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# Effect of Polylactic Acid on Mechanical, Chemical, Thermal, Morphology, Water Absorption, and Biodegradability Characteristics of Degradable Plastic from Durian Peel Waste

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## Abstract

Durian peels consist of cellulose, a potential base material for producing sustainable products, particularly degradable plastics. This study examines the impact of polylactic acid (PLA) blends on the degradable plastics derived from durian peel (*Durio zibethinus*). The mechanical characteristics of the degradable plastics: tensile strength of 2.5671–9.3498 MPa, elongation of 31–96%, and Young's modulus of 161.32–219.95 MPa. The analysis of the compound revealed the presence of the alcohol monomer (O-H), alkanes and aromatic rings (C-H), carbonyl (C=O), and alkenes (C-O) groups. The potential for soil microbes to decompose these groups is also a consideration, given their hydrophilic nature, which enables them to bind to water. X-ray fluorescence (XRF) analysis of the degradable plastic sample revealed the presence of 13 elements: Mg, Ca, Al, P, Fe, Cl, K, Sr, Zn, Sc, Rh, S, and Si. In this study, no harmful metal contaminants (Pb, Hg, or Cd) were identified. Thermal analysis, encompassing a temperature range from 357.67°C to 443.67°C, has been instrumental in identifying the phase transition that marks the onset of extreme weight loss during crystallization. Morphological analysis revealed incomplete dissolution, leading to a nonuniform shape. Solubility is directly proportional to the duration of the stirring process. The degradable plastic with the least swelling is composed of 3.5 g of cellulose and 3 g of PLA, exhibiting a degree of swelling of 4.89%. The degradable plastic is predicted to decompose most rapidly after 56 days with a PLA content of 3 g. This experimental result aligns with the provisions outlined in ASTM D2096, a standard that establishes a maximum time limit of 180 days for the degradation of plastics.

## 1. Introduction

Recently, there has been a growing trend to replace conventional fossil-based plastics with biomass-based plastics. The production of plastics derived from biomass, in whole or in part, is experiencing rapid growth [1]. The production of plastic-based materials is a significant source of carbon emissions, and their disposal poses major environmental challenges. The use of biodegradable plastics as a substitute for conventional plastics across sectors, especially in food packaging, has attracted global attention from governments and policymakers [2]. The use of biodegradable polymers as a viable alternative is becoming increasingly prominent due to their ability to decompose naturally under ecological conditions. Polylactic acid (PLA), polybutylene succinate (PBS), and polycaprolactone (PCL) are among the most widely studied biopolymers. The functions offered by these materials can be applied in various contexts, including packaging, agricultural films, and biomedical applications [3]. However, despite their environmental benefits, many of these biopolymers have limitations. These limitations include low physical strength, poor heat resistance, and high production costs. These limitations hinder their widespread use in industry [4].

To address this challenge, scientists are researching ways to reinforce biodegradable polymers with natural fibers, particularly cellulose. Cellulose is the most common type of biopolymer in the world. It is naturally biodegradable, safe for living organisms, and can be found in wood, agricultural waste, algae, and bacteria [5]. The addition of bamboo nanocellulose fibers to the PLA-poly(butylene succinate) matrix improves the composite's structural and thermal properties while allowing complete degradation in soil. This makes it a promising alternative to environmentally friendly packaging materials currently available on the market [6].

Yusoff *et al.* [7] investigated the tensile strength of biocomposites from starch and PLA. The incorporation of tapioca starch (TS) at 30 wt.% resulted in a substantial enhancement in tensile strength. However, this enhancement was accompanied by a subsequent decrease in mechanical strength as the tapioca starch content increased. Consequently, the maximum tensile strength was 9.7 MPa, while the plain PLA sample exhibited a strength of 7.7 MPa. The outcome data from impact testing analysis demonstrated that impact decreased as TS loading increased. Werchefani *et al.* [8] employed an innovative approach by using an alpha fiber and a PLA matrix to fabricate biocomposites. An elevated cellulose content has been demonstrated to exert a deleterious effect on the properties of composites, concomitantly diminishing tensile strength and elongation at break. This negative effect is more significant with larger cellulose particles [9].

This innovation represents a novel approach to modifying durian (*Durio zibethinus*) cellulose fibers with PLA. A variety of cellulose plants have been identified as potential base materials for the production of degradable plastics. These include rice husk, corn cobs, oil palm empty fruit bunches, pineapple leaves, coconut shells, and spent mushroom substrate [10]. Cellulose is a natural material that can improve the strength and consistency of PLA. This improvement depends on several factors, such as how cellulose is mixed and its properties. Some other factors that can affect the improvement include the use of chemicals that help the two materials work well together, surfactants, and plasticizers [11, 12, 13].

PLA has been demonstrated to be both hard and hydrophobic, characteristics that render it suitable for a variety of products [14]. PLA is a type of thermoplastic polyester that is derived from renewable resources. It is characterized by ease of use and rapid degradation, typically within 2 years [15]. PLA is a material that exhibits a high degree of brittleness, with a Young's modulus ranging from 2996 to 3750 MPa and an elongation at break of 1.3% to 7%. PLA has a glass transition temperature (Tg) of 60°C, at which point structural distortion becomes evident. The water permeability of PLA has been shown to cause the material to undergo hydrolytic degradation [16].

Durian fruit peel has been found to emit an unpleasant odor and may pose significant environmental concerns due to its tendency to attract insects and serve as a fertile breeding ground for bacterial and infectious diseases. The utilization of these underutilized natural resources is imperative for enhancing their economic value, necessitating the development of innovative and effective management strategies. Charoenvai [11] conducted a study that identified the main components of durian peel. The study found that cellulose constituted 47% of the main components, followed by hemicellulose (10%), lignin (10%), and ash (4%).

A notable challenge with degradable plastics is their limited moldability, which hinders the industry's ability to effectively use these materials. The strength of these materials is not commensurate with that of synthetic plastics, thereby limiting their applications. Consequently, identifying innovations capable of overcoming these deficiencies is imperative. In this study, a novel material, PLA was utilized as a filler for degradable plastic derived from durian stem cellulose, employing a thermopressing technique.

The present study explores the impact of PLA blends on cellulose-degradable plastics derived from the durian peel (*Durio zibethinus*). The cellulose concentrations used in this study are 1.5, 2.5, and 3.5 g, while the PLA concentrations are 3, 5, and 7 g. The most favorable properties of the degraded plastic were determined by analyzing variations in cellulose weight.

## 2. Experimental

### 2.1. Materials and Equipment

The materials used in this study included durian peel waste obtained from the municipal fruit market in Lhokseumawe, Aceh Province, which served as the cellulose source for the production of degradable plastic. The chemicals used were xylene (Merck Supelco 108297, Burlington, MA, USA), maleic anhydride (MA, 99%, Sigma-Aldrich 8.00408.1000), polypropylene (PP), nitric acid ($HNO_3$, 70.0%, Sigma-Aldrich 7697-37-2), polylactic acid (PLA, $C_3H_6O_3$, 90.08 g/mol, Sigma-Aldrich 38534-1G), sodium hydroxide (NaOH, 99%, Merck 1310-73-2), sodium hypochlorite (NaOCl, Merck 2828 90 00), and distilled water supplied by PT Bratachem, Surabaya, Indonesia.

The equipment used in this study included Pyrex glass beakers (50 mL and 250 mL), a 10 mL Pyrex measuring cylinder, a hot press, a stainless steel spatula, a Millipore Merck thermometer, a hot plate with an MS H280 Pro stirrer, an oven (Merck 1.88054.0005), and an analytical balance (ADB 600-C3) for weighing all materials. The variations in the mass composition of durian peel cellulose and PLA used in the preparation of the samples are summarized in Table 1.

**Table 1**. Variable mass composition of durian peel cellulose and PLA

| Durian peel cellulose mass (g) | PLA mass (g) |
|---|---|
| 1.5 | 3 |
| 1.5 | 5 |
| 1.5 | 7 |
| 2.5 | 3 |
| 2.5 | 5 |
| 2.5 | 7 |
| 3.5 | 3 |
| 3.5 | 5 |
| 3.5 | 7 |

### 2.2. Preparation of Durian Peel Powder

Two kilograms of durian peel were thoroughly washed with running water. The thorns were removed, and the peel was cut into approximately 1 cm pieces. The material was then sun-dried for 24 h to reduce its moisture content. After drying, the pieces were further reduced in size to approximately 0.5 cm to facilitate the grinding process. The dried material was subsequently ground in a blender until a fine powder was obtained, thereby increasing its surface area. Finally, the powder was stored in a sealed container.

### 2.3. Durian Peel Cellulose Extraction

Fifteen grams of durian peel powder were mixed with 300 mL of 5% NaOH solution. The mixture was heated at 60°C with continuous stirring at 150 rpm for 90 min. After heating, the mixture was filtered, and the solid residue was washed with distilled water. The washed solid was then treated with 100 mL of 2% $HNO_3$ and heated at 45°C under stirring at 150 rpm for 30 min. The solid was subsequently filtered and washed with distilled water, then treated with 200 mL of 2% NaOCl solution at 45°C, stirred at 150 rpm for 30 min. The resulting solid was filtered, washed with distilled water, and dried in an oven at 105°C for 1 h. Finally, the dried cellulose was ground again to obtain a finer product, yielding α-cellulose powder.

### 2.4. Production of Degradable Plastics

Ten milliliters of xylene were added to a glass beaker containing 3 g of PLA, 3 g of PP, and 0.5 g of maleic anhydride. The mixture was stirred at 200°C until a homogeneous melt was obtained. Subsequently, 1.5 g of cellulose was added, and the mixture was stirred at 200°C until homogeneous. The resulting blend was then molded using a hot press at 120°C and 120 atm for 15 min.

### 2.5. Characterization and Analysis of Degradable Plastics

#### 2.5.1. Mechanical Properties

The tensile properties of the samples were evaluated in accordance with ASTM D638-14. This standard is used to determine key mechanical parameters, including tensile strength, elongation at break, and Young's modulus, for plastic materials with or without reinforcement. Dumbbell-shaped specimens were prepared with dimensions of 165 mm in length, 50 mm in width, and 3.2 mm in thickness (1/8 inch), as specified by the standard, to ensure accurate strain measurement [17]. The formulations tested consisted of durian peel cellulose contents of 1.5, 2.5, and 3.5 g and PLA contents of 3, 5, and 7 g, respectively.

#### 2.5.2. Chemical Properties

Fourier transform infrared (FTIR) spectroscopy was used to identify the chemical functional groups present in the samples. The analysis was performed using a Shimadzu 8400S spectrometer (Shimadzu, Japan). This technique measures the absorption of infrared radiation by the sample, providing information on its molecular structure and chemical composition. The sample formulation used for FTIR analysis consisted of 2.5 g of durian peel cellulose and 5 g of PLA.

X-ray fluorescence (XRF) spectrometry was employed to determine the elemental composition of the samples. XRF is a widely used analytical technique applicable to various forms of materials, including powders, solids, and pellets. In this study, the SMART OXIDE method with air atmosphere mode was applied using degradable plastic powder specimens. The sample formulation for XRF analysis consisted of 2.5 g of durian peel cellulose and 5 g of PLA.

#### 2.5.3. Thermal Properties

Thermal stability of the degradable plastics was evaluated using thermogravimetric analysis (TGA). Thermal degradation refers to the decomposition of polymers upon exposure to elevated temperatures, which defines the maximum usable temperature of the material. TGA measures the change in mass of a sample as a function of temperature, allowing the assessment of thermal events such as dehydration, decomposition, and oxidation. The thermogravimetric curve provides information on the thermal stability and decomposition behavior of the material at different temperatures. The analysis was carried out using a TGA instrument (Model TGA50, SrC30025100553, New Orleans, LA, USA). The sample formulation used for this test consisted of 2.5 g of durian peel cellulose and 5 g of PLA.

#### 2.5.4. Morphological Properties

The morphology of the samples was examined using scanning electron microscopy (SEM) to observe the surface and cross-sectional structures. SEM provides high-resolution images of the material microstructure. In this study, a ZEISS SEM instrument was used with an accelerating voltage of 15 kV at magnifications of 500×, 1000×, and 3000× for a selected area.

#### 2.5.5. Water Absorption

The water resistance of the degradable plastics was evaluated by a water absorption (swelling) test. Swelling determination was performed according to ASTM D2765-16 [18]. The samples were first weighed and then immersed in a solvent for 24 h. After immersion, the samples were removed, dried, and reweighed. In this analysis, formulations containing durian peel cellulose at

1.5, 2.5, and 3.5 g, with PLA contents of 3, 5, and 7 g, were tested. The swelling percentage was calculated using Equation (1).

$$Swelling = \frac{W_a - W_b}{W_b} \times 100\% \quad (1)$$

Where, $W_a$ is the weight of the expanded sample (g), and $W_b$ is the initial dry weight of the sample (g).

### 2.5.6. Biodegradability Rate

The biodegradability of the samples was evaluated using a soil burial test in accordance with ASTM G21-13 [19]. In this method, degradation occurs through direct contact between the degradable plastic and the soil. Specimens measuring 5 cm × 2 cm were prepared, weighed (initial mass), and buried in soil at a depth of 30 cm. After 3 days, the samples were removed, cleaned, dried, and reweighed (final mass). The mass loss was used to determine the biodegradation rate.

The burial conditions were maintained at approximately 32°C and pH 5.5–7, which are generally suitable for biodegradation, although actual conditions may vary depending on the environment. The formulations tested consisted of durian peel cellulose at 1.5, 2.5, and 3.5 g and PLA at 3, 5, and 7 g, respectively. The biodegradability was calculated using Equation (2).

$$Biodegradability\ (\%) = \frac{M_0 - M_1}{M_0} \times 100\% \quad (2)$$

Where, $M_0$ is the initial mass of the sample (g) and $M_1$ is the final mass after burial (g).

## 3. Results and Discussion

### 3.1. Mechanical Properties Analysis

In general, the incorporation of cellulose fibers into polymeric materials has been reported to enhance the strength and stiffness of composites, thereby improving their tensile properties [20]. As shown in Table 2 and Figure 1, the mechanical properties of samples containing 3.5 g of durian peel cellulose and varying PLA contents of 3, 5, and 7 g were evaluated.

**Table 2**. Mechanical properties of degradable plastics with varying durian peel cellulose–PLA compositions

| Cellulose mass (g) | PLA mass (g) | Tensile strength (MPa) | Elongation (%) | Young's modulus (MPa) |
|---|---|---|---|---|
| 3.5 | 3 | 2.5671 | 31 | 146.045 |
| 3.5 | 5 | 4.9175 | 53 | 161.32 |
| 3.5 | 7 | 9.3498 | 96 | 219.95 |
| 0 (pure PLA) | - | 5.00-42.0 | 15.0 – 100 | 2960-3600 |

Reference values for pure PLA were taken from MatWeb (material property database) [21].

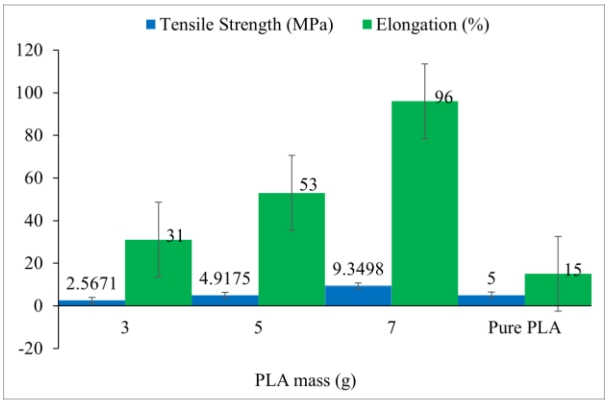

**Figure 1**. Mechanical properties of degradable plastics prepared with 3.5 g durian peel cellulose and varying PLA contents

This study investigated the mechanical properties of degradable plastics, focusing on tensile strength, elongation, and Young's modulus. In composite materials, the polymer matrix primarily functions to bind the fibers, transfer the applied load, and distribute stress uniformly, while the fibers act as the main load-bearing component due to their high strength and modulus [22]. As presented in Table 2, the tensile strength of the degradable plastics varied with PLA content at a fixed cellulose mass of 3.5 g. The sample containing 3 g of PLA showed a tensile strength of 2.5671 MPa, which increased to 4.9175 MPa for 5 g of PLA. Notably, the formulation containing 3.5 g of cellulose and 7 g of PLA exhibited the best mechanical performance, with the highest tensile strength of 9.3498 MPa, elongation of 96%, and Young's modulus of 219.95 MPa. This improvement is likely due to a more homogeneous distribution of components in the composite matrix. The results obtained in this study are comparable to the tensile strength of pure PLA reported in the literature (Table 2), indicating that the incorporation of PLA enhances the tensile strength of the plastic [23].

Table 2 also shows the elongation and Young's modulus of degradable plastics containing 3.5 g of durian peel cellulose with different PLA contents (3, 5, and 7 g). The elongation values ranged from 31% to 96%, while the Young's modulus ranged from 146.045 to 219.95 MPa. According to the MatWeb Material Properties Database, PLA typically exhibits an elongation at break of 15.0–100% and a Young's modulus of 2960–3600 MPa [20]. While the elongation values of the degradable plastics in this study are comparable to those of PLA, the Young's modulus values are still significantly lower. This may be attributed to poor dispersion of cellulose or weak interfacial bonding between the cellulose and the polymer matrix, as low compatibility can reduce the stiffness of the composite and lead to a decrease in modulus [24].

Previous studies have shown that the addition of plasticizers such as dibutyl maleate (DBM) and dibutyl fumarate (DBF) to PLA can alter its mechanical properties. In particular, DBF was reported to reduce yield strength and elastic modulus while increasing elongation at break and viscoelastic behavior [25]. PLA is inherently hydrophobic, which contributes to its rigidity and suitability for various applications [26]. Therefore, surface modification of hydrophilic fibers is necessary to improve their compatibility with the hydrophobic polymer matrix. Treated fibers typically exhibit a rougher surface texture, which promotes better interfacial adhesion, facilitates stress transfer, and enhances the mechanical interaction between the fibers and the matrix [27].

## 3.2. Chemical Properties Analysis

### 3.2.1. FTIR Analysis

FTIR was used to identify the chemical composition and functional groups of the materials. The chemical composition of a specimen influences the position of its absorption bands in the infrared spectrum. FTIR analysis was performed over the wavenumber range of 550–4000 $cm^{-1}$ using a sample formulation containing 2.5 g of durian peel cellulose and 5 g of PLA.

The results indicate the presence of hydroxyl (–OH) stretching vibrations in the cellulose, as shown in Figure 2 and summarized in Table 3. These vibrations were observed at wavenumbers of 3755.40, 3672.47, 3657.04, 3506.59, and 3120.40 $cm^{-1}$. Razali *et al.* [28] reported similar cellulose absorption bands in rice straw pulp at around 3327 $cm^{-1}$, while Rohmawati *et al.* [29] observed a significant increase in kapok cellulose content at 3349.78 $cm^{-1}$. The interaction between cellulose and PLA is associated with changes in hydrogen bonding and a decrease in O–H stretching intensity, indicating partial dissolution or improved compatibility between the components [30].

The carbonyl group (C=O) is often associated with polymer degradation, particularly in polyolefin-based materials such as polypropylene, and carbonyl-containing (C–O) compounds are commonly used as indicators of polyethylene degradation [31]. Gbadeyan *et al.* [32] reported the synthesis of degradable plastics from snail shell and bagasse cellulose with PLA, where FTIR spectra showed prominent C–O, C=O, and –CH stretching vibrations corresponding to –COOH functional groups. In the present study, the degradable plastics based on durian peel cellulose and PLA exhibited characteristic –OH, C–H, C=O, and C–O absorption bands, confirming the presence of these functional groups in the composite films.

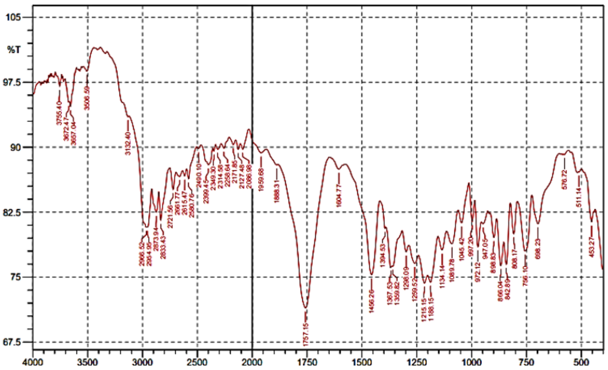

**Figure 2**. FTIR spectrum of durian peel cellulose–PLA degradable plastic

**Table 3**. FTIR absorption bands of durian peel cellulose–PLA degradable plastic

| Bond | Functional group | Wavenumber ($cm^{-1}$) | Peak shape |
|---|---|---|---|
| O-H | Alcohol | 3755.40 | Sharp |
| | | 3672.47 | |
| | | 3657.04 | |
| | | 3506.59 | |
| | | 3120.40 | |
| C-H | Alkanes | 2966.52 | Sharp |
| | | 2954.95 | |
| | | 2873.94 | |
| | | 2833.43 | |
| | | 2721.56 | |
| | | 2661.77 | |
| | | 2615.47 | |
| | | 2580.76 | |
| | | 2490.76 | |
| | | 2490.10 | |
| C-H | Aromatic rings | 453.27 | Sharp |
| | | 511.14 | |
| | | 576.72 | |
| | | 698.23 | |
| | | 756.10 | |
| | | 808.17 | |
| | | 842.89 | |
| | | 866.04 | |
| | | 898.83 | |
| | | 947.05 | |
| | | 972.12 | |
| | | 997.12 | |
| C=O | Carbonyl | 1359.82 | Sharp and Medium |
| | | 1367.53 | |
| | | 1394.53 | |
| | | 1456.26 | |
| | | 1604.77 | |
| | | 1757.15 | |
| | | 1888.3 | |
| | | 1959.68 | |
| C-O | Alkenes | 1089.78 | Medium |
| | | 1134.14 | |
| | | 1188.15 | |
| | | 1215.15 | |
| | | 1259.52 | |
| | | 1298.09 | |

The presence of abundant hydroxyl (–OH) groups indicates the hydrophilic nature of the material, which facilitates water absorption and enhances its susceptibility to degradation in soil. The additional free –OH groups are attributed to the reduced hydrogen bonding capacity between molecules, as well as to residual sodium hydroxide (NaOH) and other extractives remaining from the extraction process [33].

### 3.2.2. XRF Analysis

XRF spectrometry is a widely used analytical technique for determining the elemental composition of materials. It can analyze a broad range of elements, from boron (B) to uranium (U), based on their atomic numbers [34]. As shown in Table 4, this analysis focuses on the elemental composition of degradable plastics prepared from 2.5 g of durian peel cellulose and 5 g of PLA as the matrix. The corresponding XRF spectra are presented in Figure 3.

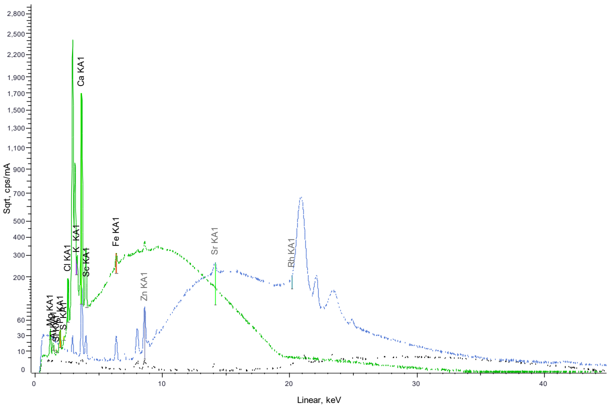

**Figure 3**. XRF spectrum of durian peel cellulose–PLA degradable plastic

**Table 4**. XRF elemental composition of durian peel cellulose–PLA degradable plastic

| Element | Concentration (wt%) | Peak position (keV) | Element name |
|---|---|---|---|
| Mg | 52.35 | 1.254 | Magnesium |
| Ca | 6.01 | 3.692 | Calcium |
| Al | 1.37 | 1.487 | Aluminum |
| P | 0.23 | 2.014 | Phosphorus |
| Fe | 0.23 | 6.404 | Iron |
| Cl | 0.32 | 2.622 | Chlorine |
| K | 0.23 | 3.314 | Potassium |
| Sr | 0.21 | 14.165 | Strontium |
| Zn | 0.19 | 8.639 | Zinc |
| Sc | 0.11 | 4.090 | Scandium |
| Rh | 0.03 | 20.216 | Rhodium |
| S | 0.01 | 2.307 | Sulfur |
| Si | 0.00 | 1.740 | Silicon |

XRF can also be used to estimate the presence of catalysts or inorganic residues within polymer matrices and to monitor material purity and safety for subsequent applications. Table 4 summarizes the XRF results for thirteen elements detected in the durian peel cellulose–PLA degradable plastics. As shown in Figure 3, peaks at 1.254, 1.487, 2.014, 2.307, 2.622, 3.314, 3.692, 4.090, 6.404, 8.639, 14.165, and 20.216 keV correspond to Mg, Al, P, S, Cl, K, Ca, Sc, Fe, Zn, Sr, and Rh, respectively. Among these, magnesium (Mg) exhibited the highest intensity, accounting for 52.35 wt% of the detected elements. Silicon (Si) was not detected in the degradable plastic sample. Previous studies have reported potassium (K) as a major inorganic element in palm bunch fiber [35]. In the present study, several elements associated with metal oxides or inorganic impurities, such as Mg, Al, Fe, Rh, and Sc, were detected; these elements are generally characterized by low toxicity [36, 37].

In a comparative study by Faten Adel Ismael *et al.* [38], various plastic wastes, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS), were analyzed using XRF. Most samples showed high silicon (Si) contents, along with lower amounts of manganese (Mn), chromium (Cr), hafnium (Hf), zinc (Zn), bromine (Br), niobium (Nb), arsenic (As), rubidium (Rb), and terbium (Tb). XRF is also commonly used to detect hazardous heavy metals in plastics, such as lead (Pb), mercury (Hg), and cadmium (Cd). In this study, the degradable plastics based on durian peel cellulose and a PLA matrix were found to be free of such hazardous metals.

## 3.3. Thermal Properties Analysis

TGA was used to evaluate the thermal stability of the degradable plastics and to examine mass changes during heating. The degradable plastic sample consisted of 2.5 g of durian peel cellulose and 5 g of PLA. Figure 4 shows the TGA curve, which plots mass as a function of temperature.

As shown in Figure 4, the TGA thermogram of the durian peel cellulose–PLA degradable plastic indicates a progressive mass loss with increasing temperature. The degradation process occurred in two main stages. The first stage took place over the temperature range of approximately 30–403.99°C, corresponding to the initial decomposition of the composite. The second stage was characterized by a rapid mass loss and occurred between 357.67°C and 443.67°C, which is associated with further degradation and structural transformation of the material. Overall, the sample exhibited a total mass loss of 94.952%, leaving a residue of 11.774 mg after the completion of the degradation process. The thermogravimetric behavior reflects both heat-induced reactions and changes in the structure and phase of the material. At higher temperatures, extensive decomposition occurred, and the material was almost completely degraded by 600°C. During this stage, the samples showed the release of hydrogen-containing groups, chain scission, and conversion into carbonaceous structures [39, 40].

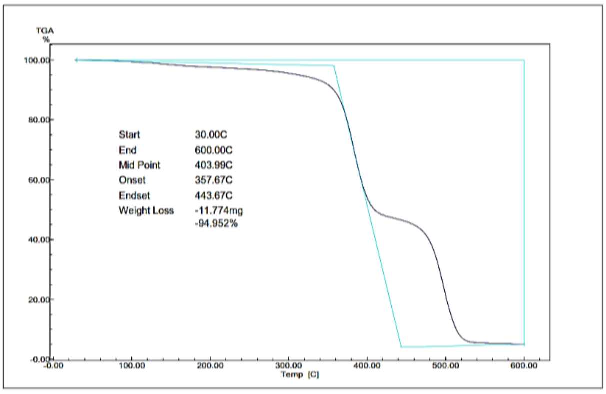

**Figure 4**. TGA curve of durian peel cellulose–PLA degradable plastic

Gunti *et al.* [41] reported that PLA in cellulose fiber–PLA biocomposites degraded at around 322°C, with the degradation process occurring within the range of 322–430°C. Similarly, Dewi *et al.* [33] investigated the thermal properties of PLA-modified avocado seed starch-based degradable plastics and observed a gradual degradation starting at 30°C, with a maximum degradation temperature ($T_{max}$) between 356.86°C and 413.64°C, leaving a residual mass of 4.290 mg (97.500% mass loss). The amorphous structure of cellulose-based degradable plastics contributes to their degradation at lower temperatures compared to pure cellulose. Between 370 and 600°C, cellulose is transformed into a polycyclic aromatic carbonaceous residue known as char, which is formed when organic materials are exposed to very high temperatures [42].

Studies have shown a correlation between the residual mass after decomposition and the thermal resistance of materials such as durian peel cellulose–PLA degradable plastics, with higher residual mass generally indicating better thermal resistance. It has also been reported that the thermal decomposition temperature of PLA (approximately 225°C) is higher than its melting point (around 170°C), which is advantageous for processing in polymer and composite applications, such as injection molding. In contrast, many other degradable plastics have narrower processing temperature windows due to their tendency to degrade shortly after melting [43].

### 3.4. Morphological Properties Analysis

SEM was used to examine the surface and cross-sectional morphology of the degradable plastics. SEM generates high-resolution images by scanning a focused electron beam over the sample surface. Figure 5 shows SEM micrographs of degradable plastics prepared from 2.5 g of durian peel cellulose and 5 g of PLA matrix.

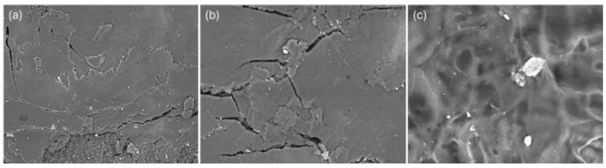

**Figure 5**. SEM images of durian peel cellulose–PLA degradable plastic at (a) 500×, (b) 1000×, and (c) 3000× magnification

The SEM images reveal the morphology of particles embedded in the polymer matrix and indicate that their distribution is not completely uniform. The durian peel cellulose–PLA degradable plastic exhibits a heterogeneous microstructure with residual porosity and voids, which are more clearly observed at 500× magnification. As shown in Figure 5(a), fibers, agglomerates, and surface depressions are evident, and the wide variation in particle size and shape suggests non-uniform dispersion of cellulose within the PLA matrix. This morphology also indicates limited interfacial compatibility between PLA and cellulose, which can restrict polymer chain mobility [44].

Improved dispersion of cellulose within the PLA matrix is essential to enhance interfacial adhesion and facilitate effective stress transfer from the matrix to the reinforcing fibers, thereby improving mechanical properties. Moreover, changes in chain mobility, as well as increases in crystallization rate and crystallinity due to the incorporation of reinforcements, have been reported to influence the thermomechanical and barrier properties of polymer composites [45].

The irregular morphology observed may also be attributed to incomplete dissolution of durian peel cellulose fibers, PLA, and other additives. The mixing process plays a critical role in controlling the solubility and dispersion of these components [33, 46]; longer stirring times generally improve homogeneity, whereas insufficient mixing leads to poorer dispersion. Moreover, the flow behavior of the polymer melt strongly influences the final morphology and density of the plastic, particularly for low-viscosity materials [47].

### 3.5. Water Absorption Analysis

Water absorption refers to the ability of degradable plastics to take up water. As shown in Figure 6, the water-absorption behavior of durian peel cellulose–PLA composites was evaluated using cellulose contents of 1.5, 2.5, and 3.5 g and PLA contents of 3, 5, and 7 g, and the amount of absorbed water is presented in the figure. This property is important because moisture uptake can influence mechanical strength, dimensional stability, and surface appearance; therefore, water absorption is a key factor in assessing the overall performance of these materials. In polymeric systems, water uptake may induce both chemical and physical changes, which in turn affect material behavior. It has been reported that PLA can absorb up to approximately 1% of its own mass in water [48].

As shown in Figure 6, the water absorption of degradable plastics prepared with 1.5 g of durian peel cellulose ranged from 9.39% to 12.28% for PLA contents of 3, 5, and 7 g, respectively. For samples containing 2.5 g of cellulose, the absorption ranged from 7.66% to 9.36%, while for 3.5 g of cellulose, it ranged from 4.89% to 8.09%. The lowest swelling was observed for the composite containing 3.5 g of cellulose and 3 g of PLA, with a water absorption of 4.89%. In comparison, pure PLA has been reported to exhibit very low water absorption (about 0.3%), corresponding to a swelling degree of approximately 0.66% in width [49].

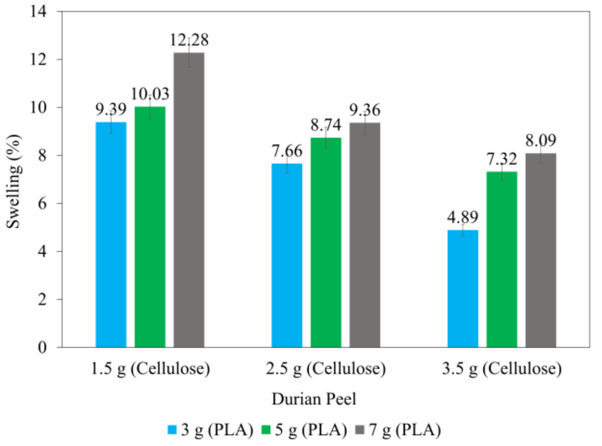

**Figure 6**. Water absorption of degradable plastics with varying durian peel cellulose–PLA compositions

Improved interfacial interaction between PLA and cellulose can be achieved through chemical modification, mainly by reducing the hydrophilicity of the cellulose surface and increasing the hydrophilicity of PLA. The surface of cellulose contains a high density of hydroxyl groups, which makes it inherently hydrophilic [50]. The highest swelling was observed for the composite containing 1.5 g of cellulose and 7 g of PLA, with a water absorption of 12.28%. This behavior can be attributed to increased porosity of the cellulose fibers, which leads to a larger specific surface area, especially for smaller fiber sizes, thereby enhancing water uptake [51].

Although PLA is biodegradable, it is sensitive to humidity at elevated temperatures, which can accelerate hydrolysis. Natural fibers are inherently hydrophilic and therefore prone to water absorption, which can cause swelling and dimensional changes in composites when exposed to moisture [52]. Dong *et al.* [53] reported that the water absorption of PLA-based cellulose biocomposites reinforced with macadamia nut shell powder was largely governed by the hydrophilic nature of the filler, with higher filler content leading to higher water uptake. Pure PLA exhibits minimal water absorption due to its hydrophobic nature, whereas durian peel cellulose–PLA degradable plastics show higher water absorption because of the abundant hydroxyl groups in untreated cellulose and the relatively poor interfacial adhesion between the fibers and the PLA matrix. In this study, durian peel cellulose was used as a reinforcement to improve the mechanical properties of PLA and reduce its brittleness. The blending process, assisted by a coupling agent (PP-g-MA), was applied to reduce the effective hydrophilicity of cellulose and to improve dispersion and interfacial bonding [54].

### 3.6. Biodegradability Rate Analysis

Biodegradation testing was conducted to evaluate the degradation rate of the degradable plastics and to estimate the time required for the materials to undergo complete decomposition in soil. As shown in Figure 7, the biodegradability of the samples containing different amounts of durian peel cellulose (1.5, 2.5, and 3.5 g) and PLA (3, 5, and 7 g) was assessed using a soil burial test.

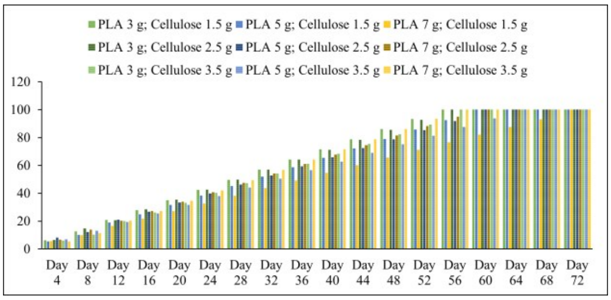

**Figure 7**. Extrapolation of the degradation rate for estimating the total plastic decomposition time

Each sample was monitored over a period of 12 days to determine the extent of mass loss due to degradation. The biodegradation rate was then estimated by extrapolation based on the observed trends, as illustrated in Figure 7. The extrapolation results suggest that the degradable plastics are expected to reach complete degradation within approximately 56 to 72 days. The fastest degradation was predicted for samples containing 3 g of PLA with cellulose contents of 1.5, 2.5, and 3.5 g, with an estimated degradation time of about 56 days. In contrast, the slowest degradation was estimated for the formulation with the highest PLA content (7 g) and the lowest cellulose content (1.5 g), which required approximately 72 days. Dewi *et al.* [33] reported that a biodegradable plastic based on avocado starch and PLA exhibited a biodegradability of 37.988% within 12 days, which is comparable to the trend observed in this study.

Brunšek *et al.* [55] investigated bioplastics reinforced with cellulose fibers and PLA and reported that flax fibers exhibited the highest mass loss after 11 days of exposure to microorganisms, followed by jute and sisal fibers. Jute showed a mass loss of 44.51%, whereas sisal exhibited a reduction of 7.92%. These results indicate that the chemical composition of the fibers significantly influences the biodegradation rate. Pure PLA shows low water absorption due to its hydrophobic nature, which generally slows its biodegradation. Studies on PLA-based biocomposites reinforced with natural fillers, such as macadamia seed shells, have demonstrated that the incorporation of natural resources can enhance biodegradation and improve sustainability [56].

Previous reviews on PLA-based plastics have shown that the mechanisms of biodegradation in both aerobic and anaerobic environments are well understood, and the use of PLA-degrading enzymes has been reported to be an effective approach to accelerate biodegradation [57]. Polymers are long-chain molecules composed of repeating monomer units and can exist as homopolymers or copolymers. For a material to be classified as biodegradable according to certain standards, at least 60% of its organic carbon must be converted to carbon dioxide within six months. The amount of filler used in a composite has a significant effect on its biodegradability, with higher filler contents generally leading to faster degradation [58].

## 4. Conclusion

This study successfully produced a biodegradable and sustainable plastic based on durian peel cellulose reinforced with a polylactic acid (PLA) matrix. The tensile strength of 9.3 MPa indicates strong potential for substituting single-use plastics, suggesting that the material is suitable for carrying typical grocery items. Chemical functional group analysis confirmed the presence of groups capable of interacting with water, which promotes degradation in a soil environment. Elemental analysis revealed the presence of metal oxides (as impurities) such as Mg, Al, Fe, Rh, and Sc, which are present at low-toxicity levels. Consequently, durian peel cellulose/PLA composites show promise as environmentally friendly alternatives to conventional synthetic food packaging materials. However, water absorption tests indicated that the material still exhibits suboptimal performance. Future work will focus on a deeper investigation of the degradation and absorption mechanisms, optimization of water-absorption properties, and incorporation of suitable additives to improve performance. In addition, appropriate molding methods for durian peel cellulose/PLA composites will be evaluated to support their practical application as food packaging materials.

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