presented in Figure 3.

Table 3. Output of the Simapro Normalization Software (dimensionless)



Weighting Weighting is the process of assigning subjective or objective weights to the resulting environmental impact categories. The results of the normalization stage are multiplied by the characterization factor and then accumulated, resulting in a total environmental impact value expressed in a standardized currency (euros). The weighted values for each impact category from the SimaPro model are shown in Figure 4.

Table 4. Output of the Simapro Weighting Software (Euros)



Single Score The single score is the final stage in the LCIA, which involves classifying the cumulative values of all impact categories based on the material or the manufacturing process. Based on this single score, it is possible to identify which scenarios contribute most significantly to environmental impacts. The single score is derived from the weighted results of each material process. The use of a currency unit (the Euro) in the single score results is a key characteristic of the Eco-costs evaluation method. Unlike the characterization stage, which still uses equivalent physical units (such as kg CO_2 eq), the Eco-costs method converts all environmental impacts into monetary terms. These Euro values specifically represent marginal prevention costs—that is, the estimated real costs that must be incurred to prevent, mitigate, or restore environmental damage caused by the packaging's life cycle. Table 5 shows the output from the Simapro software for the single score values of the three scenarios in Euros..

Tabel 5. Output Software Simapro Single Score (Euro)

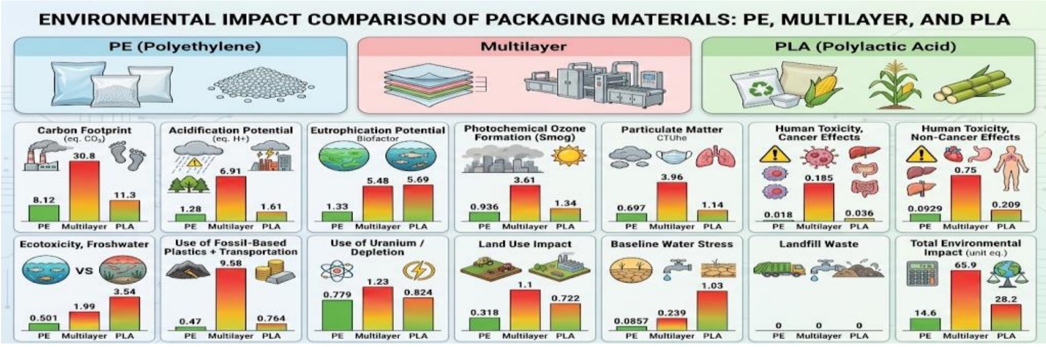


Fig 3. SimaPro Output

Based on the single score results (Table 5), it was found that the highest cumulative eco-costs were generated by Scenario 2 (Multilayer Packaging), with a total impact of 65.9 euros. Scenario 3 (Biodegradable PLA Packaging) produced the second-highest impact value of 28.2 euros, while Scenario 1 (Conventional PE Plastic Packaging) had the lowest impact footprint at 14.6 euros. The high environmental impact value in Scenario 2 is attributed to the extrusion process and the use of metal-based materials (aluminum foil), which require high energy intensity during raw material production

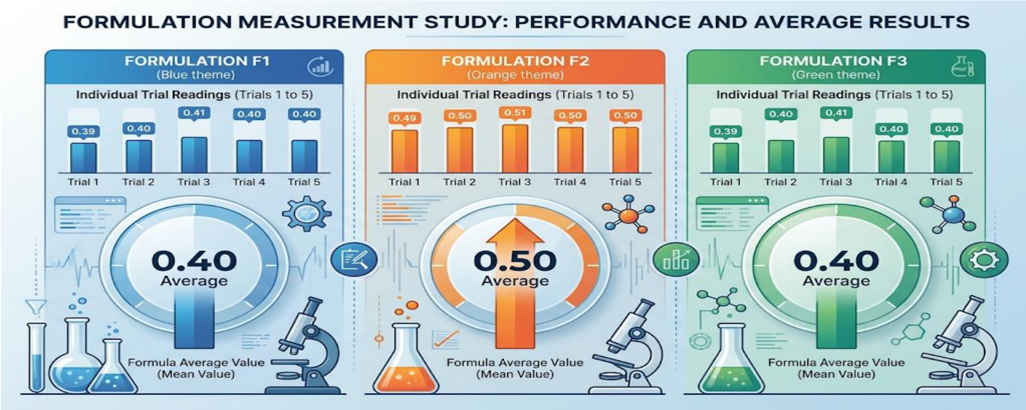
. The single score values for each environmental impact category indicate that the eco-costs of multilayer packaging are primarily driven by the carbon footprint. In this category, multilayer packaging incurs environmental costs of 30.8 euros, exceeding those of both PLA bioplastic packaging (11.3 euros) and PE plastic packaging (8.12 euros). Additionally, the use of metal materials in multilayer packaging leads to an increased environmental impact in the Metals Scarcity category, with prevention costs reaching 9.58 Euro—in contrast to PE, which incurs only 0.47 Euro in costs. This aligns with research showing that the extraction and coating processes for aluminum foil in composite packaging are major contributors to carbon emissions and the depletion of natural resource reserves.

On the other hand, Scenario 3 (Biodegradable PLA Packaging) also demonstrates environmental impacts, but its Carbon Footprint environmental cost is far lower than that of multilayer packaging. PLA has the highest environmental impact on the Eutrophication indicator (5.69 euros), Ecotoxicity, freshwater (3.54 euros), and Baseline Water Stress (1.03 euros). However, the high values for these indicators in the early stages of production are understandable. This is confirmed by research showing that when evaluated over the full life cycle (cradle to grave), the use of biodegradable materials has actually been shown to significantly reduce environmental impacts on the indicators of nutrient enrichment (eutrophication), acidification, and water footprint compared to conventional plastic and multilayer packaging.

Cradle-to-gate modeling in this study shows that while the total accumulated eco-costs of PLA (28.2 euros) are still higher than those of conventional PE plastic (14.6 euros)—due to the high energy requirements for extracting plant-based polymers—PLA is still projected to offer better sustainability prospects. Furthermore, other studies confirm that biodegradable packaging can offer highly significant environmental benefits (reducing impacts by 50–70%) when evaluated over the full life cycle, including the final disposal stage. Unlike conventional and multilayer plastics, which have the potential to become persistent microplastic waste, plant-based polymer materials—or bioplastics—will not accumulate to become a long-term ecological burden in landfills [14]. Various biodegradable materials such as PLA are highly suitable for the food industry because the costs associated with preventing human toxicity (both cancerous and non-cancerous) are minimal, as evidenced by PLA's low Human Toxicity rating. Bioplastic innovations based on plant starch degrade naturally very rapidly in composting environments. To address the environmental drawbacks of bioplastics in the agricultural sector, efforts to optimize green packaging can focus on developing renewable food packaging alternatives, specifically edible films made from locally sourced starch. During the development of these edible films, it is recommended that their physical properties—such as tensile strength and elongation at break—be tested in a laboratory to ensure their suitability as a replacement for plastic packaging in food products.

a. Substitusi kemasan platik menjadi edible film

Fig 6. Measurement Results



Description

F1 : Gliserol

F2 : Gliserol dan CMC

F3 : Gliserol, CMC, dan ekstrak jahe

Mechanical property testing was conducted using five specimens from each formulation. The selection of five specimens was based on the provisions of JIS Z 1707:2019, which requires at least five specimens for tensile force and tensile breaking elongation testing. The test results showed that F1, F2, and F3 had average thicknesses of 0.40 mm, 0.50 mm, and 0.40 mm, respectively. These differences in thickness indicate that the addition of CMC contributed to an increase in total solids and the formation of a thicker film matrix. Previous research on cassava starch-based films has shown that CMC can act as a reinforcing component in the starch matrix and influence the mechanical characteristics of the film [15].

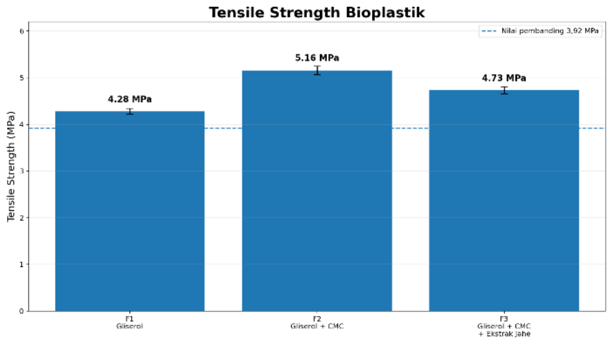


Fig 7. ***Tensile Strength***

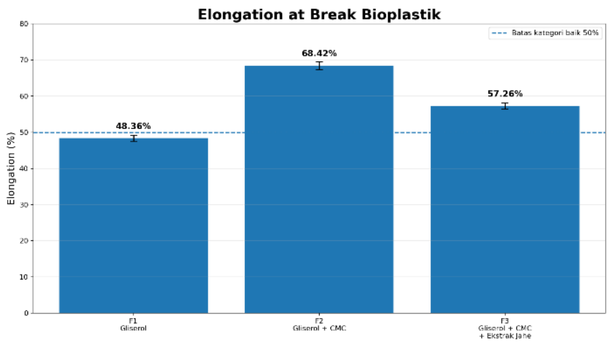
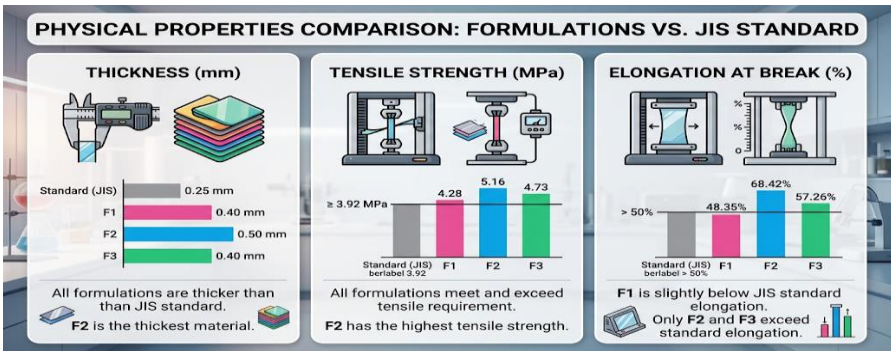


Fig. 8. Summary of Mechanical Testing

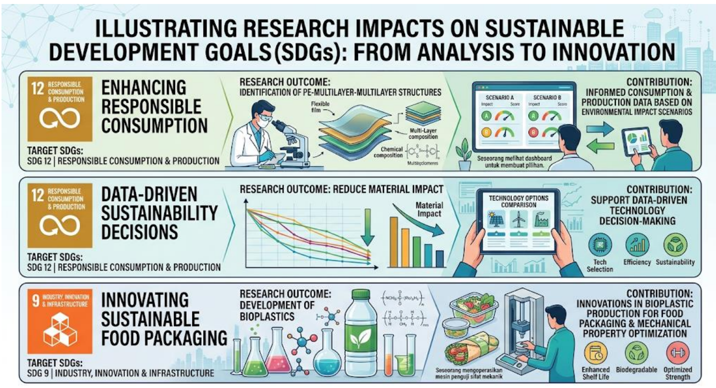


Description
F1 : Gliserol
F2 : Gliserol dan CMC
F3 : Gliserol, CMC, and ginger extract

The tensile strength values show that F1, F2, and F3 yielded values of 4.28, 5.16, and 4.73 MPa, respectively. F2 exhibited the highest tensile strength, at 5.16 MPa, representing an increase of approximately 20.56% compared to F1. This increase indicates that the presence of CMC can strengthen the starch matrix structure by enhancing cohesion and interactions among film components. These results are consistent with studies on cassava starch–CMC films, which reported that increasing the CMC concentration can improve film tensile strength [16]. Formulation F3 yielded a tensile strength of 4.73 MPa, which was lower than that of F2 but still higher than that of F1. The decrease in tensile strength following the addition of ginger extract can be attributed to changes in the interactions and homogeneity of the starch–CMC matrix due to the introduction of additional components from the extract. Thus, ginger extract has the potential to create a trade-off between enhancing the film's active function and its mechanical properties.

The elongation at break results showed values of 48.35% for F1, 68.42% for F2, and 57.26% for F3, respectively. Based on the criteria used in this study, F2 and F3 fall into the "good" category because they have elongation values exceeding 50%, while F1 is slightly below that threshold. F2 exhibited the best combination, as it possessed both the highest tensile strength and the highest elongation. This indicates that the addition of CMC to the formulation not only strengthened the structure but also preserved the film's deformability. However, previous studies have shown that increasing CMC does not always improve elongation and, at certain concentrations, can actually reduce it; thus, the mechanical response is highly dependent on the composition and processing conditions of the film [17]. Overall, F2 is the most promising formulation based on the balance between strength and flexibility. Meanwhile, F3 holds further potential as active biodegradable packaging because it combines a starch–CMC matrix with ginger extract. Future development should focus on optimizing film thickness, as the measured values of 0.40–0.50 mm are still greater than the reference value of 0.25 mm used in this study. Additionally, further testing is needed to evaluate barrier properties, biodegradability, stability, and antioxidant or antimicrobial activity before the film can be recommended for food packaging [18].

Fig. 9. SDG Contributions



This study also supports the concept of the circular economy through the application of life-cycle thinking, as well as the identification of opportunities to reduce dependence on the linear take-make-dispose packaging system. However, because the scope of the study is limited to the cradle-to-gate phase, this research has not directly evaluated the distribution, consumption, reuse, recycling, composting, or final disposal stages. Therefore, the study's contribution to the circular economy at this stage is more accurately described as support for the transition toward a circular economy, rather than as the full implementation of a circular economy. Thus, the integration of LCA and mechanical testing provides a scientific basis for developing packaging that is not only focused on replacing plastic but also on resource efficiency, functional performance, waste reduction, and life-cycle-based decision-making. This approach supports the achievement of SDG 12 through more responsible consumption and production while opening opportunities for the development of packaging systems that are more aligned with the principles of the circular economy

IV. CONCLUSION

Based on the research findings and discussion, the following conclusions were drawn:

1. A Life Cycle Assessment (LCA) analysis with a cradle-to-gate system boundary and the Eco-costs 2024 evaluation method concluded that multilayer packaging (Scenario 2) contributes the highest environmental impact, with total accumulated eco-costs of 65.9 euros. The high environmental impact of this multilayer packaging is attributed to the Carbon Footprint indicator, amounting to 30.8 Euro, and material depletion (Metals Scarcity), amounting to 9.58 Euro, due to the high energy consumption in the extraction and coating processes of aluminum foil. On the other hand, the innovative PLA bioplastic packaging (Scenario 3) resulted in the second-highest impact value of 28.2 euros, which largely stemmed from the eutrophication and water stress indicators due to the agricultural supply chain for its plant-based raw materials. Conventional PE plastic packaging (Scenario 1) recorded the lowest value within this system boundary, at 14.6 euros. As a follow-up measure to address the weaknesses of bioplastics in the agricultural sector, the next step is to develop a renewable alternative for green packaging, namely starch-based edible film.
2. The development of starch-based bioplastics through three formulations showed that variations in material composition affect the material's mechanical characteristics. F1, F2, and F3 have thicknesses of 0.40, 0.50, and 0.40 mm, respectively. Their tensile strength values are 4.28, 5.16, and 4.73 MPa, respectively, while their elongation at break values are 48.35%, 68.42%, and 57.26%, respectively. Formulation F2 (glycerol and CMC) provided the best mechanical performance with a tensile strength of 5.16 MPa and elongation at break of 68.42%, making it the most promising formulation for further development as a green packaging material.
3. This study supports SDG 9 (Industry, Innovation, and Infrastructure) through innovations in the development of starch-based bioplastic materials, as well as SDG 12 (Responsible Consumption and Production) through the evaluation of resource efficiency and environmental impacts throughout the production cycle. The life-cycle thinking approach used also provides a foundation for supporting the transition toward a circular economy, particularly through the development of alternative materials, resource efficiency, and reduced reliance on conventional plastic packaging. However, since the study used a cradle-to-gate system boundary, aspects of distribution, use, and end-of-life have not been evaluated; therefore, further research with a broader system boundary is needed to assess sustainability and circularity potential more comprehensively. Overall, the study results indicate that a full life-cycle assessment shows that bioplastic packaging is capable of offsetting its initial emissions burden through a very rapid natural degradation process and does not accumulate as persistent microplastic waste in landfills. The development of sustainable packaging cannot be determined solely based on its biodegradability or mechanical performance; rather, it must simultaneously consider both material performance and environmental impact

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