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Improving Mechanical Properties of Biofoam Using Oil Palm Fiber as Filler at Various Temperatures and Processing Times

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ABSTRACT

Biofoam, as an alternative packaging material based on tapioca starch, has become a choice for environmentally friendly packaging. However, biofoam has a drawback in terms of weak mechanical properties. The use of oil palm fiber, a by-product of CPO production, has gained interest as a material that can improve the mechanical properties of biofoam. This study aims to produce biofoam with the best mechanical characteristics as packaging material through variations in temperature and processing time. The production of biofoam was carried out using the thermopressing method on tray-shaped molds with variations in molding temperature of 180°C, 190°C, and 200°C for 180 seconds and 210 seconds. The dough formulation consisted of 80% starch, 20% fiber, with the addition of 25 grams of water. Mechanical property testing was conducted through tests for moisture content, water adsorption, biodegradability, compressive strength, and tensile strength. The variation of 190°C temperature and 210 seconds baking time resulted in biofoam with the best mechanical properties. This biofoam showed the highest compressive strength value of 26.94 kPa, tensile strength test of 83.11 kPa, the second-highest biodegradability with a percentage of 78.93%, and the second-lowest moisture content with a value of 7.56%. These results indicate that biofoam at a molding temperature of 190°C and a baking time of 210 seconds has the best mechanical properties, making it superior as an environmentally friendly alternative packaging material compared to other formulations.

1. INTRODUCTION

Currently, petroleum-based polymer packaging materials are widely used in various applications, especially in the packaging field. The consequences of using petroleum-based polymers are very serious, particularly for environmental damage (Kahvand & Fasihi, 2020). Styrofoam is one of the most widely used petroleum-based packaging materials, especially as food packaging, due to its many advantages such as practicality, good durability, and affordability (Hevira *et al*., 2021). As a widely used material, Styrofoam has a major problem, namely it is not biodegradable, and this issue causes various environmental damages (Mahmud *et al*., 2023).

Natural material-based packaging is increasingly being developed because of its biodegradability, environmental friendliness, and abundant availability (Kremensas *et al*., 2021). One such packaging is biofoam, which is now being developed because it is made from naturally degradable materials, providing a solution to the problems caused by plastic-based packaging (Tacha *et al*., 2022). Biofoam is formed through a baking process of starch mixed with water using the thermopressing method, but natural material-based packaging such as starch has the drawback of low mechanical properties (Nugroho *et al*., 2022). The thermopressing method is a heating method using a pair of upper

and lower molds combined with hydraulic pressure and individually adjusted temperatures. The mold shape used has been designed to resemble a tray with dimensions of 190mm x 120mm. The use of starch combined with natural fibers as fillers in the biofoam matrix is targeted to improve the mechanical properties of biofoam (Machado *et al*., 2020).

One abundant fiber source as a by-product of agriculture is oil palm fiber. This product is still underutilized as it is usually used as boiler fuel in CPO production sites (Bakar *et al*., 2021). Oil palm fiber as a by-product biomass contains lignocellulose with lignin content (20–30%) and cellulose (12–43%) (Pereira *et al*., 2020). The use of oil palm fiber is considered suitable when positioned as a reinforcing material for alternative packaging materials such as biofoam (Mejouyo *et al*., 2022).

Based on this background, the process of molding tapioca dough into biofoam was carried out by mixing the main ingredients, namely tapioca starch, water, and oil palm fiber as a reinforcing material in the specified proportions using the thermopressing method, followed by variations in treatment on temperature and processing time. The objective of this research is to obtain biofoam with the best mechanical characteristics as packaging material, in an effort to produce alternative packaging to reduce the impact of environmental damage caused by excessive use of plastic packaging.

2. MATERIALS AND METHODS

2.1. Materials and Tools

The main material used was Rose Brand tapioca starch from PT. Budi Starch & Sweeterner Tbk, Lampung, Indonesia. Natural fiber in the form of oil palm fiber was obtained from PT. Batu Gunung Mulia Putra Agro, Tanah Laut, South Kalimantan. The tools used included a Thermopressing machine with a tray-shaped mold measuring 120mm x 190mm with a cavity depth of 30mm, a Universal Testing Machine (UTM, Instron 3369, USA), aluminum dishes, an analytical balance, an oven, a desiccator, polybags, microfiber cloths, and measuring cylinders.

2.2. Research Method

This study was conducted to produce biofoam using the thermopressing method by mixing all materials: starch, oil palm fiber, and water. The process involved mixing all materials with a dry weight of 25 grams in the dough combination of 80% starch and 20% oil palm fiber, with the addition of 25 grams of water to mold one piece of biofoam. The treatments were combinations of two factors: the baking time (180 seconds and 210 seconds) and temperature variations (180°C, 190°C, and 200°C). The thermopressing machine used had a tray-shaped mold with dimensions of 190mm length, 120mm width, 30mm cavity depth, and a resulting thickness of 3mm. The compression pressure of the thermopressing machine with air compression was 0.6 MPa. The research was conducted with three repetitions for each dough combination, and biofoam was produced from each combination to test mechanical characteristics.

2.3. Oil Palm Fiber Preparation

The dirty fibers were sorted to separate fibers, shells, and other impurities. The oil palm fibers were then cleaned by washing with running water until completely clean. The fibers were then sun-dried for 2 days in hot sunlight to remove moisture and subsequently oven-dried at 40°C for 24 hours. Once completely dry, the fibers were ground using a blender (Miyako BL-102 3in1 Wet Mill type) to obtain smaller sizes, followed by sieving to produce fibers with a size of 30 mesh.

2.4. Water Content

The water content of the biofoam was tested using the oven method. The steps involved heating an aluminum dish at 100°C for 15 minutes, cooling it in a desiccator for 10 minutes, and weighing it as the initial weight. Biofoam samples weighing 2 grams were placed into the dish as W0 (weight of dish + sample weight), then oven-dried at 105°C for 6 hours. After drying, the samples were placed in a desiccator for 10 minutes and reweighed to obtain W1. The water content was calculated using Equation (1).

$$\text{Water Content (\%)} = \frac{W0-W1}{\text{sample(g)}} \times 100\% \quad (1)$$

2.5. Water Adsorption

The water adsorption test followed the ABNT NBR NM ISO 535 standard. Biofoam samples were oven-dried at 50°C for 5 minutes, placed in a desiccator for 10 minutes, and weighed as the initial weight (W0). Subsequently, 20 ml of water was dripped onto the samples (adjusting to the average weight of each sample) for 1 minute. Excess water on the sample surface was removed using a microfiber cloth, and the samples were reweighed (W1). The calculation was performed using Equation (2):

$$\text{Water Adsorpsion (\%)} = \frac{W1-W0}{W0} \times 100\% \quad (2)$$

2.6. Biodegradability

Biodegradability testing of the biofoam was carried out using the soil burial method. The samples were weighed as (W0) and then placed into polybags filled with soil to a height of 10cm, with the samples subsequently covered with soil to a height of 10cm. The burial was conducted for 28 days to obtain biodegradation results. After 28 days, the remaining samples were cleaned of soil residues and reweighed to obtain (W1). The percentage of biodegradation was calculated using the following formula:

$$\text{Weight loss (\%)} = \frac{W0-W1}{W0} \times 100\% \quad (3)$$

2.7. Compressive Strength

The compressive strength of the biofoam samples was tested using a Universal Testing Machine (UTM, Instron 3369, USA). Whole biofoam samples were compressed at a speed of 1 mm/s until the samples broke or fractured. The compressive strength value was obtained based on the maximum load received by the sample per unit area of the compressed surface, expressed in kilopascals (kPa).

2.8. Tensile Strength

Tensile strength testing was conducted using a Universal Testing Machine (UTM, Instron 3369, USA). Biofoam samples were cut according to ASTM D-638 standards into rectangular shapes measuring 50 mm (length) and 20 mm (width). The test involved gripping both ends of the sample and pulling it at a speed of 1 mm/s until it tore or broke. The tensile strength value was obtained based on the maximum load per unit area of the sample, expressed in kilopascals (kPa).

2.9. Data Analysis

This study used a factorial randomized block design with three repetitions for each parameter, and the data were analyzed using Analysis of Variance (ANOVA) at a 5% level. The analysis process was conducted using IBM SPSS Statistics version 25 software. Mean comparisons were performed using Tukey's multiple range test ($p \leqslant 0.05$).

3. RESULTS AND DISCUSSION

3.1. Water Content

In the measurement of water content, the biofoam sample that obtained the lowest water content was the sample with a baking time of 210 s at a temperature of 200°C resulting a water content of 7.39%. The results of ANOVA showed that there was no interaction between baking time and process temperature ($p = 0.578$), and the single factor of baking time ($p = 0.056$) as well as temperature ($p = 0.133$) also had no significant effect on the water content of the biofoam. However, the results of this study are better than the study by Machado *et al*. (2020) who conducted a water content test on tapioca starch biofoam without fiber with a water content value of 9% and biofoam with the addition of

peanut skin fiber which has a water content of 9.7%, and overall the water content value produced in this study is still lower. The overall water content value can be seen in Table 1. Based on Table 1, the results show that the longer baking time of 210 seconds overall produces biofoam with lower water content compared to biofoam baked for 180 seconds. The results also show that as the temperature increases, each factor of the baking time shows a decrease in water content. This is because higher temperatures or longer constant times result in greater water evaporation (Bruscato *et al*., 2019). Although the ANOVA results did not show any significant effect ($p > 0.05$) for both factors (temperature and baking time), the decrease trend in the graph may indicate a potential relationship of the data.

Table 1. Effect treatment factors (baking time and processing temperature) on the water content of the biofoam

Baking Time (s)	Processing Temperature (°C)			Average
	180	190	200	
180	7.97 ± 0.42	8.03 ± 0.22	7.64 ± 1.01	7.88
210	7.75 ± 0.72	7.56 ± 0.47	7.39 ± 0.16	7.57
Average	7.86	7.80	7.52	

Table 2. Effect treatment factors (baking time and processing temperature) on the water adsorption of biofoam

Baking Time (s)	Processing Temperature (°C)			Average
	180	190	200	
180	5.43 ± 0.91	6.92 ± 0.25	9.79 ± 2.51	7.38 A
210	5.29 ± 1.12	5.46 ± 1.17	9.55 ± 5.01	6.77 A
Average	5.36 a	6.19 a	9.67 b	

Note: different letters following average values indicate significant differences at α = 5% (lowercases for processing temperature, uppercases for baking time)

3.2. Water Adsorption

Water adsorption is an important parameter because as packaging material, biofoam might be used to package products containing water. Although it is not yet functionally used for this purpose, this parameter needs to be developed (Muharram, 2020). Styrofoam has excellent water resistance as a packaging material, but starch-based packaging materials like biofoam has lower water resistance compared to styrofoam. Therefore, determining the water absorption value is important for further studies to improve the mechanical properties of biofoam as packaging.

Table 2 shows the effect of baking time and temperature on the water absorption of the biofoam. The results of the ANOVA showed that the interaction between process time and temperature ($p = 0.779$) and the single factor of baking time ($p = 0.480$) did not significantly affect the water absorption value, while the single factor of temperature ($p = 0.004$) significantly affected the water absorption of biofoam. Table 2 shows that increasing the baking temperature resulted in the higher the water adsorption value. In the water adsorption test, the biofoam with the lowest absorption percentage was the biofoam baked at the lowest temperature of 180°C for 210 seconds, with a value of 5.29%. This is because higher baking temperatures result in a biofoam structure that becomes very dry, and the starch granules break, forming larger pore networks. This process produces biofoam with larger pores and higher capillarity, making it easier to absorb water. This condition aligns with the lower water content of biofoam as the baking temperature and duration increase. The results are significantly lower and better compared to the study by Muspira *et al*. (2024), which used tapioca starch and rice straw fiber, resulting in a water adsorption value of 20.6%. The results obtained in this study have far met the SNI standard value of 26.12%, as the produced biofoam has water absorption values ranging from 5.29% to 9.79% (Hutagalung *et al*., 2024).

Essentially, starch-based biofoam is very susceptible to water due to its hydrophilic nature, which allows water molecules to damage the hydrogen bonds in starch, thereby reducing the mechanical properties of biofoam (Tacha *et al*., 2022). This parameter needs to be improved to produce lower water absorption and minimize the reduction in the mechanical properties of biofoam (Lubis *et al*., 2022).

3.3. Biodegradability

Biodegradability testing was conducted to observe the degradation rate of biofoam by microorganisms, particularly soil microorganisms, when the biofoam is no longer used as packaging material (Linda *et al*., 2021; Hevira *et al*., 2021). Table 3 shows the effect of treatment factors on biodegradability of biofoam. ANOVA results show that the interaction between baking time and process temperature has no significant effect on biodegradation (p = 0.050), but the single factors of temperature (p = 0.010) and time (p = 0.013) have a significant effect on the value of the biofoam biodegradability. The biodegradability test at day 28 showed that increased processing temperatures positively affected the degradation percentage of biofoam. The sample processed at 200°C for 210 s had the highest biodegradability at 87.38%. The biodegradability percentage of biofoam can be seen in Table 3.

Table 3. Effect treatment factors (baking time and processing temperature) on the biodegradability (%) of the biofoam

Baking Time (s)	Processing Temperature (°C)			Average
	180	190	200	
180	73.21 ± 9.37	75.32 ± 0.36	75.50 ± 1.16	74.68 A
210	73.28 ± 4.84	78.93 ± 4.63	87.38 ± 2.07	79.86 B
Average	73.25 a	77.13 ab	81.44 b	

Note: different letters following average values indicate significant differences at α = 5% (lowercases for processing temperature, uppercases for baking time)

The duration of the processing time also indicates that the longer the processing time, the higher the biodegradation results. During the baking process with high temperatures and relatively longer durations, the biofoam structure becomes drier, and the starch matrix begins to break down due to excessive heat (Kaisangsri *et al*., 2019). Consequently, during the biodegradation process in soil, in addition to the naturally hydrophilic nature of starch, the water absorption capability combined with the weakening structure due to heating makes high-temperature biofoam more easily decomposed by soil microorganisms (Hutagalung *et al*., 2024). This explains why higher processing temperatures and longer processing times accelerate the biodegradation process of biofoam.

3.4. Compressive Strength

ANOVA results show that the interaction between baking time and process temperature (p = 0.169) and the single factors of time (p = 0.561) has no significant effect on the compressive strength, but temperature (p = 0.001) have a significant effect on the compressive strength of the biofoam. The compressive strength test results showed that the best compressive strength was at a processing temperature of 190°C for 210 seconds, with a value of 26.94 kPa (Table 3). This is better compared to the study by Hutagalung *et al*. (2024), which produced biofoam with compressive strength values ranging from 11-12 kPa, using tapioca starch and water hyacinth fiber. This indicates that oil palm fruit fiber plays a better role as a reinforcing material for biofoam to enhance its mechanical properties in terms of compressive strength. However, at a processing temperature of 200°C, the compressive strength significantly decreased, as shown in Table 4. This is because excessively high temperatures can damage the starch granule structure and break the amylose and amylopectin chains in the main starch material. As a result, the mechanical properties of the biofoam's components become weaker because the biofoam's cavities are no longer structured strongly (Engel *et al*., 2019).

Table 4. Effect treatment factors (baking time and processing temperature) on the compressive strength (kPa) of the biofoam

Baking Time (s)	Processing Temperature (°C)			Average
	180	190	200	
180	23.74 ± 4.87	25.50 ± 1.71	12.96 ± 5.89	20.74 A
210	19.16 ± 5.15	26.94 ± 5.54	12.79 ± 0.70	19.63 A
Average	21.45 b	26.22 b	12.88 a	

Note: different letters following average values indicate significant differences at α = 5% (lowercases for processing temperature, uppercases for baking time)

Mechanical properties such as compressive strength are analyzed to verify the structure of biofoam when subjected to external forces during its use as packaging material. The deformation ability of biofoam is assessed as part of the mechanical testing process (da Silva *et al*., 2020). The results obtained show that using temperatures above 190°C affects the structural strength of biofoam, making it weaker.

3.5. Tensile Strength

The tensile strength test results can be seen in Table 4. ANOVA results show that the interaction between baking time and process temperature has no significant effect on biodegradation (p = 0.976), but the single factors of baking time (p = 0.995) and temperature (p = 0.010) have a significant effect on the compressive strength of the biofoam. Tensile strength testing indicates the maximum ability of biofoam to withstand force before breaking (Lubis *et al*., 2022). As presented in Figure 5, based on the tensile strength test, the highest value was obtained at a baking temperature of 190°C for 210 s, with a value of 83.11 kPa. Similar to the compressive strength test, increasing the temperature to 200°C resulted in a significant drop in tensile strength compared to the process temperatures of 180°C or 190°C. Engel *et al*. (2019) explained that excessively high temperatures likely damage the starch structure in biofoam, resulting in weaker mechanical properties compared to lower processing temperatures. However, the tensile strength results obtained in this study are still lower than those in the study by Muspira *et al*. (2024), which had tensile strength values above 111 kPa, using tapioca starch with added cellulose fiber.

Table 4. Effect treatment factors (baking time and processing temperature) on the tensile strength (kPa) of the biofoam

Baking Time (s)	Processing Temperature (°C)			Average
	180	190	200	
180	80.47 ± 14.05	82.28 ± 1.80	61.39 ± 11.51	74.71
210	81.15 ± 7.28	83.11 ± 7.56	59.77 ± 1.87	74.68
Average	80.81	82.70	60.58	

Note: different lowercases following average values indicate significant differences at α = 5%.

The gelatinization process of starch adds value to the tensile strength of biofoam by creating an interconnected three-dimensional network that provides flexibility. However, if starch is heated to increasingly higher temperatures, the starch granules will break, losing the orderly structure and consequently reducing the biofoam's flexibility (Sihombing *et al*., 2022). Based on the results obtained, using temperatures up to 200°C causes a decrease in the tensile strength of biofoam due to the destruction of the starch structure, which diminishes its mechanical properties in terms of tensile strength.

4. CONCLUSION

Based on the characteristics evaluated, it was found that the biofoam processed for 210 seconds at a temperature of 190°C exhibited the best characteristics compared to biofoam subjected to other processing conditions. The highest values obtained were a compressive strength of 26.94 kPa, a tensile strength of 83.11 kPa, a biodegradability percentage of 78.93% (ranking second), and a water content of 7.56% (ranking second lowest). Several results from these parameters were particularly dominant, establishing the biofoam processed at 190°C for 210 seconds as having the best mechanical characteristics in this study.

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