Green culinary innovation in traditional banana processing: A zero waste approach to sustainable food

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ABSTRACT

In 2020, national banana production in Indonesia reached 8,182,756 tons, a 12.39% increase compared to 2019. Banana processing into *sale pisang* is one solution to address the overproduction. This study aims to utilize local banana production, reduce plastic waste, implement the zero-waste concept, and produce sustainable products. The method involves peeling bananas, drying the flesh using a solar tunnel dryer (STD), packaging with eco-friendly materials, and calculating product cost through the Cost of Goods Sold (COGS) approach. The banana peels are reprocessed by adding water and molasses to produce eco-enzymes, which function as liquid fertilizer. The outcomes are two sustainable products: *sale pisang* and eco-enzymes. Sale pisang has strong potential as a business opportunity to support the growth of micro, small, and medium enterprises (MSMEs) in Indonesia. The use of the STD enhances hygiene and food safety compared to traditional open sun drying by providing controlled temperature and airflow. To support sustainability, applying green technology and zero-waste principles is essential, as it maximizes the utilization of all banana components. In conclusion, this research demonstrates how local banana production can be converted into value-added, eco-friendly products that support sustainable development goals.

1. INTRODUCTION

Bananas are nutrient-rich food sources, containing carbohydrates, fiber, vitamins, and minerals such as potassium, magnesium, and folate. Bananas are commercial crops that grow in tropical and subtropical climates. Bananas as a source of carbohydrates not only play a role in food security but can also provide jobs (Thakur et al., 2024). Banana fleshes are one of the banana-based material processing products that can be applied with green technology, sustainability, and have the potential as a business idea. Banana fleshes can be dried using a Solar Tunnel Dryer (STD) as an application of green technology. Solar tunnel dryer is a food drying tool with the principle of hot air captured from the sun as a heat source flow. Drying food with a solar tunnel dryer as an application of the green technology concept to reduce the use of fossil fuels. Solar tunnel dryer is a dryer where the products are protected from rain, dust, insects, and rodents (Barooah et al., 2020). Plastic is an important material that causes production and consumption growth to increase. Production growth is expected growth with rising human population in the world. Increasing plastic consumption has a bad impact on environmental problems. So, we should move from plastic packaging to bioplastic to reduce world waste (Rhein & Schmid, 2020). *Sale pisang* packaging uses green packaging such as biodegradable plastic or paper packaging. Unused banana peels are used to be processed with molasses to be used as eco-enzymes as liquid fertilizer to realize the zero-waste concept. Molasses is a major by-product of the sugar industry containing 40–60% (w/w) sugar. As a by-product, molasses is usually discarded. However, molasses can be utilized in environmentally friendly bioprocesses to produce microbial bioproducts such as eco-enzymes (Zhang et al., 2021). Application of the concept of packaging and utilization of banana peels as an application of the sustainability concept that is currently being promoted. With many people already aware of the application of green technology and sustainability, *sale pisang* can be an effective and innovative choice for a business idea development that can be widely introduced at this time (Ahmadi, 2024). This research aims to utilize local banana production, reduce plastic waste, implement zero-waste concept, and produce sustainable products.

2. LITERATURE REVIEW

The Solar Tunnel Dryer (STD) is a tunnel-shaped drying device that uses solar energy to dry agricultural products such as fruits, vegetables, and fish. The STD is designed to accelerate the drying process, protect products from contamination, and save energy and costs compared to traditional drying methods. The STD consists of a tunnel structure lined with UV-stabilized transparent plastic, comprising two main components: solar panels and a drying chamber. The solar panels absorb sunlight and heat the air inside, which is then circulated into the drying chamber using a solar-powered fan. The hot air passes through the products placed on the STD shelves, absorbs moisture, and carries water vapor out through the ventilation at the end of the STD (Sharma, 2021). STD is shown in Figure 1.

Figure 1. Solar Tunnel Dryer (credit by Ethan and Najwa)

Pre-treatment is an initial treatment of food materials prior to the drying process, aimed at accelerating the drying rate, preventing unwanted chemical reactions, enhancing microbiological safety, and preserving the appearance, taste, and consumer acceptance. In the context of drying using STD, pre-treatment is a critical stage because this process heavily relies on varying factors such as sunlight intensity, temperature, and ambient humidity. These factors can cause the dried material to become unstable, so pre-treatment is necessary to ensure more efficient and stable drying (Deng et al., 2019).

Banana peels are organic waste obtained from the production of *sale pisang* and can be used as a raw material for eco-enzymes. Eco-enzymes are fermented solutions that are useful in agriculture, plantations, and the environment. Eco-enzymes derived from organic waste such as vegetables and fruit are useful for improving plant growth (Salsabila et al., 2024).

Green packaging, also known as eco-friendly packaging or sustainable packaging uses eco-friendly materials that must be effective and safe for human health and environment. Eco-friendly packaging is a trend in recent years to fulfill the Sustainable Development Goals (SDGs). Sustainable packaging has two kinds which are paper packaging and bioplastic packaging. Both are biodegradable packaging, but bioplastic packaging is more effective for *sale pisang* packaging because it is waterproof (Wandosell et al., 2021).

3. METHODOLOGY

Materials

Materials needed are 1 bunch of ripe bananas (*kepok* or *raja siam* variety) as the main materials, 5 g of sodium metabisulfite, 1 L of distilled water, molasses, and eco-friendly packaging (bioplastic) (Mukanema & Simate, 2024).

Instrumentation

Tools and equipment required for the research are solar tunnel dryer (Figure 1.), tray, cutting board, fruit knife, mixing bowl, digital scale, sealer, thermogun, moisture analyzer (Shimadzu MOC63u Unibloc), eco-friendly packaging (bioplastic), fermentation containers with lids (glass jar), filter paper, storage bottles (bottle glass) (Mawire et al., 2024).

Procedure 1

The sodium metabisulfite pre-treatment solution is prepared by dissolving 5 g of sodium metabisulfite in 1 L of distilled water in a mixing bowl.

Procedure 2

Ripe bananas are thoroughly washed and peeled to separate the flesh from the peel and was sliced into ± 3 mm thick using a knife. Then soaked in a 0.5% sodium metabisulfite for 10 minutes. The banana flesh was dried using a solar tunnel dryer (STD) for 4 hours, depending on weather conditions. During drying, the water content was measured every 2 hours using a moisture balance. The water content was measured to determine the texture and appearance of the *sale pisang* so that they resemble commercial *sale pisang*. Once the optimal water content achieved, the *sale pisang* packaged with attractive and eco-friendly materials (bioplastic). Product pricing was determined based on a Cost of Goods Sold (COGS) calculation, which includes the cost of raw materials, labor, energy consumption, and packaging innovation. The processing diagram is shown in Figure 2.

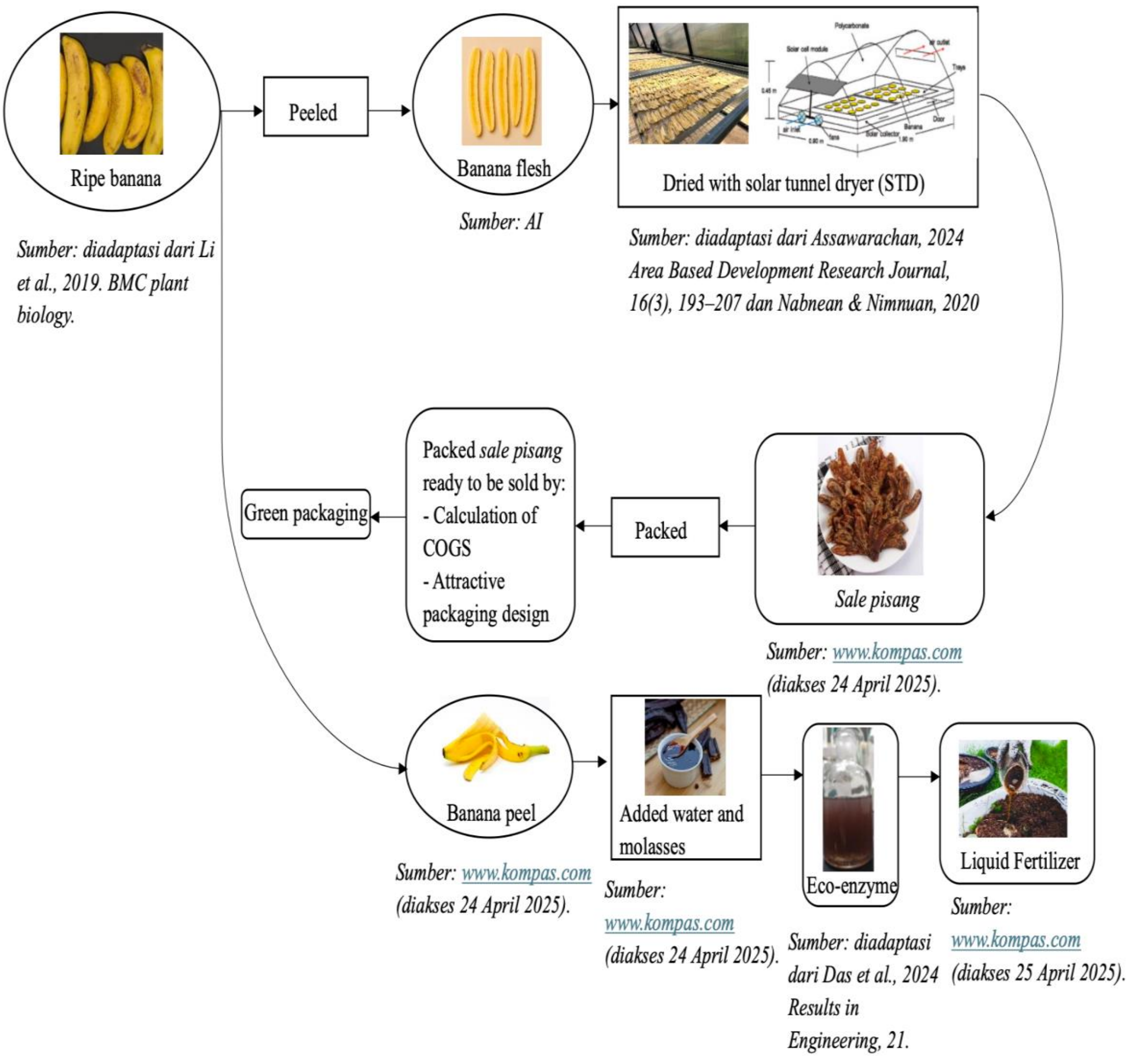


Figure 2. Processing Diagram of *Sale Pisang* Production Using Zero Waste Concept and Green Technology

Procedure 3

Banana peels were chopped into smaller pieces. The mixture was prepared using a ratio of 3 parts banana peel, 1 part molasses, and 10 parts water. Then the mixture placed in a sealed container and left to ferment at room temperature for three months and stirred regularly to prevent gas buildup. After the fermentation period, the liquid was filtered to obtain the eco-enzyme, which can be used as an organic liquid fertilizer (Salsabila et al., 2024).

4. RESULTS AND DISCUSSION

Based on Table 1, pre-treatment was carried out using five different treatments on the samples, namely control, soaked in 5% lemon juice + 0.5% acetic acid, soaked in 10% sucrose, soaked in 1% citric acid + 1% ascorbic acid, and soaked in 0.5% sodium metabisulfite, each for 10 minutes. Drying was done on August 15, 2025. The water content is checked regularly every 2 hours. Observation time is 8.40 AM; 10.40 AM; 12.40 PM; 2.40 PM. Moisture content measurements were taken every two hours using a Shimadzu MOC63u Unibloc Moisture Analyzer. The water content of *raja siam* bananas ranged from 4.70% to 51.35%, while that of *kepok* bananas ranged from 4.32% to 63.37%. The standard temperature (STD) during drying ranged from 39.1°C to 55.2°C.

Table 1. Results of Observations of Several Pre-treatment on the Reduction of *Sale Pisang* Water Content

Time	Pre-treatment	Raja Siam Water Content (%)	Kepok Water Content (%)	STD Temperature (°C)
8.40 AM	Control (No pre-treatment)	39.57	45.42	44.1
	5% Lemon juice + 0.5% Acetic Acid	51.35	49.95	
	10% Sucrose	45.53	55.32	
	1% Citric Acid + 1% Ascorbic Acid	41.91	44.58	
	0.5% Sodium Metabisulfite	43.32	63.37	
10.40 AM	Control	33.36	22.58	44.0
	5% Lemon juice + 0.5% Acetic Acid	33.71	38.95	
	10% Sucrose	35.1	41.31	
	1% Citric Acid + 1% Ascorbic Acid	40.00	38.14	
	0.5% Sodium Metabisulfite	32.92	36.64	
12.40 PM	Control	13.63	23.6	55.2
	5% Lemon juice + 0.5% Acetic Acid	23.39	23.65	
	10% Sucrose	26.74	24.38	
	1% Citric Acid + 1% Ascorbic Acid	26.16	31.19	
	0.5% Sodium Metabisulfite	23.38	23.53	
2.40 PM	Control	6.79	4.32	39.1
	5% Lemon juice + 0.5% Acetic Acid	4.70	9.25	
	10% Sucrose	13.32	10.67	
	1% Citric Acid + 1% Ascorbic Acid	14.60	8.73	
	0.5% Sodium Metabisulfite	10.55	8.77	

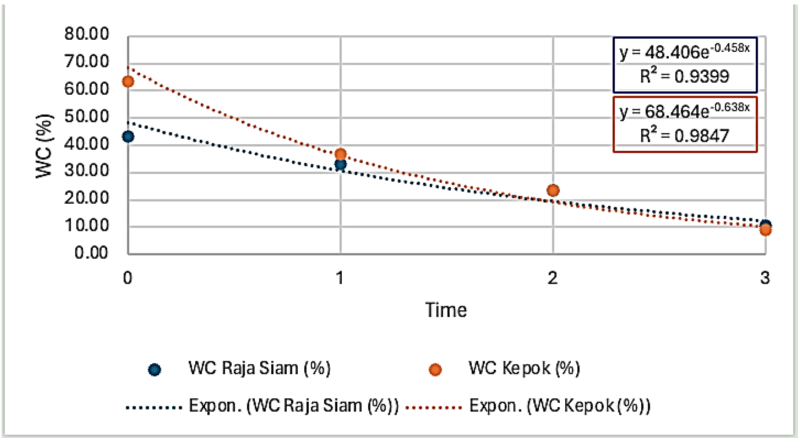
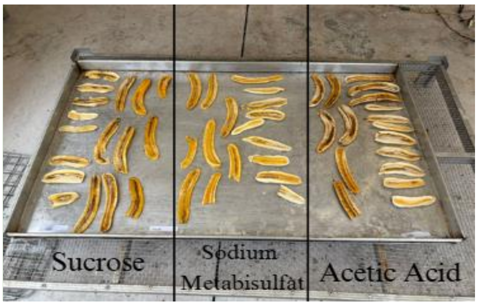


Figure 3. The Correlation between the Drying Time of Samples with 0.5% Sodium Metabisulfite Pre-treatment and Water Content

According to SNI 01-4319-1996, the maximum water content for sale pisang is 40% (]Badan Standardisasi Nasional, 1996). Meanwhile, according to Zara & Mustakim (2025), the recommended moisture content for sale pisang to be microbiologically safe is around 30-40%. Based on Figure 3., the most optimal pre-treatment is to soak in a 0.5% sodium metabisulfite solution for 10 minutes and dry for 4 hours. The water content produced by drying for 4 hours is 23.38% for the raja siam variety and 23.53% for the kepok variety. The drying time of 4 hours was also chosen because they produced a texture, aroma, and appearance similar to commercial sale pisang.

Pre-treatment & Drying Result

Sodium metabisulfite was chosen as the pre-treatment material because it is considered capable of providing the best characteristics in sensory evaluation, particularly in terms of color and texture. Sodium metabisulfite can also inhibit enzymatic browning in bananas by binding phenolic compounds and reducing the activity of the PPO (polyphenol oxidase) enzyme through pH reduction. Additionally, the sulphite from sodium metabisulfite has antimicrobial properties, thereby extending the shelf life of sale pisang. The bright color, preserved taste, retained aroma, and chewy texture make this pre-treatment the most widely used in the industry for producing uniform commercial sale pisang that are acceptable to consumers (Abd El-Wahhab et al., 2023; Iswari et al., 2024). Sale pisang that has been dried for 4 hours is shown in Figure 4. Based on Figure 4., the results of drying sale pisang for 4 hours with pre-treatment by soaking in a 0.5% sodium metabisulfite solution showed brightly colored sale pisang with a strong and preserved banana aroma, a chewy texture similar to commercial sale pisang, and a uniform shape.



 → *Raja Siam* Banana

 → *Kepok* Banana

Figure 4. Sale Pisang Drying after 4 Hours (credit by Ethan and Najwa)

Nutrients Component in Bananas and their Benefits

Bananas are nutrient-rich food sources, containing carbohydrates, fiber, vitamins, and minerals such as potassium, magnesium, and folate. Banana contains several bioactive compounds, such as phenolics, carotenoids, biogenic amines and phytosterols (Ranjha et al., 2022). The content of these bioactive compounds is a factor that makes bananas a functional food. Bananas as a source of carbohydrates also act as antioxidants like other fruits to help ward off free radicals. Banana consumers also vary from the smallest to the original. Bananas can be processed into smoothies, juices, or included in breads.

The Effect of Using STD on Product Hygiene and Quality

A common method used to dry banana flesh is open sun drying, which is relatively poor in terms of hygiene and food quality. The use of a solar tunnel dryer (STD) has a significant positive impact on the hygiene and quality of dried bananas. Unlike open sun drying, which exposes the bananas to dust, bacteria, unpredictable weather, and other contaminants, the STD offers a more controlled and enclosed environment. This reduces the risk of contamination and improves overall hygiene. Additionally, the consistent temperature and airflow within the STD help achieve more uniform drying, which enhances the quality of the final product.

The quality of *sale pisang* can be affected by the drying system. They compared banana drying using a photovoltaic-ventilated solar dryer with traditional open sun drying. The results showed that drying with the solar dryer at 60°C for 8 hours produced a final moisture content of 8.57%, with an average drying rate of 0.0921 g/min. In comparison, open sun drying had an average drying rate of 0.0529 g/min. Analysis revealed a smoother and more uniform surface structure in bananas dried using the solar dryer. Furthermore, GC-MS analysis identified 20 volatile compounds, including ascorbic acid (vitamin C), indicating a higher product quality compared to the open drying method (Suherman et al., 2024).

Solar tunnel dryer also can accelerate the drying process. In a study, bananas dried using STD reached a final moisture content of around 20% water content much faster than open sun drying, whereas the traditional open sun drying method only reduced the moisture content to 32% over 4 days (Nabnean & Nimnuan, 2021). STD also offers protection against rain, insects, and air pollution, so that STD can contribute to better hygiene and high quality in flavor, texture, and aroma. By utilizing solar energy and being equipped by a solar-powered fan, the solar tunnel dryer can be used in rural areas without electricity, making it an effective and sustainable solution (Mukanema & Simate, 2024).

The Effects of Using Green Packaging and Sustainability

Green packaging is the packaging choice made by both producers and consumers in response to current issues surrounding green technology and sustainability. Many consumers demonstrate environmental awareness and are therefore willing to purchase and use green packaging. However, some consumer groups still base their decisions on the price of the green packaging offered. Some types of green packaging are relatively affordable, such as paper-based packaging (Wandosell et al., 2021). Others, like biodegradable plastics, require more complex manufacturing processes and are therefore more expensive. To promote the use of green packaging both nationally and globally, support is needed from all stakeholders, including the government, communities, educational institutions, and society at large. Economic feasibility and the successful implementation of green packaging will only be possible if all stakeholders contribute directly and optimally (Nawang & Astuti, 2025).

Environmental Effects of Eco-enzyme Production

The manufacture of eco-enzymes from fruit skin waste produces O_3 gas (ozone) during the fermentation process so that it can produce cleaning fluids and fertilizers. Eco-enzymes contain several enzymes such as amylase, lipase, caseinase, protease, and cellulase. In the environmental sector, eco-enzymes can be used as ecological cleaning agents, reducing environmental toxicity, and liquid fertilizers. The use of liquid fertilizers provides significant results on plant growth, for example chili plants. Chili plants that are given eco-enzymes grow with an increase in plant height, stem diameter, leaf width, and more assertive and striking colors (Fadlilla et al., 2023). The relationship between plant height and eco-enzyme treatment is shown in Figure 5. (Nasution et al., 2024).

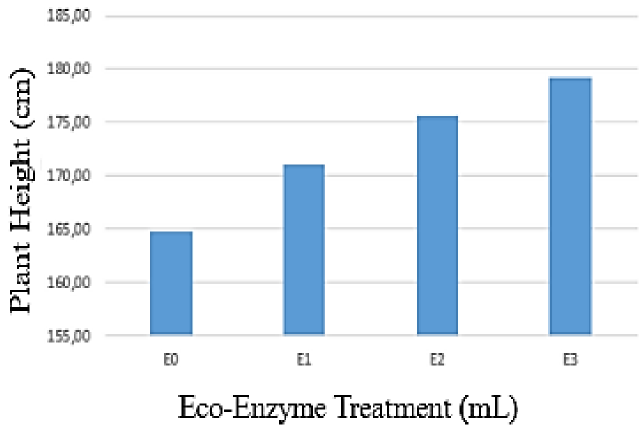


Figure 5. Relationship between Plant Height (cm) and Eco-enzyme Treatment (mL)

Eco-enzyme derived from young Manado *kepok* banana peels have a pH range of 4.0-5.5 and contain flavonoids, tannins, and saponins. Antibacterial tests showed that the solution effectively inhibited the growth of *Bacillus sp.* and *Xanthomonas campestris* at 50% and 75% concentration (Salsabila et al., 2024). Other research showed an evaluation of consumer preference to eco-enzyme made by banana peel. The results are 90% of the respondents liked the dark brown color and 70% of the respondents liked the acid aroma. This type of eco-enzyme also has a potential to be used as natural liquid fertilizers and cleaner (Warella, 2023). Some studies also characterized the chemical compounds in eco-enzyme produced from banana, orange, and pineapple peels. The eco-enzyme derived from banana peels contains bioactive compounds such as organic acids and enzymes that are beneficial for agricultural applications and organic waste management (Prasetyo & Maharani, 2024).

The Increasing Sales of *Sale Pisang* and Increasing Consumer Awareness of Green Concepts and Sustainability

The potential for *sale pisang*, especially in Indonesia, is increasing every year. The data obtained was 8,182,756 tons in 2020 or an increase of around 12.39% compared to the previous year. This potential is reinforced by the large number of banana-producing agro-industries that are used as raw materials for making *sale pisang*. Local raw materials make *sale pisang* a suitable product to be developed by local MSMEs in Indonesia (Priandari, 2023). Green concepts and sustainability are currently being promoted to be applied to all stakeholders. There have been many approaches through education and socialization to business actors and consumers as widely as possible. So it is considered that many consumers are aware of the green concept and sustainability (Widianingsih et al., 2023).

Estimated Cost of Goods Sold (COGS) for *Sale Pisang* that can be Applied to MSMEs

On average, *sale pisang* business actors (MSMEs) are able to produce as many as 420 units per day. The 420 units consist of 400 units of fresh *sale pisang* and 20 units of fresh *sale pisang* (Kurniawansyah, 2021).

Table 2. Components of Raw Material Costs per Day for Wet *Sale Pisang*

Raw Material	Amount of a Bunch	Cost of a Bunch	Total Cost per Day
Banana	500 bunch	IDR 5,000	IDR 2,500,000

Table 3. Direct Labor Cost Components per Day of Wet *Sale Pisang*

Production Activities	Amount of Direct Labor	Wage per day	Total Wage Costs Per Day
Stripping Drying Sorting Oven	4 people	IDR 30,000	IDR120,000
Packaging		IDR 7,500	IDR 30,000
	Total Direct Labor Costs		**IDR 150,000**

Table 4. Overhead Components Cost

Type of Cost	Estimated Quantity	Estimated Cost	Total Cost Per Day
Honey	2 kg	IDR 115,000	IDR 230,000
Seasoning/Flavor	1 unit	IDR 24,000	IDR 24,000
Sticker	5 roll	IDR 19,000	IDR 95,000
Plastic	10 roll	IDR 15,000	IDR 150,000
Lighting	1 unit	IDR 7,000	IDR 7,000
Gas	3 kg	IDR 19,000	IDR 19,000
	Total Overhead Cost		**IDR 525,000**

Table 5. Raw Material Cost Components per Day for Fried *Sale Pisang*

Raw Material	Amount of a Bunch	Cost of a Bunch	Total Cost per Day
Banana	40 bunch	IDR 5,000	IDR 200,000

Table 6. Direct Labor Cost Components per Day of Fried *Sale Pisang*

Production Activities	Amount of Direct Labor	Wage per day	Total Wage Costs Per Day
Stripping Drying Sorting Oven Packaging	2 people	IDR 35,000	IDR 70,000
	Total Direct Labor Costs		**IDR 70,000**

Table 7. Overhead Component Cost

Cost Type	Estimated Quantity	Estimated Price	Daily Total Cost
Indirect Raw Materials (Supporting Materials):			
Rice Flour	1.5 Kg	IDR 6,000	IDR 230,000
Sugar		IDR 500	IDR 500
Salt		IDR 500	IDR 500
Cooking Oil	1 Kg	IDR 12,500	IDR 25,000
Sticker	1 package	IDR 4,000	IDR 4,000
Plastic	2 packages	IDR 10,000	IDR 20,000
Indirect Labor Cost:			
Supervisor	1 Person	IDR 20,000	IDR 20,000
Energy Cost			
Lighting (1 Lamp, 5 watts)		IDR 2,000	IDR 2,000
Gas	1.5 Kg	IDR 5,000	IDR 7,500
Total Overhead Cost			**IDR 82,500**

Table 8. Cost of Goods Manufactured per Day

Type	Wet Sale Pisang	Fried Sale Pisang
Raw Material Cost	IDR 2,500,000	IDR 200,000
Direct Labor Cost	IDR 150,000	IDR 70,000
Overhead Cost	IDR 525,000	IDR 82,500
Total Production Cost	IDR 3,175,000	IDR 352,500
Product Units	400 Units	20 Units
Cost per Unit	**IDR 7,936**	**IDR 17,626**

5. CONCLUSION

The research conclusion is local banana production in Indonesia is utilized as a sale pisang product. The use of STD can become one of the green technology applications for sale pisang production and green packaging can reduce plastic waste. Using banana peels as liquid fertilizer is a zero waste and sustainable concept.

Research Contribution

This research contributes by providing a solution to the overproduction of bananas in Indonesia. It produces sustainable dual-product output, namely sale pisang and eco-enzyme. It can improve food safety standards for MSMEs by drying using a solar tunnel dryer (STD), which maintains product hygiene and safety. Social and economic contributions can also be made by encouraging MSME empowerment because this product is easily replicated and sold in various regions, especially banana-producing areas. This research can also raise awareness of environmentally friendly local products and increase the selling value of local products. Further contributions from this research are contributions to the Sustainable Development Goals (SDGs), namely SDG number 8 (Decent Work and Economic Growth) by encouraging economic activity through MSMEs, SDG number 12 (Responsible Consumption and Production) by implementing zero-waste and recycling principles, and SDG number 13 (Climate Action) by reducing organic waste and utilizing solar energy through STD.

Research Implications

This research has significant scientific implications, particularly in supporting the principles of a circular economy through the utilization of organic waste into value-added products. These findings can serve as the basis for further studies related to optimizing organic waste utilization, developing renewable energy-based drying technology, and designing sustainable business models suitable for food MSMEs. Practically, this research encourages the implementation of a zero-waste business model in the MSME sector, which has an impact on increasing production efficiency and food security. In addition, the research results also contribute to the development of diversified products based on local agriculture, which can increase the economic value of agricultural commodities in the region. From an environmental and sustainable development strategy perspective, this research supports the achievement of the Sustainable Development Goals (SDGs) at both the local and national levels, particularly goals number 8 (Decent Work and Economic Growth), 12 (Responsible Consumption and Production), and 13 (Climate Action).

Research Limitations

This study was limited by its small-scale, campus-based production which may not fully represent MSME conditions. The drying process in the solar tunnel dryer (STD) was not consistently controlled and remained weather-dependent, while long-term shelf-life testing, eco-enzyme evaluation, and key quality assessments such as sensory analysis, consumer acceptance, and market response were not conducted. Environmental impacts, including carbon footprint and comparative drying technologies, were also beyond the study's scope. These limitations indicate the need for further comprehensive research to strengthen applicability and sustainability.

Future Research

Future research should assess the shelf life and quality of sale pisang through microbiological, Aw, and nutrient analyses to ensure safety and stability. Studies on eco-enzyme effectiveness and its impact on product quality are also needed. In addition, real-scale implementation in MSMEs, combined with business feasibility and market testing, will be essential to evaluate commercialization potential.

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