Physical, thermal and functional groups' characteristics of biofoam cup made from coconut fibre waste, soy flour and *Rhizopus oligosporus*

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Abstract. Biofoam is a replacement packaging for Styrofoam made from natural fibres that are naturally biodegradable and food-safe. Many studies use chemicals and starch as a matrix adhesive in the manufacture of biofoam. In previous studies, biofoam cups have been developed using the mold *Rhizopus oligosporus* which is found in coconut fibre. The objective of this study was to analyse the physical, thermal and functional groups' characteristics in order to determine the most durable biofoam cup. The mixtures of fibre, *tempeh* mold, and soy flour were fermented for 3 days at 35°C in two stacked plastic cups and were dried for 46 hours at 50°C to stop the fermentation process. The biofoam cups were then analysed for the physical, thermal and functional groups' characteristics. The most favourable characteristics of the biofoam cup is not easily destroyed and resistant to heat. The results showed that it had 0.08 g/cm^3 ± 0.1 g/cm^3 of density and 320.54°C of *thermal gravimetry analysis.* It also had a hydroxyl functional group (O-H) at wave number 3273.20 cm^{-1}, an alkyl group (C-H) at wave number 2937.59 cm^{-1}, a carbonyl group (C=O) at wave number 1654.92 cm^{-1}, 1535.34 cm^{-1}, and 1259.52 cm^{-1}, and the C-O functional group at the wave number 1060.85 cm^{-1}.

Keyword. *Biodegradable; Coconut fibre; density; TGA; functional groups.*

1. Introduction

The practical lifestyle of the Indonesian people causes the need for food packaging to continue to increase. Styrofoam is a food packaging that is widely used by manufacturers in packaging disposable food and beverage products. Styrofoam is used widely because of its advantages — namely it is leakproof, practical, lightweight, can withstand food temperatures well and is inexpensive. However, based on Fikri and Veronika (2018) [1], Styrofoam packaging does not decompose in nature, causing countless environmental problems. Based on a study from the Indonesian Institute of Sciences (LIPI), Styrofoam packaging is the most common material waste found in Indonesian oceans, reaching 0.27-0.59 million tons in 2018 [2].

Styrofoam is a type of plastic packaging made from polystyrene which consists of benzene and ethylene as the constituent materials. This type of plastic was originally only used to cushion electronic goods from minor impacts [3]. The plastic element in Styrofoam can mix with the hot food in the container and cause health issues for consumers who eat it [4]. Therefore, the use of Styrofoam packaging for food or beverages over 60°C should be avoided to prevent migration, in the case that the higher the temperature of the food, the more components migrate into the food [5]. Some of the monomers that are thought to be dangerous are vinyl chloride, acrylonitrile, meta-acrylonitrile vinylidene chloride and styrene. Vinyl chloride can react with DNA components, namely guanine and cytosine, while acrylonitrile reacts with adenine, and vinyl chloride monomer undergoes metabolism in the body [6].

Biofoam is a replacement packaging for Styrofoam made from natural fibres that are naturally biodegradable and safe for health. The raw materials used in the manufacture of biofoam packaging must meet several requirements, namely that the natural resources used must be renewable and biodegradable, the manufacturing process is inexpensive and energy efficient, not harmful to health or the environment, and the waste generated can be recycled [7].

According to Etikaningrum et al. (2016) [8], the manufacture of biofoam is carried out through a thermoforming method by adding tapioca, polyvinyl alcohol (PVA) to various types of modified cellulose. Some of those types would be1% cellulose empty fruit bunches (STKS), 3% nanocellulose palm empty bunches (NTKS), and 5% cellulose acetate palm empty bunches (SATKS). The results showed that the modified type of NTKS in the form of a gel with a diameter of 92.07 nm was not able to form a quality biofoam because its consistency was too viscous. The modified type of SATKS with acetyl content of 41.61% was not able to reduce the water absorption of biofoam and has a low mechanical strength because the dough is not compatible. However, the STKS treatment produced the best biofoam seen, notably by a few characteristics, including that it has the lowest water absorption value (23.40%), the highest compressive strength (13.92 N/mm^2) and the highest density (0.28 g/cm^3).

Irawan *et al*. (2018) [9] showed that biofoam from *mahuli* banana hump and *nagara* sweet potato with a composition of 60:40 obtained the best results. In the hardness test, the two samples added with PVA had strength values ranging from 3.49–4.02 MPa, while those without PVA had hardness values ranging from 3.42to 3.59 MPa. The resulting value is higher than the value of commercial Styrofoam (1.3–1.39 MPa). The results of the Differential Scanning Calorimetry (DSC) test with the addition of PVA obtained a melting point of 166.50°C and without PVA of 166.45°C. The results of the Scanning Electron Microscope (SEM) test with the addition of PVA showeda higher amount of air cavities than the sample without PVA. Biofoam made from both materials can completely decompose after two months of being buried in the ground.

Hendrawati *et al.* (2019) [10] conducted research on biofoam from various starch raw materials (sago, cassava, and corn). The results showed that biofoam from sago starch had a lower absorption than cassava starch and corn starch. In terms of the level of biodegradation, cassava starch is more easily decomposed than samples made from sago and corn starch. Biofoam made from sago starch with the addition of 30% w/w chitosan has the highest tensile strength value at 20 MPa.

These studies use chemicals and starch as a matrix adhesive in the manufacture of biofoam. Ghazvinian *et al*. (2020) [11] used *Pleurotus ostreatus* mycelium as an adhesive for sawdust and straw. The results of his research show that biofoam can be applied as a masonry material in architecture with the characteristics of being lightweight, degradable and renewable.

In previous studies, biofoam cups were made using the mold *Rhizopus oligosporus* on bagasse and coconut fibre [12]. The physical properties of the biofoam cup were further improved by adding soy flour (20–28 g) and varying the fermentation time (3–5 days). The results showed that the best biofoam cups were obtained from 28 g soybean flour after a 3-day fermentation which exhibits 73% water absorption capacity, 72.3% porosity value, 3.27 kg/cm^2 of puncture strength value, and 3.17 kPa of compressive strength value [13]. The objective of this study was to analyse the physical, thermal, and functional groups' characteristics of the best biofoam cup.

2. Materials and methods

2.1 Materials

The main material in this experiment was coconut fibre which was collected from street vendors around Universitas Syiah Kuala campus, Banda Aceh, Indonesia. The coconut fibre was prepared by following procedures mentioned by [12]. The prepared fibre (200 g), *tempeh* mold (*Rhizopus oligosporus*; 12 g) and soy flour (28 g) were then mixed as the final ingredients.

2.2 Production of Biofoam Cup

Production of biofoam cup followed the methods from [13]. The mixtures of fibre, *tempeh* mold, and soy flour were fermented for 3 days at 35°C in two stacked plastic cups and were dried for 46 hours at 50°C to stop the fermentation process. The biofoam cups were then analysed for the physical, thermal and functional groups' characteristics.

2.3 Density [10]

The density test is carried out by calculating the dry mass of the sample in grams and measuring the length, width, and height of the sample to get the volume value in cm^3 units. The sample density value can be calculated using Formula 1.

$$\rho = \frac{m}{v} \quad \text{..... (Formula 1)}$$

whereas:

ρ = density (g/cm^3)
m = sample dry mass
v = sample volume (cm^3)

2.4 Thermal Gravimetry Analysis (TGA; [14])

Thermal stability was carried out using a Mettler TG 50 Module A equipped with a Mettler TC 11 4000 Thermal Analyzer (USA). Specimens were analysed in a nitrogen atmosphere at a flow rate of 50 ml/min. The temperature is set from 30 to 800°C at a rate of 20°C per minute.

2.5 Functional Groups (Fourier Transform Infrared Spectrophotometer; FTIR; [14])

FTIR analysis was performed using an FTIR spectrometer (Nicolet iS10, Thermo Scientific). The matrix was cut to about 3 cm and directly loaded to analyse the transmission spectrum in the range of 4000-400 cm^{-1}.

3. Results and discussion

3.1 Density

A desired packaging characteristic is expected to have a high-density value, where the resulting structure is tight [15]. The density value in this research was 0.08 g/cm^3 ± 0.1 g/cm^3. Based on direct communication with Muliani who also researched about biofoam cups made from bagasse, the highest density value in bagasse biofoam cups without cork was 0.04 g/cm^3. According to [12], the standard density of Styrofoam is in the range of 0.9-1.1 g/cm^3.

The low-density factor is due to the high expansion ability and vice versa. The expansion increases if the water in the biofoam mixture acts as a blowing agent which can produce a hollow structure. Dough that has a high moisture content causes excessive expansion, so that the resulting biofoam has many irregular cavities with low density values [8].

The optimum density value is due to the presence of lignin and cellulose compounds in coconut fibre which are composed of free groups, namely C=C and –CH aromatic groups which can bind and reach empty cavities to form strong and tight covalent bonds. In addition, the density is also influenced by the coarseness of the coir fibre due to the reduced lignin content when there is friction between the fibre surfaces caused by the stirring process [16].

3.2 Thermal Gravimetry Analysis (TGA)

Thermal analysis can be measured using a tool called a Thermogravimetric Analyzer. The purpose of this test is to show the nature of the sample. Thermal analysis occurs during the temperature change from 30°C to 600°C, where the analysis process includes the process of phase change, softening, melting, decomposition, and oxidation. The results of the TGA are in the form of a thermogram showing endothermic and exothermic enthalpy changes [17].

The TGA curve shows that the thermogram provides information about the decrease in mass due to an increase in temperature. The heat given to the sample will continue to increase with time, and with this, the mass in the sample decreases because the mass escapes as a gas [18]. In addition, the decrease in sample mass was due to the decomposition process when it reached a certain temperature which resulted in the breaking of the chain bonds [19]. The expected characteristic result in biofoam packaging is that it can withstand the highest temperatures. Weight loss of biofoam during heating can be seen in the curve of Figure 1.

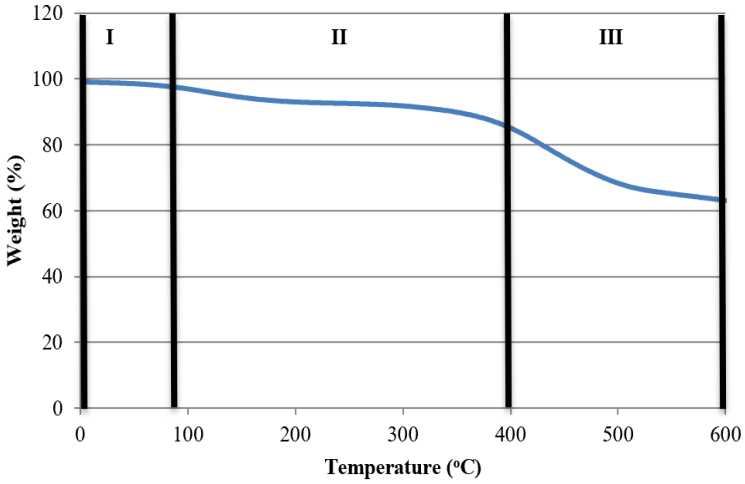

Figure 1. Thermogram of thermal gravimetry analysis of biofoam cup

In Phase I, the curve decreases in weight while being heated up from 0°C to 600°C 600°CDuring the heating time, the water in the sample evaporated, which is an endothermic process [17]. At this stage, the thermal degradation process is not occurring, and the sample weight reduction is 87%–90%.

Stage II is a degradation temperature stage, where the high degradation temperature shows the biofoam cup has an heat retaining characteristic. The thermal degradation temperature of biofoam cup in this study was 320.54°C, which is higher than biofoam cup from bagasse with cork, which also has a higher thermal degradation temperature of 264.38°C. The high degradation temperature is due to the breaking of glycosidic bonds in cellulose which results in the presence of CO_2, H_2O compounds, volatile compounds, and various hydrocarbon derivatives [14]. In addition, the temperature that can still be used on biofoam is 70°C because natural materials are susceptible to high temperatures and to avoid carbonization [20].

Stage III is the residue produced after the thermal degradation process while heating from 400°C to 600°C, where the resulting compound will evaporate and result in a weight loss of between 53.2% and 66%, resulting in ash. According to [21], the factors that affect the rate of decomposition are due to the presence of cellulose, hemicellulose, and lignin compounds. Cellulose is a compound that has a high rate of decomposition and produces volatile components. Meanwhile, hemicellulose and lignin are compounds that will increase the carbonation residue.

3.3 Functional Groups (Fourier Transform Infrared Spectrophotometer; FTIR)

In order to determine more about the molecular makeup of the biofoam, a FTIR analysis was performed. The results of the difference in the amount of absorption of this material are used to identify the functional group of biofoam [18]. The wave number used in the FTIR test ranges from 500–4000 cm^{-1}. The purpose of FTIR identification is to obtain a vibration graph from a photoelectric detector [22]. The FTIR graph of coconut fibre biofoam cup can be seen in Figure 2.

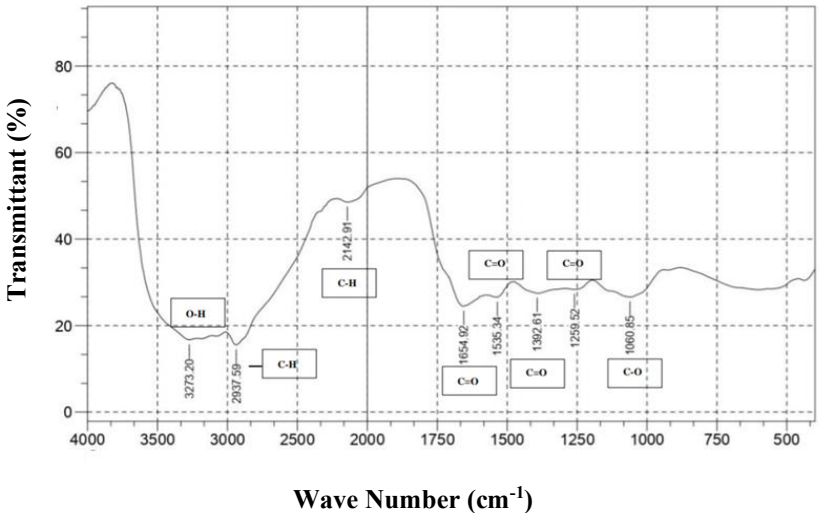

Figure 2. Thermogram of functional groups analysis of biofoam cup

Figure 2 shows the absorbance character for polysaccharides with a glucopyranose ring such as a hydroxyl group (O-H) occurring at 3273.20 cm^{-1} in the biofoam cup. This result is not much different from the study of [21] about sugarcane bagasse as an alternative to activated carbon, where the wave number produced is 3270.48 cm^{-1}.

The alkyl group (C-H) has a wave number of 2937.59 cm^{-1} and reappears at a wave number of 2142.91 cm^{-1}. The results of C-H biofoam cup are in accordance with research on coconut fibre powder as a thermoplastic composite, which was found at 2920.35 cm^{-1} [23], on nanocellulose from empty oil palm fruit bunches, at 2900 cm^{-1} [14] and in bagasse cellulose at 2162 cm^{-1} [17].

A peak at a wavelength of 1060.85 cm^{-1} indicates the absorption of the C-O functional group. The wavelength is not much different from the research results of [21] where the range of absorption peaks of the C-O functional group occurs at wave numbers of 1050–1300 cm^{-1} for bagasse samples, which is also shown in research by [17] at a wave number of 1030 cm^{-1} for bagasse cellulose samples.

The results of Muliani's research biofoam cups made from bagasse (personal communication) showed at a wavelength of 1600–1700 cm^{-1}. It was suspected that the NH_2 functional group in the mycelium overlapped with the N group present in coconut fibre cellulose. According to Indarti et al. (2015) [14], the formation of the NH_2 peak is thought to also occur at a wavelength of 1500 cm^{-1}. However, the results of this study showed that at a wavelength of 1654.92 cm^{-1} and 1535 cm^{-1}, a carbonyl group (C=O) was shown. This is presumably due to the presence of the N group from coconut fibre cellulose that can bind the H group to form the NH_3 functional group. In this study, the coconut fibre was not analysed for the FTIR test. Thus, the wave number value and the comparison of the functional groups of coco fibre refer to the results of research by [23] which can be seen in Table 1.

Table 1. Comparison of wave number between coconut fibre and the biofoam cup

Functional Groups	Wave Number (cm^{-1})	
	Coconut Fibre Biofoam Cup	Coconut Fibre [23]
O-H	3273.20	3417.04
C-H	2937.59	2920.35
C=O	1654.92	1735.04
C=O	1535.34	1512.28
C=O	1259.52	1257.84
C-O	1060.85	1049.32

The biofoam cup contained fewer O-H functional groups, which was indicated by the high transmittance value of O-H groups in the sample. Based on the Lambert-Beer law, it states that the transmittance value is inversely proportional to the absorbance, where the higher the transmittance value, the lower the number of components in the sample [24].

4. Conclusions

Biofoam cup which was made from coconut fibre waste with addition of 28 g soy flour and was fermented for 3 days had the following characteristics: 0.08 $g/cm^3 \pm 0.1$ g/cm^3 of density and 320.54°C of *thermal gravimetry analysis.* The biofoam cup has a potential to replace the Styrofoam. However, reducing the size of the raw material should be done to improve the physical properties of the biofoam cup. Based on *Fourier Transform Infrared Spectrophotometers (FTIR)* analysis, the presence of the N group from coconut fibre cellulose was detected indicating that the mould's mycelium has an important role in binding the fibres matrix.

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