Development and Characterization of Eco-Friendly Bioplastics from Saba (*Musa acuminata x balbisiana*) Peel Starch Reinforced with Alkali-treated Pineapple Leaf Fiber (PALF)

Glenn D. Ongayo and Abegail L. Ulep*
Department of Chemistry
University of Science and Technology of Southern Philippines
Cagayan de Oro City, 9000 Philippines
**ulep.abegail@gmail.com*

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Abstract

This study aimed to develop a bioplastic using saba peel starch, reinforced with alkali-treated pineapple leaf fiber (PALF). The saba peel starch was obtained through blending, filtering, settling, decanting, and oven-drying. PALF was extracted from pineapple leaves and treated with a 6% sodium hydroxide solution. The bioplastic was developed by heating, casting, and oven-drying a mixture of starch, glycerol (20%, 30%, 40% w/w), alkali-treated PALF (10%, 20%, 30% w/w), and water. The bioplastic's surface contact angle, tensile strength, and biodegradability were evaluated, and FTIR analysis was conducted on the sample with the highest tensile strength. The samples displayed distinct surface textures, with surface contact angles ranging from 39.3° to 88.3° for smooth surfaces and 23.3° to 86.5° for rough surfaces, The best-performing sample, BP-5, which had 30% w/w glycerol and 20% w/w alkali-treated PALF filler, achieved contact angles of 88.3° and 86.5° for smooth and rough surfaces, respectively. For tensile strength, values ranged from 2.67 to 8.17 MPa, with BP-3, containing 20% w/w glycerol and 30% w/w alkali-treated PALF, exhibiting the highest strength of 8.17 MPa. For the soil biodegradation test, weight loss ranged from 36.3% to 68.1% after ten days, with BP-1, which included 20% w/w glycerol and 10% w/w alkali-treated PALF, showing the highest biodegradability at 68.1%. All samples were fully degraded within twenty days. FTIR analysis revealed the presence -OH, -CH, C-O, and -OH (bending of water) functional groups. These results suggest that bioplastic is well-suited for various applications, including packaging, single-use containers, and potentially drinking straws.

***Keywords**:* agricultural waste, bioplastic, glycerol, pineapple leaf fiber, saba peel starch

1. Introduction

Plastic, primarily derived from crude oil and gas, has been widely used for various applications over the past century. The growing global population has increased plastic consumption and production, reaching 367 million metric tons in 2020 (Errera, 2022). Conventional plastics, composed of polymers like ethylene, propylene, vinyl chloride, and styrene, decompose very slowly because natural enzymes do not easily break down their chemical bonds. As a result, plastic waste has accumulated significantly, with individuals generating between 69 and 221 kg of plastic waste per year, but only 9% of it is recycled, and 22% is mismanaged (Organization for Economic Co-operation and Development [OECD], 2022). Plastic pollution is a major environmental issue, particularly affecting the oceans, where about 11 million metric tons of plastic waste enter annually, disrupting marine ecosystems and causing irreversible harm to marine life (Ocean Conservancy). Moreover, studies have shown that plastic degradation contributes to ocean acidification (Romera-Castillo *et al*., 2023). Plastic pollution is expected to worsen, but eliminating plastic use is impractical due to its essential role in numerous applications. Therefore, alternatives to non-biodegradable plastics, such as bioplastics made from renewable biomass, are needed to reduce its production and consumption. Starch, a natural biopolymer made of amylose and amylopectin, is the most common source of bioplastic production, offering a lower consumption of non-renewable resources than conventional plastics. However, using food crops like corn, cassava, wheat, rice, and potatoes for starch extraction raises concerns about competition for food supplies and arable land. To address this, recent studies have focused on using agricultural waste, such as banana peels, as a sustainable source of starch (Bunag *et al*., 2017; Gaonkar *et al*., 2017; Getnet, 2019; Kanesen *et al*., 2016; Sofiah *et al*., 2019). Saba banana peels (*Musa acuminata x balbisiana*) are particularly abundant and cost-efficient, often discarded without proper disposal in local markets, making them a viable raw material for bioplastic production.

The other key components in bioplastic production are the bioplastic additives, plasticizer, and filler. A plasticizer is a substance added to promote plasticity and flexibility. Glycerol, one of the most commonly used plasticizers, is known for its high plasticizing capability, thermal stability, and excellent biodegradability (Inayati *et al.*, 2019). Due to its compatibility with starch-based polymers was selected as a plasticizer for the saba starch bioplastic. On the other hand, fillers are materials added to composites to change or enhance the composite's properties. Natural fibers are fillers that are typically used to

reinforce starch-based bioplastics. Pineapple leaf fibers (PALF) were selected as filler for this study due to their excellent mechanical properties and availability in the locality.

The general objective of this study was to produce bioplastic using starch extracted from saba banana peels, reinforced with alkali-treated pineapple leaf fiber (PALF), and to characterize the produced bioplastic. The specific objectives were to: extract starch from saba peels and determine its percent yield (1); identify the concentration of glycerol (20%, 30%, and 40% w/v starch basis) and PALF (10%, 20%, and 30% w/w thermoplastic starch basis) that yields a bioplastic with optimal physical properties regarding its surface contact angle and tensile strength (2); determine the concentration of glycerol (20%, 30%, and 40% w/v starch basis) and PALF (10%, 20%, and 30% w/w thermoplastic starch basis) that results in a bioplastic with the best chemical properties related to its biodegradability (3); and identify the functional groups present in the bioplastic sample that exhibits the highest tensile strength (4).

2. Methodology

2.1 Extraction of Starch from Musa acuminata x balbisiana (BBB Group) Peels

The extraction of starch was performed according to the method proposed by Chávez-Salazar *et al*. (2017) with slight modifications. Three hundred grams of banana peels were washed and cut into pieces sized 2-3 cm^2. These pieces were then added to a solution containing 1.5 grams of sodium bisulfite and 500 mL of water. After immersing for 15 minutes, the mixture was homogenized using a blender at low speed for 2 minutes. The resulting homogenate was filtered through a 200-mesh sieve and washed repeatedly until the rinse water ran clear. Subsequently, the starch was allowed to settle from the filtrate for about thirty minutes. The crude starch was separated from the supernatant by decantation. The collected starch was washed with distilled water and dried in a convection oven for six hours at 50°C. Finally, the dried starch was ground into a fine powder using a mortar and pestle.

2.1.1 Percent Yield

The determination of the percent yield of extracted starch was calculated using Equation 1:

$$Yield(\%) = \frac{mass\ of\ starch\ (g)}{mass\ of\ dray\ banana\ peels\ (g)} \times 100 \quad (1)$$

2.1.2 FTIR Analysis

The spectrum for the extracted starch from saba peels was determined using the spectrophotometer (IR Tracer 100, Shimadzu, United States of America). A small portion of the sample was scooped and placed on the ATR (Attenuated Total Reflectance) built into the equipment. Pressure was then applied to ensure the contact between the powdered samples and the ATR.

2.2 Preparation of Alkali-treated Pineapple Leaf Fiber (PALF)

The collected pineapple leaves were washed under running water to remove the dirt and were blot-dried. After cleaning, the pineapple leaves were cut into thin strips. These pineapple leaf strips were soaked in water for 48 hours to soften the leaves and facilitate fiber extraction. After this, the pineapple leaf strips were scraped with a metal scraper to extract the fiber. These extracted fibers were dried in an oven for 24 hours. The dried fibers were immersed in a 6% NaOH solution for 3 hours. The NaOH solution was made by dissolving 60 g of NaOH pellets in 1 L of distilled water. After the immersion, the PALF was rinsed off with distilled water until pH seven was reached. Then, the fibers were dried for 24 hours at 60°C. The dried modified PALF was cut into 1-3 mm-sized pieces (Gaba *et al*., 2021; Zin *et al*., 2018).

2.3 Production and Characterization of Bioplastic Films

The bioplastic films were prepared following the method proposed by Getnet (2019) with some modifications. The film-forming dispersion was prepared by mixing 5 g of extracted banana peel starch with 100 mL of distilled water, 3 mL of 0.1 M HCl, and 3 mL of 0.1 M NaOH in a 250 mL beaker. Glycerol (20%, 30%, and 40% w/w starch basis) was also added to the beaker, followed by the alkali-treated PALF (10%, 20%, and 30% w/w thermoplastic starch basis). The dispersion was magnetically stirred at 90°C for 30 minutes until it became gelatinized. Then, it was cooled to 50°C before it was cast on an acrylic sheet. Afterwards, the mixture was dried in an oven for 8 hours at 65°C.

Finally, the bioplastic film was peeled off the sheet, cooled, and stored at room temperature inside polyethylene bags for further analysis.

2.3.1 Surface Contact Angle

The wettability of the bioplastic films was determined by measuring the water contact angle on the flat surface of the films. An amount of 10 µL of water was dropped onto the surface of the samples at room temperature. With the use of a digital microscope, the image of the drop was captured. The images were opened with ImageJ, and the contact angles were determined using the drop analysis plugin, specifically, LB-ADSA (Low Bond Axisymmetric Drop Shape Analysis). The LB-ADSA plugin is interactive using five variables; *b* (base), *x* (horizontal position), *y* (vertical position), *h* (height), and *d* (reflection height) to manipulate a green Young-Laplace drop shape that is superimposed upon the drop image (Lamour *et al*., 2010; Williams *et al*., 2010).

2.3.2 Tensile Strength Test

The tensile strength of the bioplastic films was tested according to ASTM D638-10 standard parameters using a Universal Testing Machine (Shimadzu Autograph AGS-X series). The samples were cut into a dog bone or dumbbell shape. The test was carried out by drawing the sample from two directions so that the length increases and the diameter shrinks (Intertek, n.d). The tensile strength was calculated using Equation 2:

$$T = \frac{F}{S} \tag{2}$$

where F is the maximum ultimate breaking force, and S is the cross-sectional area.

2.3.3 Biodegradation Test (Soil Burial Test Method)

The biodegradation of the bioplastic films was determined following the method described by Vaithanomsat *et al*. (2021) with some modifications. The films were cut into 2.5 x 2.5 cm-sized pieces. The initial weight of each sample was then determined. Three replicates for each sample were buried in compost soil at a 4 cm depth in a plastic box and left for 30 days. Distilled water was added to the soil in an adequate amount to ensure sufficient moisture during the test. After every 10 days, the samples were removed from the soil, brushed

softly, and washed several times with distilled water. Then, they were dried at 50°C. The final weight was determined after drying. Soil biodegradability was determined by calculating weight loss using Equation 3:

$$Weight\ loss\ (\%) = \frac{W_1 - W_2}{W_1} x100 \quad (3)$$

where w_1 is the initial weight of the bioplastic film, and w_2 is the final weight of the bioplastic film.

2.3.4 FTIR Analysis

The functional groups present in the bioplastic will be determined using a spectrophotometer. A small portion of the bioplastic sample was cut and directly placed on the ATR installed in the spectrometer. Pressure was applied to ensure the contact between the sample and the ATR.

3. Results and Discussion

3.1 Banana Peel Starch

Musa acuminata x balbisiana (saba) peel was chosen as the starch source for this study due to its availability in the local area. Starch extraction was carried out from both ripe (yellow) and unripe (green) saba banana peels, following the method proposed by Chávez-Salazar *et al*. (2017) with some adjustments. The inclusion of both the ripe and unripe peels in the starch yield analysis aimed to demonstrate the significant difference in starch content. The starch yield for both samples is shown in Table 1.

Table 1. Starch percent yield of *Musa acuminata x balbisiana* (saba) peel

	Trial #	Mass of dry peel (g)	Mass of starch (g)	Yield (%)	Average yield (%)
Ripe	1	27.59	1.71	6.20	6.22
	2	27.53	1.85	6.72	
	3	27.57	1.58	5.73	
Unripe	1	20.54	5.25	25.6	25.9
	2	20.51	5.33	26.0	
	3	20.58	5.36	26.0	

The starch yield for ripe banana peels is 6.22% while the unripe banana peels have a starch yield of 25.9%, on a dry basis. The notable difference in starch yield between green and ripe banana peels is attributed to the enzymatic conversion of starch to sugars during the ripening process (Khattak *et al*., 2022). In practical terms, this suggests that for bioplastic production, more ripe peels will be required to extract the same amount of starch as unripe peels. This comparison helps inform the feasibility of using banana peels from different stages of ripeness in bioplastic production, which may vary depending on local availability. The FTIR spectrum of the extracted starch is shown in Figure 1.

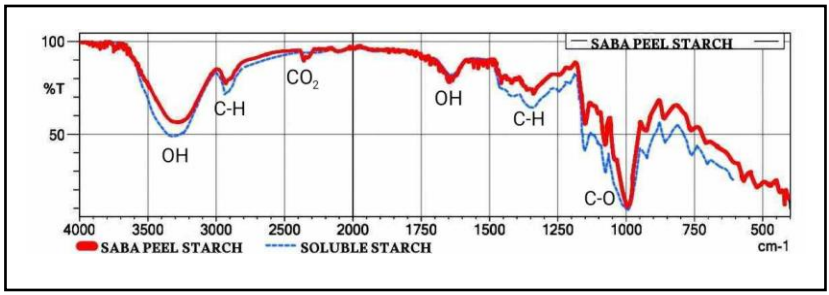


Figure 1. FTIR spectrum of saba peel starch

The absorption band at around 3600-300 cm^{-1} indicates the presence of -OH functional group (Ren *et al*., 2018). The peak at ~2900 cm^{-1} corresponds to C-H functional group. The uncommon peak at ~2350 cm^{-1} indicates the presence of CO_2, which might result from measuring conditions. (Abdullah *et al*., 2018). The peak at ~1150 cm-1 indicates the presence of C-O-C functional group and the band at 1100-900 cm-1 indicates the presence of C-O functional group (Johari and Sultan, 2017).

3.2 Bioplastic

The bioplastic films were synthesized using the starch extracted from *Musa acuminata x balbisiana* (saba) peels, plasticized with glycerol and reinforced with alkali-treated pineapple leaf fiber filler. Each sample contained different amounts and combinations of plasticizers and fillers; however, the amount of starch was kept constant for all samples.

The synthesized bioplastics were subjected to preliminary analyses through visual and tangible inspection. The results are shown in Table 2.

Table 2. The physical characteristics of developed bioplastics

Sample Code	Sample Mixture	Color	Optical Property
GC-20	BPS, 20%G, Control	Light Brown	Transparent
GC-30	BPS, 30%G, Control	Light Brown	Transparent
GC-40	BPS, 40%G, Control	Light Brown	Transparent
BP-1	BPS, 20%G, 10% PALF	Light Brown	Transparent
BP-2	BPS, 20%G, 20% PALF	Light Brown	Transparent
BP-3	BPS, 20%G, 30% PALF	Light Brown	Translucent
BP-4	BPS, 30%G, 10% PALF	Light Brown	Transparent
BP-5	BPS, 30%G, 20% PALF	Light Brown	Transparent
BP-6	BPS, 30%G, 30% PALF	Light Brown	Translucent
BP-7	BPS, 40%G, 10% PALF	Light Brown	Transparent
BP-8	BPS, 40%G, 20% PALF	Light Brown	Transparent
BP-9	BPS, 40%G, 30% PALF	Light Brown	Translucent

**Note: BPS- Banana Peel Starch; %G- Glycerol Concentration (%w/w starch basis); %PALF- Pineapple Leaf Fiber Concentration (%w/w thermoplastic starch basis); BP-Bioplastic; GC-Glycerol Concentration*

The bioplastic samples were observed to possess a light brown color. This coloration aligns with the observed brownish color of other starch-based bioplastics from the following studies: durian seed starch-based bioplastic (Jannah *et al.*, 2021), biodegradable plastic from corn starch and corn husk filler (Azsarinka *et al.*, 2020), and starch-based bioplastic from jackfruit seed (Nguyen *et al*., 2022). Despite the similarity in color, the bioplastic samples exhibited differences in their optical property. As shown in Table 2, samples containing 30% PALF appeared translucent. The translucent appearance can be attributed to the amount of PALF in these samples.

3.2.1 Surface Contact Angle

The measurement of the surface contact angle was carried out to assess the hydrophobicity or hydrophilicity of the developed bioplastics. By examining the angle formed between the surface of the bioplastic and a droplet of water placed on it, the bioplastic's interaction with water molecules can be discerned. A surface contact angle exceeding 90° signifies hydrophobic behavior while an angle less than 90° indicates hydrophilic behavior. The developed bioplastics exhibited contrasting surface textures. The surface in contact with the acrylic sheet is glossy and smooth, while the surface exposed to the air is rough. The difference in textures is shown in Figure 2.

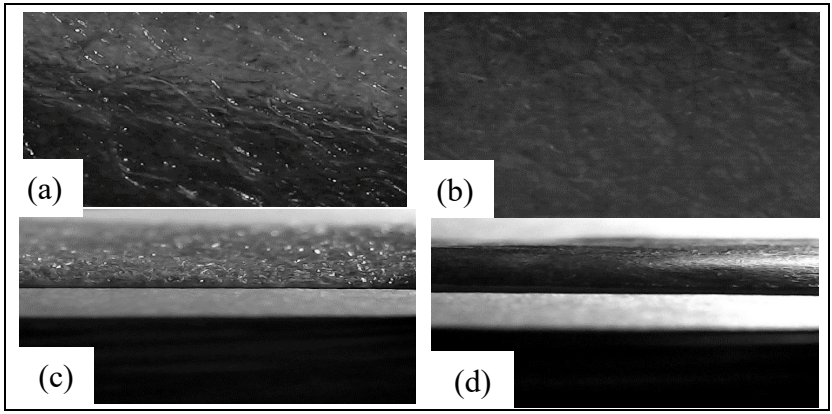


Figure 2. Bioplastic Surfaces: Rough surface-top view (a), Smooth surface-top view (b), Rough surface-side view (c), and Smooth surface-side view (d)

Surface contact angle measurements were conducted for both sides. The summary of results for the surface contact angle of the developed bioplastics is shown in Table 3.

Table 3. Surface Contact Angle

	Smooth Surface		Rough Surface	
Sample Code	Ave. Contact Angle (°)	SD	Ave. Contact Angle (°)	SD
GC-20	74.579	5.332	45.135	0.688
BP-1	75.978	5.500	57.290	4.587
BP-2	81.670	8.363	60.918	5.707
BP-3	84.033	3.875	63.508	2.073
GC-30	48.260	2.119	40.040	1.552
BP-4	48.415	3.594	31.399	2.957
BP-5	88.348	2.342	86.543	1.115
BP-6	56.681	1.770	40.340	9.111
GC-40	36.906	0.575	33.045	2.660
BP-7	39.330	3.161	23.261	1.791
BP-8	41.657	2.221	36.766	2.318
BP-9	53.917	1.743	40.997	0.984

As depicted in the table above, the surface contact angle for both the smooth-textured surface and the rough-textured surface of the bioplastic did not surpass 90°. This observation indicates that all of the developed bioplastics are hydrophilic in nature. Such a result was anticipated, considering the inherent hydrophilicity of the components constituting the bioplastic mixture.

Furthermore, it can be observed that the surface contact angle for the rough-textured surfaces is less than that of the smooth-textured surfaces. This can be attributed to the underlying causes of surface roughness. The rough surface is primarily a result of fiber exposure within the bioplastic matrix. Fibers protruding from the surface increase surface area and alter surface interactions. The presence of exposed fibers facilitates greater interaction with the water molecules, leading to enhanced wetting and reduced contact angle (Boey *et al.*, 2022). The scanning electron microscopy (SEM) analysis could have provided direct visual evidence contributing to this effect; however, such imaging was beyond the scope of this study. Nonetheless, the observed trend is consistent with previous literature that links increased surface roughness and fiber exposure to reduced contact angles.

The influence of the two bioplastic additives on the surface contact angle of the bioplastic was evaluated to understand their effects on the material's hydrophobicity or hydrophilicity. The results are illustrated in the figures presented below, providing a comprehensive view of how each additive impacts the surface characteristics of the bioplastic.

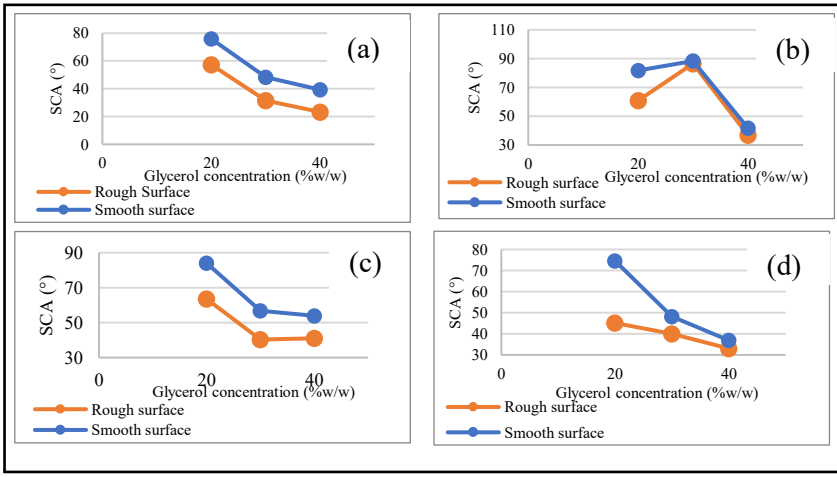


Figure 3. Effect of glycerol: at 10% w/w PALF (a), At 20% w/w PALF (b), at 30 % w/w PALF (c), and at 0% w/w PALF (d)

In Figure 3, the results indicate an overall trend of decreasing contact angle with increasing glycerol concentration. This observation suggests that glycerol enhances the hydrophilic nature of the bioplastic. This phenomenon can be attributed to the hygroscopic properties of glycerol, which promote the absorption of water molecules, leading to increased interactions between the

bioplastic surface and water (Abdullah *et al*., 2019). On the other hand, the concentration of PALF has an opposite effect on the surface contact angle of the bioplastic samples.

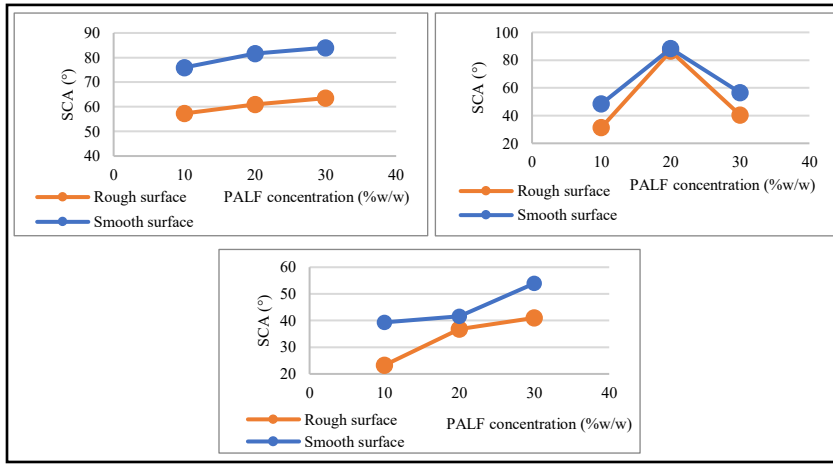


Figure 4. Effect of PALF: at 20% w/w glycerol (a), at 30% w/w glycerol (b), and 40 % w/w glycerol (c)

In Figure 4, a general trend can be observed wherein the surface contact angle increases as the PALF filler concentration increases. This is because of the reduced water absorption of alkali-treated PALF filler—the alkali treatment of fiber results in the removal of hemicellulose, pectin, and lignin. The presence of hemicellulose promotes the increase in water absorption due to its hygroscopic nature. Thus, the removal of this component significantly decreases the water absorption of fiber (Yew *et al.,* 2019). Furthermore, alkali treatment effectively eradicates the hydroxyl groups on the surface of natural fibers, enhancing the adhesion between the fiber and the thermoplastic starch matrix (Liu *et al*., 2019). The increase in alkali-treated PALF concentration further improves this adhesion. As a result, surface contact angle increases with the increase in alkali-treated PALF concentration. To support these observations, a two-way ANOVA was conducted, and the results are shown in Tables 4 and 5.

Table 4. Summary of Two-way ANOVA values on surface contact angle test (SS)

Source of Variation	*F*	*P-value*	*F crit*	Statistical Decision
Concentration of Glycerol	249.8595	8.58E-17	3.402826	S
Concentration of PALF	39.76874	1.80E-09	3.008787	S

Table 5. Summary of Two-way ANOVA values on surface contact angle test (RS)

Source of Variation	*F*	*P-value*	*F crit*	Statistical Decision
Concentration of Glycerol	119.2695	3.41E-13	3.402826	S
Concentration of PALF	76.0616	2.12E-12	3.008787	S

3.2.2 Tensile Strength

Tensile strength is the amount of maximum strength needed to break the bioplastic film. It was determined in accordance with ASTM D638-10 standard method. This test was conducted to assess the effectivity of the additives present in the bioplastic in terms of durability (Safitri *et al*., 2022). The summary of results for the tensile strength test is presented in Figure 5.

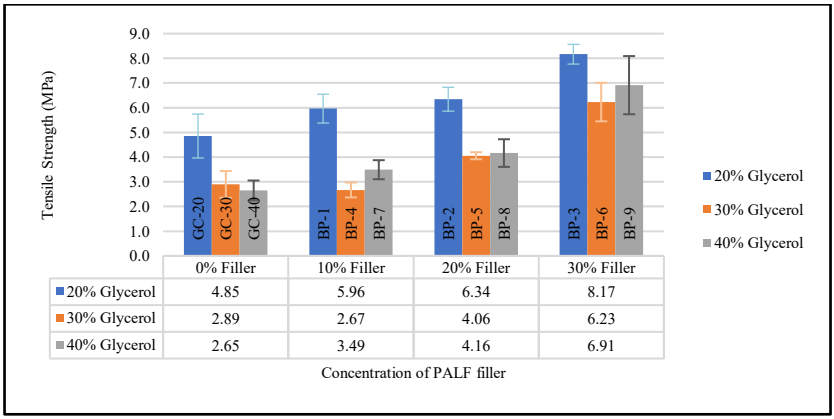


Figure 5. Tensile strength

The results for the tensile strength of the developed bioplastics ranged from 2.67 to 8.17 MPa. These results are within the standard of moderate bioplastic properties namely 1-10 MPa. For comparison, other starch-based bioplastics have reposted tensile strengths ranging from 0.22 to 18.49 MPa (Gabriel *et al*., 2021).

The impact of additives on the tensile strength of bioplastics was evaluated, revealing that tensile strength increases with higher concentrations of PALF filler, as plant fibers improve strength by binding to the thermoplastic starch matrix. Alkali-treated fibers, which have smoother surfaces and better fiber-matrix interactions, further enhance tensile strength (Boey *et al.*, 2022). Conversely, tensile strength decreases with increasing glycerol concentration (Hopkins *et al*., 2019); this trend can be observed among the control samples. Bioplastic samples with 20% w/w glycerol showed higher tensile strength compared to those with 30% or 40% w/w glycerol. Glycerol, as a plasticizer, disrupts hydrogen bonds between starch molecules, enhancing flexibility and elasticity but reducing tensile strength. Interestingly, bioplastics with 40% w/w glycerol displayed higher tensile strength than those with 30%, most likely due to the presence of alkali-treated fiber fillers. Although a detailed compatibility analysis was beyond the current study, the finding suggests a possible interaction effect between plasticizer and fiber filler concentrations. Further investigation is required to confirm the reproducibility and underlying mechanism of this behavior.

3.2.3 Biodegradability

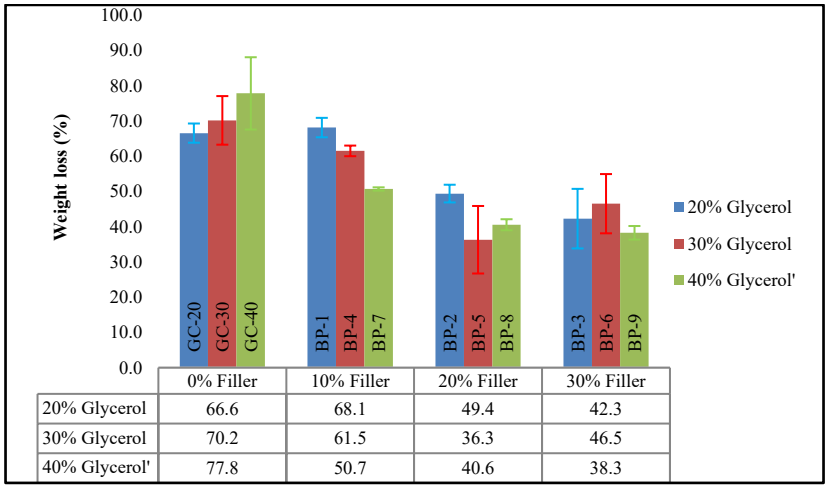
The biodegradation test was conducted to assess the bioplastic's susceptibility to enzymatic activity in compost soil under aerobic conditions. In this test, the samples were buried for 30 days, with degradation measured every 10 days. Film thickness, density, and moisture retention can influence weight loss rates. However, these variables were not normalized in the current study as the primary focus was on the overall biodegradability trend.

The compost soil used in this test was analyzed at the Regional Soils Laboratory-Department of Agriculture, with results shown in Table 6.

Table 6. Soil composition analysis

Test Analysis	Compost
Organic Matter, %	23.9
Phosphorus, ppm	72.1
Potassium, ppm	2885
pH	7.41

Figure 6 shows the summary of the results for the biodegradability of the developed bioplastic expressed in graphical representation measured after 10 days of burial.



	0% Filler	10% Filler	20% Filler	30% Filler
20% Glycerol	66.6	68.1	49.4	42.3
30% Glycerol	70.2	61.5	36.3	46.5
40% Glycerol'	77.8	50.7	40.6	38.3

Figure 6. Biodegradability of bioplastic

The bioplastic samples exhibited remarkable biodegradability in compost soil, as demonstrated in Figure 6, which illustrates their complete degradation within 20 days. At day 10, the percent biodegradability of the bioplastic samples ranged from 36.3% to 68.1 % and completely degraded at day 20. The biodegradability of the developed bioplastics is within the acceptable biodegradability according ISO 14855:1999. Other bioplastics have been reported to completely disintegrate within 45–60 days (Krishnamurthy and Amritkumar, 2019), while some exhibited 30%–70% weight loss by day 30 (Chowdhury *et al*., 2022), and others showed a biodegradability of around 48.73% (Asim *et al*., 2019).

The effect of bioplastic additives on biodegradability was examined. Increasing the concentration of glycerol accelerates the process of bioplastic degradation (Fauziyah *et al*., 2021). This is due to the hydrophilic nature of glycerol, which promotes moisture absorption form the soil. The presence of moisture facilitates the microbial degradation process, thereby enhancing the degradation process of the bioplastic (Ungprasoot *et al*., 2021). However, this effect is only evident among the control samples; GC-20, GC-30, and GC-40. The effect of glycerol does not follow the same trend in all variations; hence, it can be said that glycerol has no significant effect on the biodegradability of

the samples containing alkali-treated PALF. On the other hand, the general trend indicates that the increase in the concentration of PALF filler led to a decrease in the biodegradability of the bioplastic. This is attributed to the reduced hydrophilicity of alkali-treated PALF, which absorbs less moisture and slows microbial activity, and improved fiber-matrix adhesion that further inhibits degradation (Kamarudin e*t al*., 2022). Consequently, bioplastics with higher PALF content exhibited the least weight loss.

The primary focus of this characterization test was on visual and weight loss assessments, which are commonly used as indicators of biodegradation in the literature (Chowdhury *et al*., 2022; Krishnamurthy and Amritkumar, 2019; Amin *et al*., 2019). However, it is acknowledged that more comprehensive analysis would provide more thorough understanding of the underlying degradation mechanisms. It is also acknowledged that normalizing for the aforementioned factors could provide more thorough understanding of the biodegradation rates.

3.2.5 FTIR Analysis

FTIR analysis was performed to determine the functional groups present in the bioplastic. However, only the sample that exhibited the highest tensile was selected to undergo the analysis. This approach was based on the assumption that the primary functional groups would be consistent across formulations due to the uniformity of components. Figure 7 shows the FTIR spectrum of the bioplastic composed of 20% w/w glycerol and 10% w/w PALF.

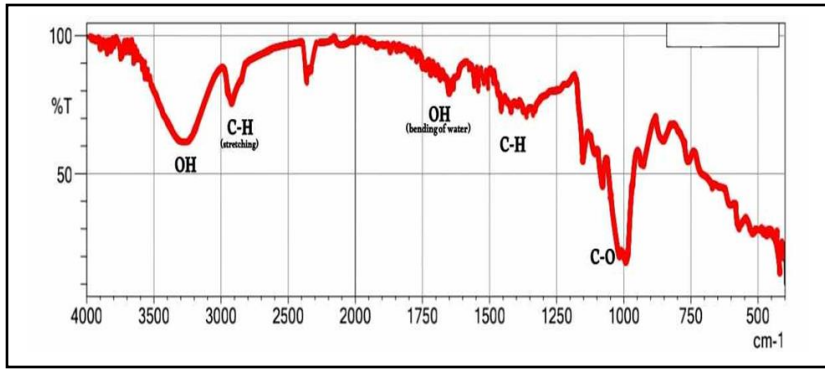


Figure 7. Infrared spectrum of BP-3

This spectrum demonstrated the presence of four characteristic absorption peaks: O-H, C-H, OH (bending of water), and C-O. The broadband in the

range 3589-3010 cm^{-1} corresponded to the OH stretching. This band was associated with the free, inter-, and intramolecular-bound hydroxyl groups (Ren *et al*., 2018). The absorption peak in the range 2972-2823 cm^{-1} corresponded to the symmetric and asymmetric vibrations of C-H bonds present in the polysaccharide structure. The peaks in the range 1336-1446 cm^{-1} also correspond to C-H bonds (Abdullah *et al*., 2018). The peak in the range 1053-918 cm^{-1} corresponded to C-O bond stretching. This peak is a characteristic of the anhydro-glucose ring present in carbohydrates (Johari and Sultan, 2017). The peak at 1647 cm^{-1} corresponded to the O-H (bending of water) or H-O-H which is attributed to the interaction between cellulose and water (Nazir *et al*., 2013) or the adsorbed water present in starch (Saallah *et al*., 2020). The peak at 2360 cm^{-1} indicates the presence of CO_2. This can be attributed to the manner of CO_2 adsorption that took place during FTIR analysis due to the measuring conditions (Abdullah *et al.,* 2018).

4. Conclusion and Recommendation

The use of agricultural wastes, saba (*Musa acuminata x balbisiana*) banana peel, and pineapple leaves has demonstrated their effectiveness as components in bioplastic production. The saba banana peel proved to be an excellent source of starch for bioplastic production, with an average yield of 6.22% for ripe samples and 25.87% for unripe samples, on a dry basis.

Three different samples demonstrated excellence in the characterization tests for surface contact angle, tensile strength, and biodegradability. For the surface contact angle test, sample BP-5 exhibited an excellent result of 88.3° on its smooth surface and 86.5° on its rough surface. This indicates that this specific sample possesses the lowest degree of water absorption or wettability and is almost hydrophobic. For the tensile strength test, the highest result obtained is 8.17 MPa by the sample BP-3, which contained the lowest amount of glycerol (20% w/w starch basis) and the highest amount of alkali-treated PALF filler (30% w/w thermoplastic starch basis). For the soil biodegradation test, BP-1 displayed the highest rate of biodegradation at 68.1% after ten days of burial. These results indicate that the bioplastic sample is highly suitable for a range of packaging and covering applications, such as wrapping fresh produce, creating biodegradable bags, and manufacturing single-use containers. Additionally, the bioplastic shows promising potential for use in

making drinking straws, providing a sustainable alternative to conventional plastic materials.

For future studies, several recommendations are proposed to improve bioplastic production. First, it is advised to use a method that ensures the bioplastic film dries evenly to achieve a uniform surface texture on both sides; hence, selecting an appropriate material for pressing the bioplastic mixture is crucial to avoid crushing the material. Furthermore, evaluating the thermal properties and solubility of the bioplastics in oil, acidic, and alkaline solutions will provide a deeper understanding of their characteristics and potential applications. Additionally, conducting biodegradation assessments using CO_2 evolution or microbial analysis and normalizing for factors could provide definitive insight into degradation behavior. Including SEM imaging and FTIR analysis for multiple samples would further support conclusions regarding surface morphology and chemical structure. Lastly, comparing the best-performing bioplastic samples with conventional plastics will help assess whether the developed bioplastic can stand up to commercially produced alternatives.

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