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Physical and Mechanical Properties of Biodegradable Pot Derived from Oil Palm Empty Fruit Bunch and Sodium Alginate

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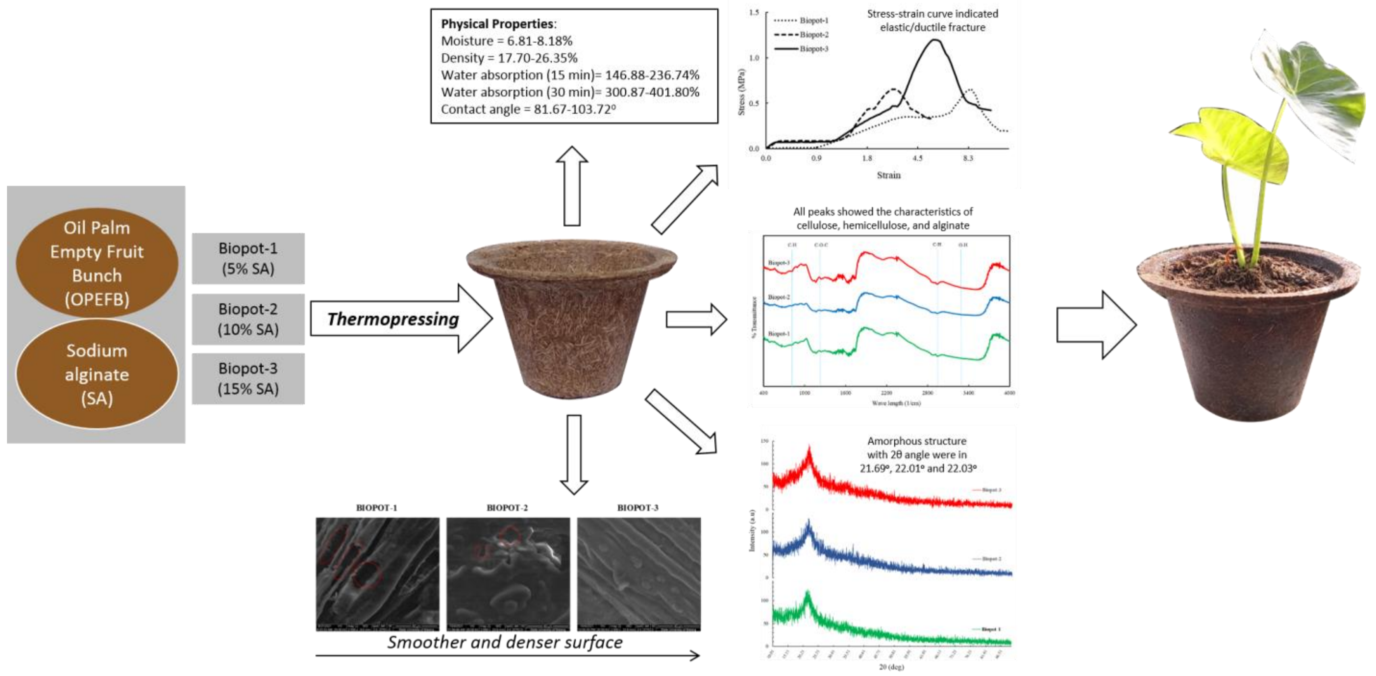
HIGHLIGHTS

- Oil palm empty fruit bunch is sufficient to be used as reinforcement on the biopot production.
- Application of sodium alginate deliver a positive effect on the biopot's mechanical properties.
- Properties of the developed biopot indicate the possibility to substitute the plastic pot use.

Abstract: Efforts to overcome the problem of agroplastic waste (in the form of pots, polybags, and other planting containers) continue to be studied. This research investigated the use of oil palm empty fruit bunch (OPEFB) and sodium alginate in the production process of biodegradable pots. This study also investigated the comprehensive features of biodegradable pots which included physical, mechanical, structural (chemical), and morphological properties. Physical and mechanical characterization showed that the moisture content, specific gravity, water absorption, ultimate tensile strength (UTS), and elongation at break of the examined biodegradable pots increased with increasing sodium alginate content. Biopot-3 with 15% sodium alginate exhibited the highest UTS at 1.29 MPa and elongation at break at 6.77%. FTIR spectra in the 400-4000 cm^{-1} region showed that all examined biodegradable pots exhibited identical spectra which most of the peaks showed the characteristics of cellulose, hemicellulose, and alginate. While, XRD patterns showed that the biodegradable pot material has an amorphous structure with 2θ angles being 21.69º, 22.01º, and 22.03º, respectively. Surface morphology analysis by SEM revealed that Biopot-1 containing 5% sodium alginate (the lowest sodium alginate content) exhibited many porous cavities, indicating that the matrix could not completely fill the space between the fibers. It contrasts with Biopot-2 and Biopot-3 (10% and 15% sodium alginate, respectively), which have a morphology with a denser surface. In general, the produced biodegradable pots exhibited adequate functional properties as ecologically friendly planting containers, but further research is required to investigate their field applicability.

Keywords: agroplastic; biocomposite; biopot; cellulose; thermopressing.

GRAPHICAL ABSTRACT



INTRODUCTION

Plastic waste, including agro-plastics such as pots and polybags, has been the most severe environmental problem due to their resistant to decomposition by natural processes [1,2]. Organic materials based-planting containers or biodegradable pots are alternatives to answer the issues. Moreover, biodegradable pots (biopots) are not harmful to the plant roots because they can be transferred directly from the nursery to the plantation without disassembly [3–10]. Various high fiber biomass, such as coconut frond and fiber, wood fiber, paddy husk and straw, mushroom substrates, banana peel, and also cow manure have been studied as reinforcing substances in the production of biopots [3,4,11–15]. Oil palm empty fruit bunch (OPEFB) is one of the interesting and potential material for biopot reinforcement due to its high content of fibers (72%).

As the world's largest palm oil producer, Indonesia produce more than 50 million tons of crude palm oil (CPO) in 2020 and simultaneously generates the same amount of OPEFB as the waste of the CPO production process [16,17]. Comparing to other biomass, OPEFB seems to have a good potential to be utilized as reinforcing material in the production of planting container due to its abundance, low price, and high fiber content. OPEFB has been reported to contains good nutrient composition that potential to be used for improvement of soil structure and reduction of the uses of chemical fertilizers [17–20]. Investigation on the physical and mechanical performance of biopots reinforced with OPEFB has not been performed.

Physical and mechanical properties of biopots are determined by the reinforcement materials and also the matrix. Many natural and synthetic polymers have been used as matrix in the biopot production such as cassava starch, formaldehyde copolymer, polyethylene glycol, polyhydroxy butyrate, paraffin wax, and sodium alginate [4,5,7,9,21–23]. Sodium alginate has been reported to have appropriate properties as a polymeric matrix because of its abundance, effectiveness in the gel formation, good mechanical performance, and affordable price [4,24]. This study was aimed to investigate the effects of the application of OPEFB as the reinforcement and various concentration of sodium alginate matrix on the physical, mechanical, structural, and morphological characteristics of the biopots.

MATERIAL AND METHODS

Material Preparation

The material used in this research was Oil Palm Empty Fruit Bunches (OPEFB). OPEFB waste was collected from the Palm Oil Processing Plant in Pelaihari, Indonesia. The material was crushed and sun-dried for 2-3 days to produce OPEFB with a moisture content below 10%. The material was then homogenized in size with a sieve (25 mesh). To get early information regarding the OPEFB material, lipid content, moisture content, and lignocellulose content were analyzed. In the production of biopots, sodium alginate was employed as a matrix that also acts as an adhesive. Prior to use, sodium alginate was combined with distilled water and agitated until a homogenous gel formed.

Production of Biodegradable Pot

Sodium alginate was dissolved in 50 mL of distilled water and stirred for 5 min to form a homogeneous gel. The OPEFB material (10 g) and glycerol (0.5 g) was then added to the adhesive solution and homogenized with a stirrer to create a ready-to-mold paste. Sodium alginate was employed at concentrations of 5% (Biopot-1), 10% (Biopot-2), and 20% (Biopot-3) of the weight of the OPEFB. The formulation of the biopot was put into an iron mold designed to resemble the desired shape of the pot with an upper diameter of 9 cm, a bottom diameter of 6 cm, and a height of 7 cm. The thermopressing process was employed to mold at a temperature of 150°C for 5 min. Biopot was removed from the mold and stored in a dry container.

Physical Characterization

Moisture Content

The empty cup was dried for 15 min at 105°C, cooled in a desiccator, and weighed (W_2). The weight of the biopot specimen was measured (W) and then put into the cup. Following that, the specimen was placed in a 105°C oven for 4 hours or until the weight remained steady. The cup containing the sample was cooled in a desiccator and then weighed (W_1). The moisture was calculated using the following formula.

$$\boldsymbol{Moisture} = \frac{\boldsymbol{W-(W_1-W_2)}}{\boldsymbol{W}} \times \mathbf{100}\% \quad (1)$$

Water Absorption

Biopot dry specimens were weighed and marked as W_0. The specimens were then immersed in distilled water for 15 and 30 min at room temperature and weighed. The excess water on the specimen's surface was gently wiped away with a damp cloth/tissue before weighing. W_t represented the weight after immersion. Each of these treatments was repeated three times, and the average results were used to determine the water adsorption value (Q) using the equation below:

$$\boldsymbol{Q} = \frac{\boldsymbol{W_{H_2O}}}{\boldsymbol{W_0}} \times \mathbf{100}\% \quad (2)$$

Note; $W_{H_2O} = W_t - W_0$
$W_{H_2O} = Weight\ of\ water\ absorbed$

Density

The biopot specimens were prepared to a size of 20 mm × 30 mm. Their thickness was measured with a micrometer screw. Volume was calculated by multiplying the area and thickness of the specimen. Furthermore, the specimen was dried in an oven, weighed (W), and measured its density (d) using the following equation:

$$\boldsymbol{d} = \frac{\boldsymbol{W}}{\boldsymbol{V}} \quad (3)$$

Colorimetric Analysis

A colorimeter (CR-400 Konica Minolta, Japan) was used to determine the color of the biopot. The *CIELab* color system (*L** (a lightness factor); *a** (redness factor); and *b** (yellowness factor) was used to determine the color difference between biopot samples of various compositions.

Contact Angle Analysis

Contact angle analysis using plug-in drop analysis was used to determine the hydrophobicity of biopot specimens. Furthermore, the contact angle and hydrophobicity were determined. The instrument used in this test is a contact angle goniometer (Dataphysic Instrument, TBU 100).

Mechanical Characterization

Mechanical characteristics of biopot were investigated through the tensile test. Tensile strength, elongation at break, and other tensile properties are critical indicators of a biopot's performance and quality [25]. The test was carried out with three replications using prepared specimens of the biopot (25 mm ×30 mm) with a 2 mm/min extension rate. The following formulas were used to determine the tensile characteristics of the biopots:

$$\boldsymbol{Tensile\ strength} = \boldsymbol{stress} = \frac{\boldsymbol{F}}{\boldsymbol{A}} \tag{4}$$

$$\boldsymbol{Elongation}\ (\%) = \boldsymbol{strain} = \frac{\Delta \boldsymbol{L}}{\boldsymbol{L_0}} \times \ \mathbf{100}\ \% \tag{5}$$

Note; *F = Force; A = cross-sectional area;* ΔL *= length extension;* L_0 *= initial length*

Structural and Morphological Characterization

Fourier Transform Infra-Red (FTIR) Analysis

The functional groups of the chemical components in the biopot composite mixture were qualitatively analyzed using FTIR. The samples were dried, pulverized, and pelletized with KBr before being examined by FTIR using the Shimadzu IR Prestige 21 instrument. Spectra were obtained in the wavelength range of 4000-600 cm^{-1} with 40 scans at a resolution of 4 cm^{-1}.

X-ray Diffraction (XRD) Analysis

X-ray Diffraction (XRD) analysis aimed to identify the crystalline phase in the biopot sample. The test was carried out with the X-ray Diffractometer PANAanalytical-E'xpert Pro equipped with High Score Plus Software. The instrument was run with a Cu radiation source at a range of 2θ from 10º to 90º.

Scanning Electron Microscopy (SEM) Analysis

SEM analysis using the FEI Inspect-S50 SEM instrument was used to determine the surface of the biopot sample microscopically, which includes the material's surface topography and appearance. Micrographs obtained with magnifications of 2500×.

RESULTS AND DISCUSSION

OPEFB was the primary material used in the production of biopots. Drying, refining, and size sorting were carried out at this initial stage to obtain OPEFB fibers with homogeneous sizes. Additionally, OPEFB fiber was tested for moisture, lipid, and lignocellulose content in order to acquire uniform and suitable raw materials. Table 1 showed the initial characteristics of OPEFB material which were then used for further study.

In this study, biopots were made by combining OPEFB natural fiber with sodium alginate. In this mixture, the fiber functions as a reinforcement, while the sodium alginate acts as a matrix and adhesive. A total of 10 g of OPEFB was mixed with sodium alginate with variations of 5%, 10%, and 15% and then formed using the thermopressing method at a temperature of 150°C for 5 min. The thermopressing process was chosen due to its simple technology, ease of use, and timeliness of application [26]. Figure 1 shows the biopots produced using this method.

Table 1. Physical and chemical characteristics of OPEFB fiber used in biopot production.

Parameters	Value
Moisture (%)	8.83±0.35
Lipid content (%)	4.11±0.80
Fiber length (mm)	10-15
Fiber size (µm)	≤ 710
Hemicellulose content (%)	32.00±1.88
Cellulose content (%)	41.35±1.64
Lignin content (%)	16.07±2.04

Figure 1. Physical appearance of the produced biopots - Biopot-1 (5% sodium alginate); Biopot-2 (10% sodium alginate); Biopot-3 (15% sodium alginate).

Furthermore, biopots were characterized to determine their suitability for use as an alternative planting container. Comprehensive characterization of biopots was then performed, including physical, mechanical, structural (chemical), and morphological characterization.

Physical Characteristics

Moisture content, water absorption, density, colorimetric and contact angle were the physical properties examined in this study. The moisture analysis revealed that the more sodium alginate in the biopot, the higher the moisture. Biopot-3 containing 15% sodium alginate showed the highest moisture of 8.18%. Meanwhile, Biopot-1 containing 5% sodium alginate showed the lowest moisture of 6.81% (Table 2). It is critical to understand the moisture of biopots in order to predict their susceptibility to damage caused by organisms such as bacteria and fungi, particularly during storage [12,27,28]. On the other hand, the moisture of biopots could be allowed because it will contact with water while watering or when transferred to the soil in agricultural application.

Table 2. Physical properties of the examined biopots

Treatment	Parameters			
	Density (g/cm^3)	Moisture (%)	Water Absorption (%)	
			15 min water immersion	30 min water immersion
Biopot-1	0.177±0.039	6.81±0.35	146.88±22.32	300.87±49.57
Biopot-2	0.230±0.021	7.29±0.06	157.06±11.37	305.15±16.78
Biopot-3	0.264±0.024	8.18±0.19	236.74±22.58	401.80±38.06

The water absorption test was used to ascertain the specimen's interaction with the water. The application of biopots for planting containers will undoubtedly contact with water molecules in the environment. The material was immersed in distilled water for 15 and 30 min to determine its water absorption capacity. Biopot's specimens with higher sodium alginate concentrations had higher water absorption than specimens with lower sodium alginate concentrations. Biopot-3 with 15% sodium alginate content showed highest water absorption of 236.74% at 15 min of immersion and 401.80% at 30 min of immersion, respectively. While, Biopot-1 containing 5% sodium alginate showed the lowest water absorption of 146.88% at 15 min of immersion and 300.87% at 30 min of immersion (Table 2). This finding is almost the same as the water absorption capacity of biopot made of tomato, hemp fiber, and cow manure which showed values of 190 % and 476% [4,15]. The longer it is immersed, the higher the moisture in the biopot. The water absorption capacity of the biopot is determined by the constituent materials and is closely related to the porosity and density of the biopot [15]. On the other hand, the ability to absorb water could also be an advantages to biopot, since it can be employed as a water reservoir when used in agricultural application [6].

Another physical property observed in this study was density. Density indicates the compactness of the biopot's ingredients. Density values are strongly dependant on fiber density and the degree of compression used during processing. In general, fiber composites have a relatively low density [3,4,9]. Biopots made of OPEFB with sodium alginate had a density of 0.177–0.264 g/cm^3 (Table 2). The higher the sodium alginate level, the higher the density, as alginate works as both a matrix and an adhesive in the mixture [4]. Due to the high concentration of sodium alginate, the component materials' cohesiveness is increased, resulting in an increase in density. When compared with similar products from previous studies made from waste of tomato-hemp fibers [4] and straw fibres [9] as raw materials, which showed densities of 0.43 g/cm3 and 0.81 g/cm3, respectively, the biopots produced from this research were lighter, so that expected to be simpler in transportation and storage.

Colorimetric analysis was carried out to see the difference in the color and appearance of each biopots, as done in several studies [29,30]. Color values were expressed in lightness (*L*), redness (*a*), and yellowness (*b*) measured using a colorimeter. The lightness (*L*) of the combination tends to increase as the sodium alginate concentration in the mixture increases. Meanwhile, Yellowness (*b*) tends to decrease with the increasing concentration of sodium alginate. Similarly, as the concentration of alginate in the mixture increases, the redness (a) decreases slightly. The color of biopots is determined by two critical factors: the composition and the heating technique during thermopressing.

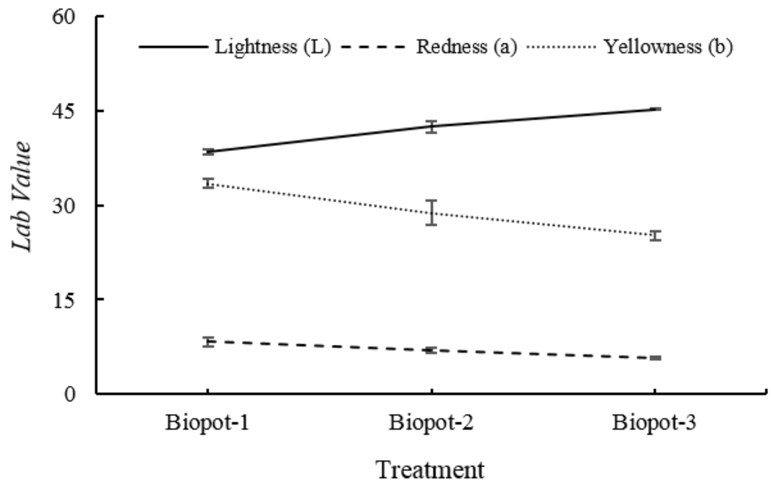


Figure 2. Colorimetric value of the tested biopots.

Another physical property analyzed in this study was the contact angle. In principle, the contact angle indicates the surface's wettability. Hydrophilic liquids have a contact angle of less than 90° with the solid surface, whereas hydrophobic (non-wetting) liquids have a contact angle of 90-180°. In this study, the contact angle of the examined biopot ranged from 81.67-103.72°. Biopot-3, which contained 15% sodium alginate, was hydrophilic based on the contact angle value, whereas Biopot-1 and Biopot-2 were classified as hydrophobic (non-wetting). The contact angle is further influenced by the material's porosity, roughness, and heterogeneity of the surface topography.

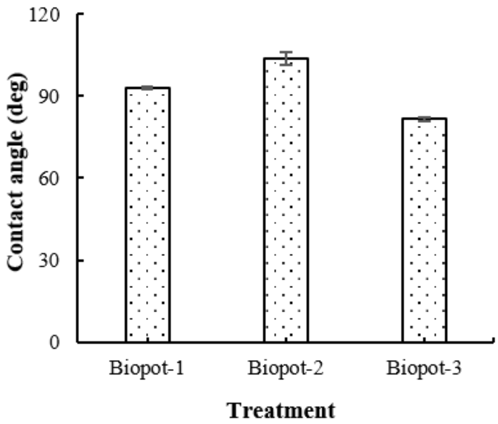


Figure 3. Contact angle of the examined biopots.

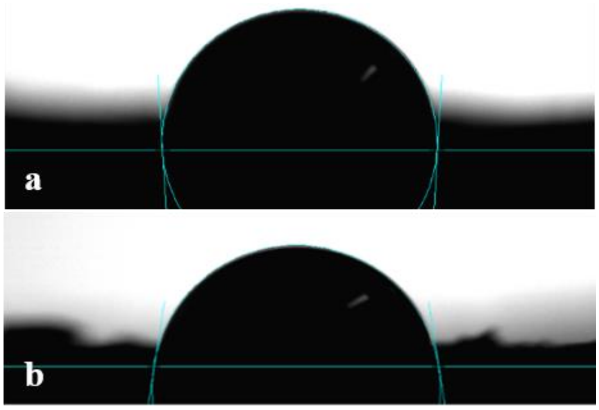


Figure 4. Contact angle of Biopot-3 with hydrophobic angle of <90º (a) and Biopot-2 with hydrophilic angle of >90º (b).

Mechanical characteristics

Mechanical characteristics of biopot were investigated through tensile test. Tensile properties are critical characteristics of biopots. The tensile properties studied were ultimate tensile strength (UTS), elongation at break, and stress-strain curve. UTS is the maximum stress that a specimen can withstand when stretched. Biopot-1, Biopot-2 and Biopot-3 had a UTS value of between 0.617 and 1.290 MPa. Increasing the sodium alginate content resulted in a rise in the biopot's UTS value. This value is almost similar to that of biopots originating from wood fiber of 0.1 M.Pa [15]; tomatoes and hemp fiber of 0.46 MPa [4]. In several studies, adding plasticizers such as polyester and polyethylene glycol to the biopots resulted in higher UTS values as shown in previous studies [22,25].

The elongation value ranged between 4.79% and 6.77% during cracking, with the maximum value occurring at Biopot-3. The relationship between tensile strength and elongation is illustrated on a stress-strain graph that showed a similar pattern for all biopots. When the curve reaches the peak point (UTS), there is a decrease in stress due to cracks in the test specimen. In general, all test specimens exhibited the same pattern, with a broad peak indicating that the test specimen was elastic (ductile fracture), as opposed to non-elastic specimens, which had sharper peaks (Figure 6) [15].

The performances of the biopots were relatively better compared to other related or similar products of the previous research, such as biopot, biocontainer, and green polybag [3,4,9,15,22]. Table 3 shows the comparison of the physical and mechanical properties of the tested biopots with other related products. As shown, the tested biopots were better in three parameters of biopot quality (water adsorption, density, and tensile strength).

The biopot is also economically reliable because of its low production cost, either the material price or the processing cost. OPEFB is the waste of CPO production process and generally worthless. Sodium alginate is also can be obtained at the affordable price and it is only used in a small quantity of around 1 g for each single biopot. In addition, in term of time efficiency, thermopressing method is more preferable than the cold process which takes up to 3 days [4,31,32]. This is essential in efforts to save the storage space and working hour.

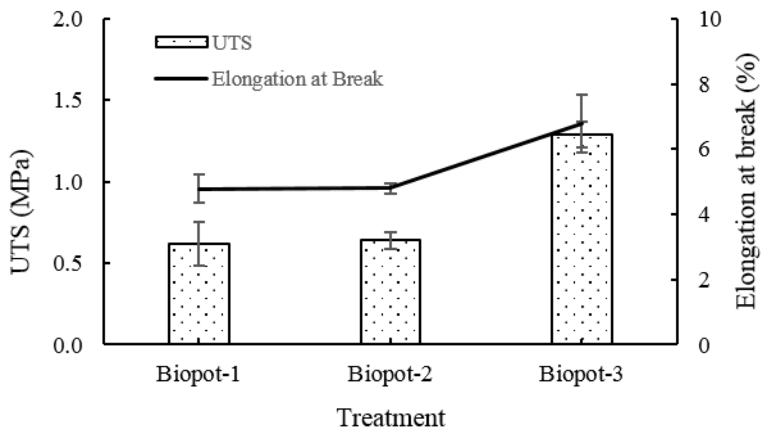


Figure 5. Ultimate tensile strength (UTS) and elongation at break of the examined biopots.

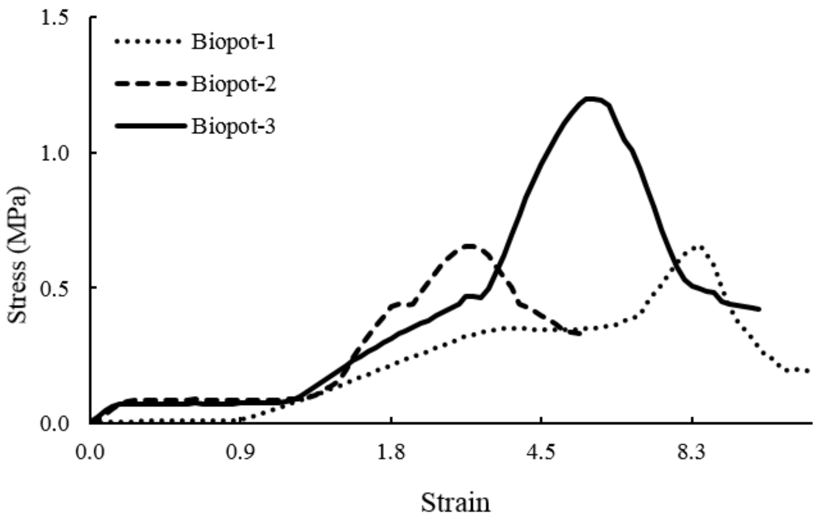


Figure 6. Curve of stress-strain of the examined biopots.

Table 3. Comparison of the physical and mechanical properties of the tested biopots with other related products

Parameter	Raw materials	Value	Ref.
Water adsorption (%)	OPEFB	146.88	Research data
	Tomato waste Hemp fibers	190.00	[4]
	Cow manure	476.00	[15]
Density (g/cm^3)	OPEFB	0.18	Research data
	Tomato waste Hemp fibers	0.43	[4]
	Straw	0.81	[15]
Tensile strength (MPa)	OPEFB	1.30	Research data
	Tomato waste Hemp fibers	0.46	[4]
	Wood fibers	0,10	[15]
Elongation at break (%)	OPEFB	6.77	Research data
	Protein Hydrolysate-PEG-Wood Flour	1.00	[22]
	Biodegradable Polyester Plant fibers	48.70	[25]

Structural and Morphological Characteristics

FTIR spectra

The FTIR test was performed to understand about the chemical linkages found in the biopot sample, which the different peaks indicate the typical chemical bonds. A biopot is a composite consisting of OPEFB fiber as reinforcement and sodium alginate as a matrix. The results showed that the spectra of Biopot-1, Biopot-2, and Biopot -3 were similar. Most of the peaks showed the characteristics of cellulose, hemicellulose, and alginate. Only the transmittance intensity was slightly different at certain peaks, indicated the difference in quantity of each functional groups. The infrared spectrum revealed a strong broad absorption band at 3321 and 3344 cm^{-1}. It indicated the presence of stretching OH groups in cellulose and alginate compounds, which are associated with a high number of hydrogen bonds. Absorption bands at wavelengths 2945, 2943, and 2941 cm^{-1} were asymmetric stretching of CH, CH_2, and CH_3 (methylene and methyl group) in cellulose. The absorption bands at 1168 and 1166 cm^{-1} indicated the presence of C-O-C stretching vibration in cellulose and alginate. Similarly, the bands at 820 and 817 cm^{-1} showed a C-H deformation of the *β*-(1,4) glycosidic linkage in cellulose, as well as a C-H deformation of the linkage in alginate [30,33].

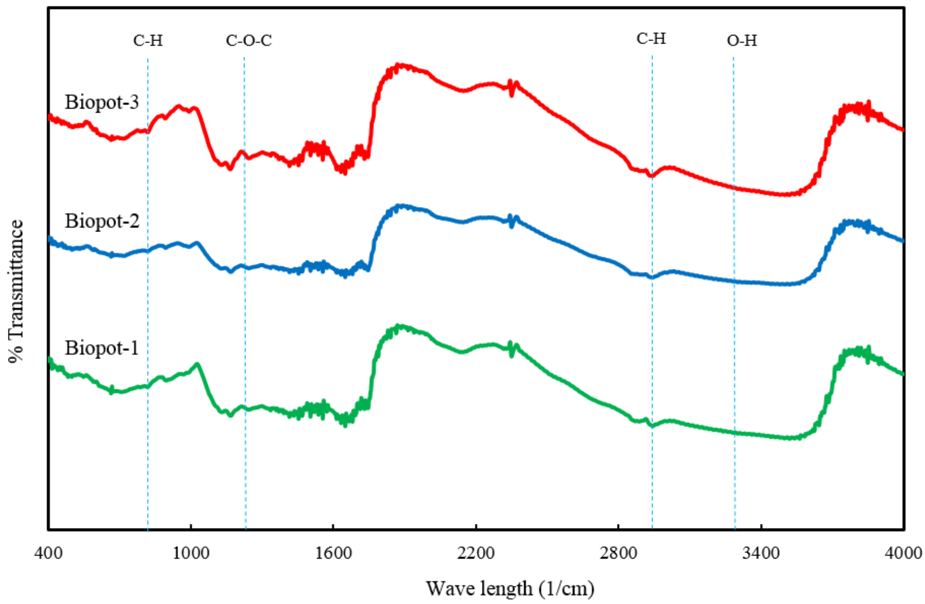


Figure 7. FTIR Spectra of the examined biopots.

X-ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) analysis was aimed to identify the crystalline phase in the biopot from OPEFB with the different content of sodium alginate. Diffraction patterns of Biopot-1, Biopot-2 and Biopot-3 can be seen in Figure 8, showing that the biopot material has an amorphous structure with 2θ angles being 21.69º, 22.01º and 22.03º, respectively. The peak intensity of the tested biopot showed a slight increase with increasing sodium alginate [($C_6H_7NaO_6$)n] in samples. Lignocellulosic fiber and sodium alginate are the main constituents of the biopots. Those materials are organic that naturally are irregular (amorphous) [34–38]. This condition will affect the results of the XRD analysis of the biopots which are also amorphous as indicated by the absence of crystalline peaks.

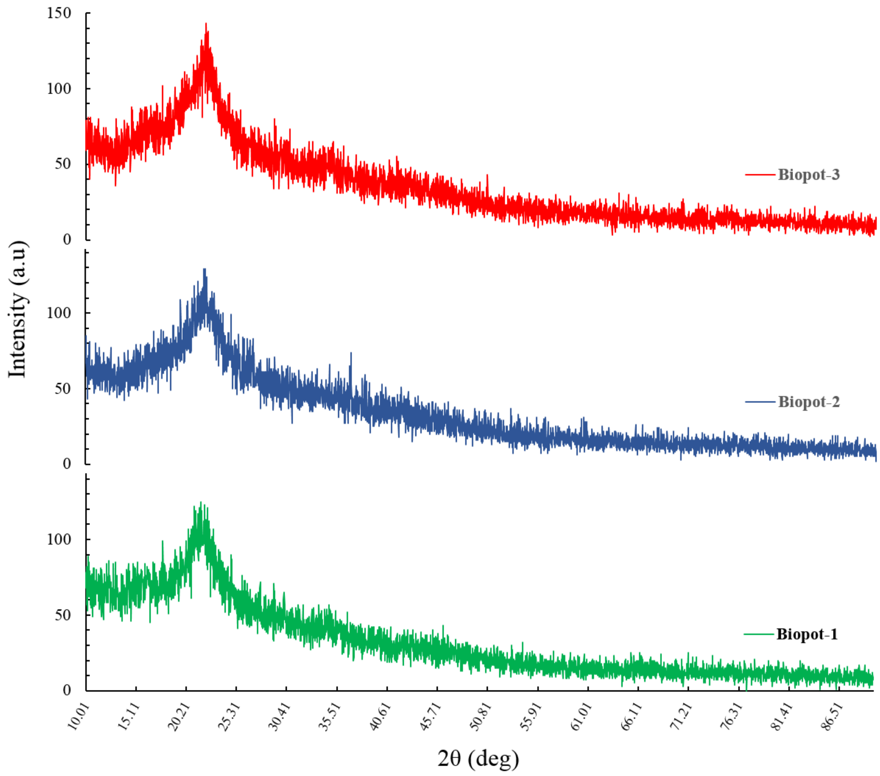


Figure 8. X-ray diffractogram of the examined biopots.

Scanning Electron Microscope (SEM)

The morphology of the biopot, which was composed of fiber and sodium alginate, was examined using SEM analysis. On the surface of the Biopot-1 containing 5% sodium alginate (the smallest sodium alginate content), several porous cavities formed, indicating that the matrix could not completely fill the space between the fibers. It contrasts with Biopot-2 and Biopot-3, which contain higher sodium alginate (10% and 15% sodium alginate), showing denser morphology. A sodium alginate matrix strongly influences the level of porosity of the biopot. Additionally, biopots containing a higher concentration of sodium alginate (Biopot-3) had a smoother surface than biopots containing a lower concentration of sodium alginate (Biopot-1). The matrix acts as a filler, transferring tension to the fiber, forming a coherent link between the fiber and matrix surface, and protecting the fiber.

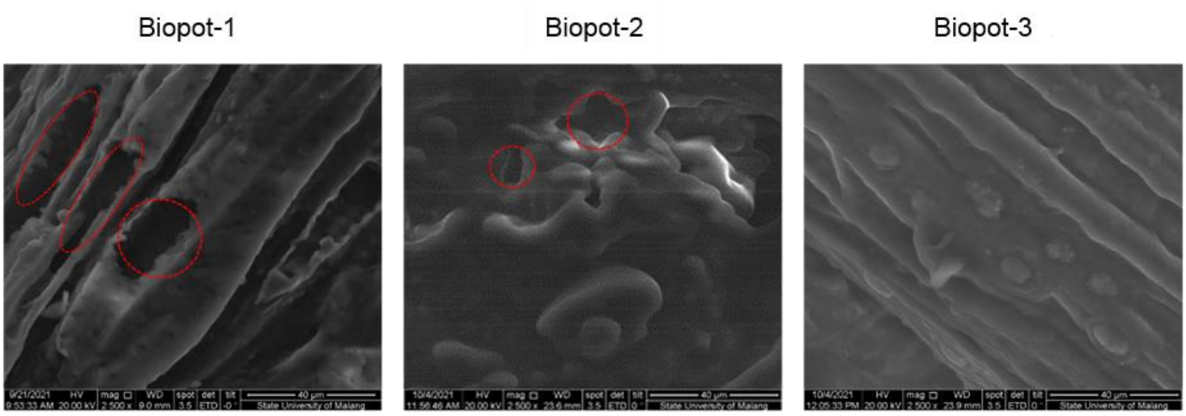


Figure 9. SEM micrograph of the examined biopots with 2500x magnification.

CONCLUSION

Biopots made of oil palm empty fruit bunches (OPEFB) and sodium alginate have the potential to be an environmentally friendly alternative to conventional planting containers. The quality of biopots is determined by product characteristics such as the material's physical, mechanical, structural (chemical), and morphological properties. The final characteristics of the biopot are primarily determined by the type of filler and matrix used, and this study used OPEFB and sodium alginate. The development and application of biodegradable containers are intended to be a novel method to achieve the sustainable agricultural objective of balancing productivity and environmental concerns.

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Conflicts of Interest: The authors declare no conflict of interest.

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