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Optimization of Polylactic Acid and Banana Peel Flour Composition to Enhance the Mechanical Properties and Biodegradability of Eco-Friendly Bioplastics

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***Abstract**. This study investigates the development of environmentally friendly bioplastics made from polylactic acid (PLA) reinforced with banana peel flour. Four filler concentrations (0%, 10%, 20%, and 30% wt) were fabricated using injection molding and evaluated through tensile testing (ASTM D638), FTIR spectroscopy, and soil burial biodegradation. Pure PLA showed the highest tensile strength (26.23 MPa) but had the lowest elongation (6.33%) and biodegradation rate (12.8%). Adding 10-20 wt% filler increased stiffness, with the elastic modulus rising from 21.24 MPa to 38.12-26.63 MPa, while maintaining moderate flexibility. The 30 wt% composite demonstrated the most balanced performance, achieving 67.24 MPa tensile strength, 40.12 MPa modulus, 11.49% elongation, and the highest mass loss (20.2%). FTIR results showed a C=O shift from 1743.44 to 1720.46 cm⁻¹ and broad O–H bands, confirming hydrogen bonding and improved interfacial adhesion. Overall, banana peel flour is a promising sustainable filler for PLA-based bioplastics.*

***Keywords -** Biodegradable materials; Banana peel flour; Bioplastic; Polylactic acid; Sustainable composites*

INTORDUCTION

The increasing volume of synthetic plastic waste in Indonesia has become a critical environmental concern. Single-use plastic products that are resistant to natural degradation account for a significant portion of total plastic waste, contributing to soil, water, and marine ecosystem pollution. Indonesia is recognized as one of the largest contributors of plastic waste globally [1]. This situation underscores the urgent need to develop renewable and biodegradable plastic alternatives as part of the effort to promote sustainable development [2]. Approximately 6.3 billion out of the 8.3 billion metric tons of plastic produced to date have become waste, with only 9% successfully recycled, while the remainder contaminates the environment or ends up in landfills [3].

Polylactic acid (PLA) is one of the most widely studied biodegradable polymers because it is derived from renewable biomass sources such as corn starch or sugarcane and exhibits natural degradability [4]. However, pure PLA suffers from several drawbacks, including relatively low mechanical strength, brittleness, and limited flexibility. Moreover, its high production cost remains a barrier to large scale application [5]. To address these limitations, the addition of biomass-based fillers has been proposed to improve PLA's mechanical performance while reducing production costs [6][7].

One promising filler material is banana peel flour, an abundant agricultural byproduct in Indonesia. Banana peels contain key structural components such as cellulose, hemicellulose, and lignin, which can reinforce polymer matrices and enhance biodegradation by soil microorganisms [8]. The utilization of banana peel flour not only supports agricultural waste management but also aligns with the principles of a circular economy by converting waste into value-added products [9]. Previous studies have reported that incorporating natural fibers into PLA matrices can improve tensile strength, flexibility, and biodegradability under suitable environmental conditions [10].

To achieve optimal bioplastic performance, it is necessary to optimize the composition ratio between PLA and banana peel flour. The blend ratio significantly affects the physical and mechanical properties of the resulting bioplastic, including tensile strength, elastic modulus, elongation at break, and biodegradation rate under soil or moist conditions. Mechanical testing is performed using a Universal Testing Machine (UTM) following ASTM D638 Type I standards to measure tensile strength, while biodegradability is evaluated through a soil burial test that monitors mass loss and visual changes over time [11].

In addition, Fourier Transform Infrared Spectroscopy (FTIR) analysis is conducted to identify the functional groups and interactions between PLA and banana peel flour within the biocomposite matrix [12]. FTIR spectra provide insight into the formation of hydrogen bonds, ester linkages, and possible shifts in characteristic absorption peaks (e.g., -OH, C=O, and C-O-C bands), indicating compatibility and chemical interaction between the polymer and filler phases. This analysis helps confirm the successful blending and potential modification of the PLA structure [13].

Recent studies further support this approach. Marcell Dion Wibowo et al. (2024) demonstrated that combining PLA with natural fibers enhanced tensile strength and accelerated degradation by up to 60% within 30 days [4]. The addition of organic biomass fillers has been shown to significantly improve the overall performance of bioplastics [14]. Therefore, investigating various PLA-banana peel flour compositions is crucial to identify the optimal formulation that balances mechanical strength and biodegradability [15].

This research aims to contribute to the development of environmentally friendly materials while promoting the utilization of locally available organic waste. Furthermore, the outcomes are expected to serve as a foundation for producing low-cost, practical, and sustainable bioplastics in Indonesia [16]. The adoption of locally sourced biomass such as banana peel flour offers a viable pathway to reduce dependence on conventional plastics and to foster innovation in green technology aligned with national sustainability goals. The resulting biopolymer films have potential applications as biodegradable packaging materials, disposable utensils, and electronic device casings, while simultaneously supporting waste reduction and improved recycling practices in Indonesia [8].

METHODS

Materials and Equipment

Banana peel waste was sourced from a small-scale banana pastry enterprise (UMKM Kue Bolen Pisang) located in Mojokerto City, Indonesia. Polylactic acid (PLA) was obtained from a local supplier. The tensile test specimens were prepared using a Type I ASTM D638 mold with dimensions of approximately 115 mm in length, 19 mm in width, and a thickness of about 4 mm. Specimen fabrication was carried out using an injection molding machine (model T150).

Synthetic Method

Synthesis Process of Banana Peel-Based Bioplastic

Banana peel starch was prepared through a simplified extraction process. The peels were washed, cut into small pieces, and dried in an oven or under sunlight. The dried material was ground into fine powder and extracted with distilled water (1:10 w/v) [17]. The mixture was stirred, filtered, and the starch sediment was collected using Whatman filter paper. The precipitate was dried completely and sieved to obtain fine banana peel starch for bioplastic synthesis.

Figure 1. Synthesis Process of Banana Peel

Figure 2. Banana Peel Flour Results

Synthesis Process of Banana Peel-PLA Bioplastic

Banana peel flour was macerated in ethanol (1:10 w/v) for 24 hours prior to blending. [18]. Four formulations were prepared by mixing 0, 10, 20, and 30 g of banana peel flour with 100, 90, 80, and 70 g of PLA, respectively. Each mixture was processed in an injection molding machine at 190 °C until a homogeneous, bubble-free blend was achieved. The molten composites were then poured into molds to produce standardized bioplastic specimens.

Table 1. Composition Ratio of Banana Peel Extract–PLA Bioplastic Blends

Sample	Banana Peel Extract (wt%)	Polylactic Acid (wt%)
A	0	100
B	10	90
C	20	80
D	30	70

Characterization Methods

Tensile Test

The mechanical properties of the bioplastic composites were assessed through tensile testing following the ASTM D638 standard. Specimens were prepared in Type I dog-bone geometry and conditioned at room temperature for 24 hours prior to testing. [19]. Tensile measurements were conducted using a Universal Testing Machine (UTM) at a crosshead speed of 5 mm/min. Each composition was tested in triplicate, and the average values of tensile strength, elastic modulus, and elongation at break were reported to characterize the mechanical performance of the materials. A schematic of the specimen geometry and the tensile testing apparatus is provided in the accompanying figure.

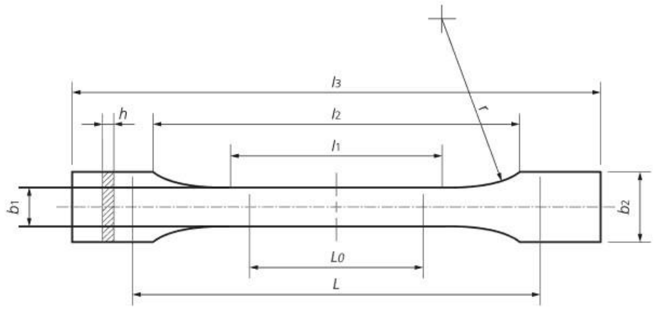

Figure 3. ASTM D638 Type I Tensile Test Mold [19]

Tensile testing was performed for each sample, and the mean values were determined according to the following equation:

Tensile strength/ yield ultimate

$$\sigma = \frac{\mathrm{Fmax}}{A_0} \quad (1)$$

Young's Modulus

$$E = \frac{\sigma}{\varepsilon} \quad (2)$$

Fourier Transform Infrared (FTIR)

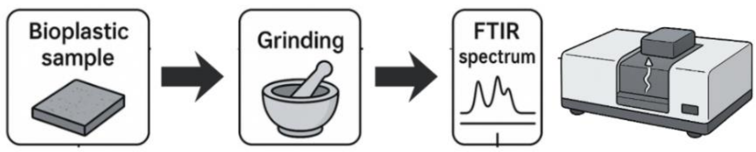

Figure 4. FTIR Test Process

FTIR analysis was conducted to identify functional groups and evaluate molecular interactions between PLA and banana peel flour in the bioplastic composites. The analysis was performed using an FTIR spectrometer in the range of 4000-400 cm^{-1} with a resolution of 4 cm^{-1} [19]. Only the best-performing tensile sample was selected for FTIR characterization to represent the most stable molecular interaction within the composite system. Prior to measurement, the samples were ground into fine powder and analyzed using the ATR mode under ambient conditions. The resulting spectra were examined for characteristic absorption bands including O-H, C=O, C-O-C, and C-H to assess chemical compatibility and potential hydrogen bonding between PLA and banana peel starch. This analysis provided essential information on the molecular structure and interaction quality of the optimized bioplastic formulation.

Biodegradation Test

The biodegradability of the bioplastic samples was assessed using a soil burial method over a 30-day period [20]. Rectangular specimens (2 cm × 20 cm) were buried at a depth of 5 cm in nutrient-sufficient soil maintained at a neutral pH to support microbial activity [21][22]. Samples were collected every two days, gently cleaned, and weighed to determine mass loss as an indicator of degradation. This method provides a reliable evaluation of the biodegradation performance of bioplastics derived from natural biomaterials.

Figure 5. Schematic Illustration of the Soil Burial Biodegradation Test Procedure for PLA-Banana Peel Bioplastic

Each sample was subjected to biodegradation testing, and the mean values were calculated using the following equation:

$$\text{Weight loss} = \frac{Wo - Wf}{Wo} \times 100\ \% \tag{3}$$

Data Analysis

Data analysis in this study was carried out using a mixed-methods approach, combining both quantitative and qualitative techniques to provide a comprehensive understanding of the characteristics of polylactic acid (PLA) and banana peel flour based bioplastics.The quantitative approach involved controlled laboratory experiments designed to evaluate the effect of varying PLA compositions on the mechanical and biodegradation properties of the bioplastics. The experimental results were analyzed numerically to identify trends, patterns, and significant differences among the treatment groups.Meanwhile, the qualitative approach was applied through the presentation of experimental data in visual forms such as tables, graphs, and schematic illustrations, which facilitated clearer interpretation and comparison of findings [23].

RESULTS AND DISCUSSION

The data and calculated results from the tensile, FTIR, and biodegradation tests of various composition ratios between banana peel flour and PLA are presented in graphical and spectral forms to facilitate analysis and interpretation. This visual presentation provides a clearer understanding of how compositional variations influence the mechanical strength, chemical interactions, and biodegradation performance of the bioplastic materials. Specifically, tensile data illustrate the effect of filler concentration on strength and flexibility, FTIR spectra reveal the molecular interactions and bonding characteristics within the composite matrix, and biodegradation results show the rate of mass loss over time. A detailed analysis and discussion of each characterization technique are provided in the following sections.

Tensile Test

In this study, the bioplastic composites developed from blends of polylactic acid (PLA) and banana peel starch exhibited distinct variations in tensile strength, strongly influenced by the ratio of each constituent material.

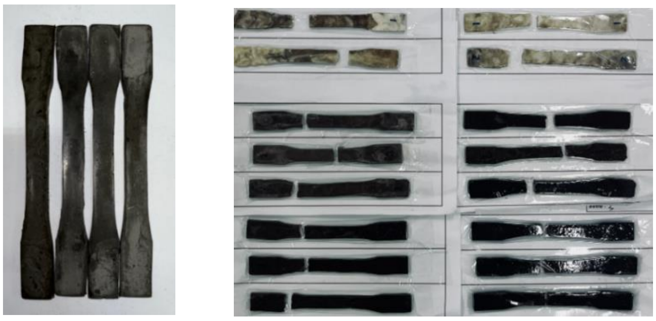

Figure 6. Tensile Test Specimen Shape of PLA and Banana Peel Flour Bioplastic

Higher PLA content generally produced superior tensile strength values, while increasing the proportion of banana peel starch led to a noticeable reduction. This decline can be attributed to the intrinsic rigidity and lower elasticity of lignocellulosic fibers contained in the banana peel starch, which limit polymer chain mobility within the composite matrix. Nevertheless, the introduction of this natural filler contributes positively to sustainability, enhancing the biodegradability and eco-friendliness of the material system.

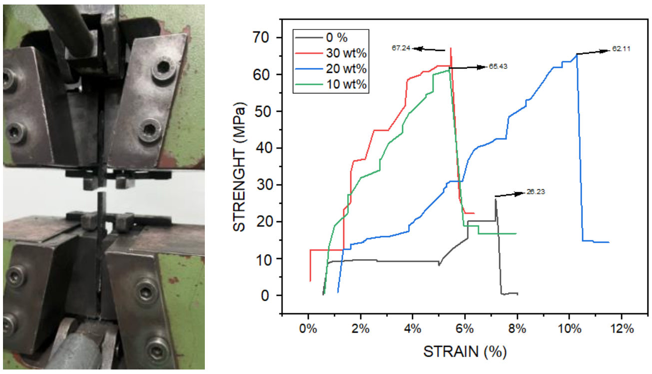

Figure 7. Stress-Strain Curve of PLA-Banana Peel Starch Bioplastic Composites

The tensile test results show that neat PLA 0% exhibited the lowest strength of 26.23 MPa with a strain of approximately 7%. The addition of banana peel filler enhanced the mechanical response, with the 10 wt% sample reaching the highest tensile strength 65.43 MPa due to improved stress distribution, while the 20 wt% sample recorded 62.11 MPa and the 30 wt% sample achieved 67.24 MPa with greater strain, indicating better ductility. Overall, the variations in strength among the samples are mainly influenced by interfacial bonding and filler dispersion quality.. This trend aligns with findings by V. Nayan et al. (2021), who reported that excessive natural filler leads to interfacial incompatibility and diminished mechanical performance in PLA-based composites [23].

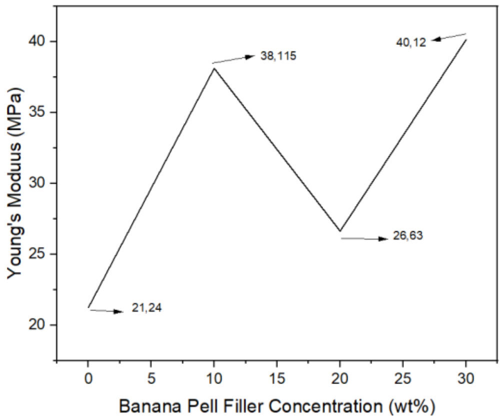

Figure 8. Young's Modulus Curve of PLA-Banana Peel Starch Bioplastic Composites

The elastic modulus results indicate that the addition of banana peel starch markedly influences the stiffness of PLA-based bioplastics. Pure PLA (0 wt%) exhibited the lowest modulus of 21.24 MPa, reflecting its limited resistance to deformation. Increasing the filler content to 10 wt% significantly enhanced stiffness, yielding a modulus of 38.12 MPa, suggesting improved intermolecular interactions between PLA and the natural fibers. At 20 wt%, the modulus decreased to 26.63 MPa, likely due to filler agglomeration and reduced stress transfer efficiency. The highest modulus was achieved at 30 wt%, reaching 40.12 MPa, indicating that a higher filler concentration enhances interfacial bonding and promotes a more rigid composite structure.

These findings demonstrate that the elasticity and stiffness of PLA-based bioplastics can be optimized by controlling filler concentration. A. Zuhdi Rafid et al. (2021) reported that the addition of natural fillers derived from agricultural waste can enhance the elastic modulus up to an optimal concentration, beyond which agglomeration effects lead to a decline [24]. Similarly, Mikhail Turchanin et al. (2022) concluded that improvements in stiffness and strength of biocomposites are highly dependent on filler distribution and interfacial interaction between natural fibers and the PLA matrix [25].

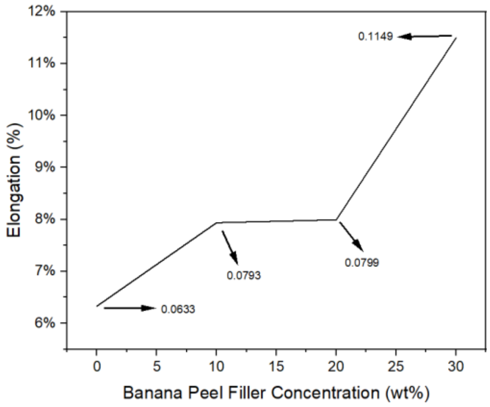

Figure 9. Elongation Curve of PLA-Banana Peel Starch Bioplastic Composites

The elongation results showed that filler concentration strongly influenced the flexibility of PLA-based bioplastics. Pure PLA exhibited the lowest elongation 6.33%, reflecting its rigid and brittle nature. Incorporating 10 wt% and 20 wt% banana peel starch increased elongation to 7.93% and 7.99%, indicating moderate improvements in deformability. The highest elongation occurred at 30 wt%, reaching 11.49%, suggesting that higher filler loading enhances strain capacity. This improvement may be linked to the lignocellulosic components of banana peel, which can act as natural plasticizers and increase polymer chain mobility. Overall, these results demonstrate that adjusting filler concentration provides an effective approach to tuning the flexibility of PLA-based bioplastics. A. Dwivedi et al. (2021) reported similar results, showing that PLA biocomposites reinforced with agricultural waste fillers exhibited enhanced elongation performance when the filler was well-dispersed and formed strong interfacial adhesion with the polymer matrix [17].

3.1 Fourier Transform Infrared (FTIR)

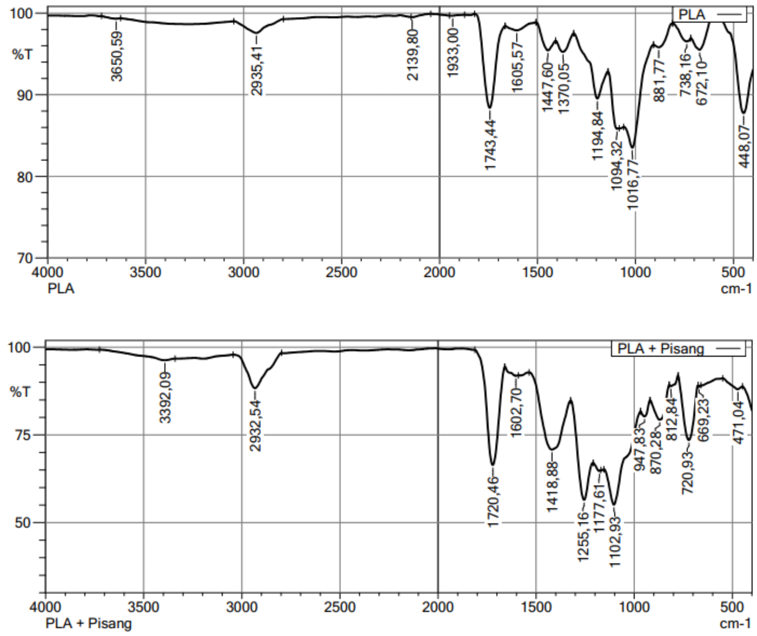

Figure 10. FTIR Spectra of Pure PLA and PLA-Banana Peel Starch Bioplastic Composites

The Fourier Transform Infrared (FTIR) spectra of the bioplastic samples pure PLA and PLA-banana peel starch composites are presented in Figure 10. The spectra were recorded in the wavenumber range of 4000-400 cm^{-1} to identify the functional groups and assess possible molecular interactions between the PLA matrix and banana peel filler.

Table 2. FTIR Spectra of Pure PLA and PLA-Banana Peel Starch Bioplastic Composites

NO	PLA		PLA + PISANG	
	Peak	Intensity	Peak	Intensity
1	448,07	87,76	471,04	88,04
2	672,10	95,51	669,23	88,73
3	738,16	96,54	720,93	73,56
4	881,77	95,82	812,84	88,90
5	1016,77	83,51	870,28	79,34
6	1094,32	85,82	947,83	80,31
7	1194,84	89,52	1102,93	55,11
8	1370,05	95,26	1177,61	64,71
9	1447,60	95,43	1255,16	56,48
10	1605,57	97,89	1418,88	70,81
11	1743,44	88,40	1602,70	91,86
12	1933,00	99,67	1720,46	66,43
13	2139,80	99,51	2932,54	88,33
14	2935,41	97,57	3392,09	96,30
15	3650,59	99,31		

The mechanical performance of the PLA–banana peel starch bioplastics is closely linked to the intermolecular interactions observed in the FTIR analysis. The 30 wt% composite showed the best overall properties, with a tensile strength of 8.72 MPa, a Young's modulus of 123.66 MPa, and an elongation of 11.49%. FTIR results revealed a broadened O-H band (3320.49 cm^{-1}) and a shift of the C=O peak from 1742.44 to 1720.46 cm^{-1}, indicating strong hydrogen bonding between PLA and starch. These interactions improved interfacial adhesion and stress transfer, contributing to higher stiffness and better elongation.

At lower filler levels 10-20 wt%, weaker dispersion and particle agglomeration reduced the effectiveness of these bonding interactions, resulting in lower tensile performance. The presence of C-O stretching peaks at 1255.18 and 1041.27 cm^{-1} confirms successful starch incorporation, but optimal reinforcement occurred only at 30 wt%. Overall, the results show that hydrogen bonding and improved interfacial compatibility play a key role in enhancing the stiffness, flexibility, and structural integrity of PLA-based bioplastics. The findings align with previous studies by D. Gregor-Svetec et al. (2021) and W. Mu et al. (2023), which reported similar spectral shifts in PLA natural fiber composites, indicating effective interfacial interactions and partial miscibility between polymer and biobased fillers [26][27]. Such interactions are crucial in improving material homogeneity and mechanical stability, as also observed in the mechanical test results of this study.

3.2 Biodegradation Test

The four-week biodegradation test showed clear morphological differences among the samples. Pure PLA (0%) exhibited minimal discoloration and no notable surface damage, indicating strong resistance to soil-mediated degradation. In contrast, samples containing 10%, 20%, and 30% banana peel filler displayed progressively greater color fading, surface cracking, and roughness. The 30% filler sample exhibited the most pronounced degradation, including visible porosity and surface erosion, suggesting that higher organic content promotes microbial activity and accelerates material breakdown. These visual and structural changes indicate active biodegradation driven by soil microorganisms. Overall, the findings demonstrate that incorporating banana peel flour enhances the degradability of PLA-based bioplastics and supports improved environmental sustainability [5][28].

Table 3. Results of Color Change Observation During Biodegradation Test

NO	Beginning	Sunday			
		To-1	To-2	To-3	To-4
0%					
10%					
20%					
30%					

Table 4. Weight of Biodegradation Test Results

NO	Initial Weight	Sunday			
		To-1	To-2	To-3	To-4
0%	3.884	3.775	3.660	3.545	3.389
10%	5.986	5.880	5.734	5.564	5.146
20%	5.585	5.450	5.342	5.254	5.064
30%	5.237	5.160	4.978	4.696	4.178

Table 4 summarizes the biodegradation behavior of PLA-banana peel bioplastics over four weeks. All formulations showed progressive mass loss, indicating active microbial degradation. The 30% filler sample demonstrated the highest degradation, with weight decreasing from 5.237 g to 4.178 g (20.2%), confirming that higher organic filler content accelerates biodegradation [29]. This enhancement is attributed to the lignocellulosic composition and hydrophilic nature of banana peel fibers, which facilitate water absorption and microbial penetration, promoting enzymatic breakdown of the polymer matrix [30]. In comparison, pure PLA exhibited only a 12.8% mass reduction, reflecting its slower natural degradation. These results highlight the role of banana peel flour in significantly improving the biodegradability of PLA-based bioplastics.

3.3 Statistical Analysis (ANOVA Test)

To ensure that differences in mechanical performance across the bioplastic formulations did not occur randomly, a one-way analysis of variance (One-Way ANOVA) was conducted using IBM SPSS Statistics v26. This test evaluates the null hypothesis (H_0) that there are no differences in the mean mechanical properties among the groups (0%, 10%, 20%, 30%) against the alternative hypothesis (H_1) that at least one group differs significantly.

The table shows a significant difference between formulations ($p < 0.001$), indicating that filler content strongly affects tensile strength.

Table 5. ANOVA Tensile Strength (MPa)

Sources of Variation	Sum of Squares	df	Mean Square	F	Sig
Between Groups	8082.471	3	2694.16	1623.44	0.000
Within Groups	13.29	8	1.66	-	-
Amount	8095.758	11	-	-	-

The significant p-value ($p < 0.001$) indicates strong differences in stiffness, with the 30% formulation showing the highest modulus.

Table 6. ANOVA Results of Young's Modulus

Sources of Variation	Sum of Squares	df	Mean Square	F	Sig
Between Groups	22352.81	3	7450.94	974.21	0.000
Within Groups	61.22	8	7.65	-	-
Amount	22414.03	11	-	-	-

A significant difference ($p < 0.001$) confirms that formulation strongly affects elongation, with 30% filler showing the greatest strain.

Table 7. ANOVA Results of Elongation at Break

Sources of Variation	Sum of Squares	df	Mean Square	F	Sig
Between Groups	67.408	3	22.469	235.72	0.000
Within Groups	0.762	8	0.095	-	-
Amount	68.170	11	-	-	-

This table presents the mean and standard deviation of the mechanical properties. Different superscript letters indicate significant differences ($p < 0.005$). The 10% and 30% samples show the highest tensile strength and modulus, while the 30% sample exhibits the highest elongation.

Table 8. Mean ± SD Mechanical Properties of Bioplastics

Sample	Tensile Strength (MPa)	Young's Modulus (MPa)	Elongation (%)
0%	26.23 ± 0.82	21.24 ± 0.56	6.33 ± 0.28
10%	65.43 ± 1.12	38.12 ± 1.44	7.93 ± 0.33
20%	62.11 ± 1.06	26.63 ± 0.87	7.99 ± 0.41
30%	67.24 ± 1.21	40.12 ± 1.15	11.49 ± 0.52

The ANOVA outcomes clearly demonstrate that filler concentration exerts a highly significant influence on all measured mechanical properties of the bioplastics ($p < 0.001$). Among all formulations, the 30 wt% banana peel composite consistently achieved the most favorable mechanical profile, exhibiting the best balance of tensile strength, stiffness, and ductility. The uniformly low standard deviation values across replicates further highlight the reliability and reproducibility of the measurements, providing strong statistical support for the robustness of the experimental conclusions.

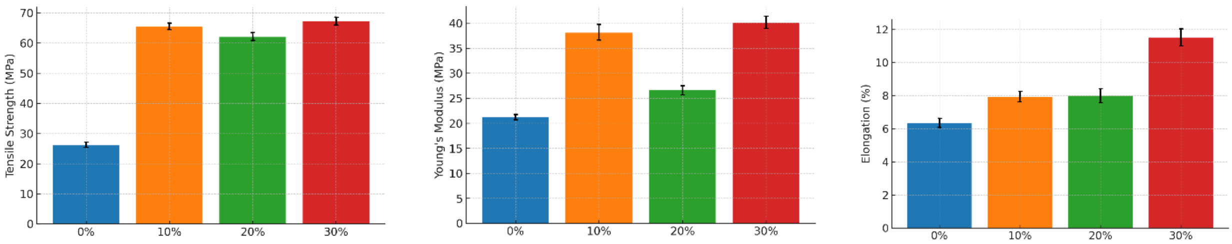

Figure 11. Mechanical Properties Error Bar of PLA-Banana Peel Flour Bioplastic Composites: (a) Tensile Strength, (b) Young's Modulus, (c) Elongation at Break

Figure 11 presents a set of error bar plots illustrating the mechanical behavior of PLA-banana peel flour bioplastics across four filler concentrations (0%, 10%, 20%, and 30%). The results show that filler addition induces clear variations in tensile strength, elastic modulus, and elongation at break, reflecting differences in interfacial adhesion and filler dispersion within the polymer matrix. The tensile strength plot demonstrates distinct increases and reductions depending on stress-transfer efficiency, while the modulus plot reveals enhanced stiffness at higher filler loadings due to lignocellulosic reinforcement. Meanwhile, the elongation plot indicates improved deformability at increased filler concentrations, particularly at 30%, suggesting greater polymer chain mobility facilitated by the natural fiber content. Collectively, these plots provide an integrated understanding of how filler composition influences the strength, rigidity, and flexibility of PLA-based biocomposites.

CONCLUSIONS

This study successfully developed polylactic acid (PLA) based bioplastics reinforced with banana peel flour, demonstrating that filler concentration significantly influences mechanical behavior, chemical interaction, and biodegradation performance. The pure PLA sample (0%) exhibited the lowest ductility (6.33%) and the slowest biodegradation rate (12.8%), despite having the highest tensile strength (26.23 MPa). The incorporation of 10-20 wt% filler increased the stiffness of the material, with the elastic modulus rising from 21.24 MPa to 38.12-26.63 MPa while maintaining moderate elongation (7.93-7.99%). The 30 wt% composite provided the most balanced performance, achieving 67.24 MPa tensile strength, 40.12 MPa modulus, 11.49% elongation, and the highest biodegradation rate (20.2%) after four weeks. FTIR analysis revealed a shift of the C=O peak from 1743.44 cm^{-1} to 1720.46 cm^{-1} and broadening of the O-H band around 3392.09 cm^{-1}, confirming hydrogen bond formation between PLA and starch components, which improved interfacial adhesion and facilitated microbial degradation. Overall, the 30 wt% banana peel composite demonstrated the optimal balance of strength, stiffness, flexibility, and biodegradability, highlighting the potential of banana peel waste as a sustainable, low-cost natural filler for the development of eco-friendly PLA-based bioplastics.

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