



Synthesis and Characterization of Water Hyacinth Stem (*Eichhornia crassipes*) Cellulose-Based Degradable Plastic Incorporated with Poly(lactic acid)

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ABSTRACT

Plastic pollution drives the urgent need for eco-friendly alternatives. This study successfully synthesized a homogeneous degradable plastic based on water hyacinth stem cellulose (WHSC) and poly(lactic acid) (PLA). The research method consisted of several stages, namely the preparation of cellulose from WHSC (including pre-delignification and delignification), the formulation of the degradable plastic, and characterization of the resulting material. FTIR analysis confirmed successful blending through hydrogen bonds (–OH) and carbonyl groups (C=O) interactions. This synergy yielded high thermal stability (T_{onset}) = 342.43°C, ensuring safe processing at 180–200°C. An optimal formulation of 1.5 g WHSC and 7 g PLA significantly enhanced mechanical properties, achieving a tensile strength of 10.993 MPa and an elongation of 84.10%, while minimizing water swelling to 5.3%. Despite a Young's modulus below pure PLA due to interfacial bonding limitations, this optimal degradable plastic demonstrated accelerated biodegradability and holds great potential for commercial eco-friendly material applications.

Keywords: biodegradability, degradable plastic, mechanical properties, poly(lactic acid), water hyacinth cellulose.

1. INTRODUCTION

The issue of plastic waste has reached crisis proportions on a global scale. The primary cause for concern is the non-degradable nature of the polymer, which has led to its accumulation in various ecosystems. In the face of mounting volumes of plastic waste, the development and implementation of effective and sustainable management strategies is paramount [1]. One of the most important products made from petrochemicals is plastic. Plastics are used in all aspects of life. The majority of polymers

have their origins in oil, and are produced using techniques of either addition or condensation polymerization [2]. These substances are widely regarded as having a detrimental effect on the environment due to their resistance to biodegradation. The disposal of oil-based plastics is a contentious issue. Such plastics are not easily disposed of and have a detrimental effect on the environment, contributing to both landfills and environmental pollution [3].

The growth in global demand for bio-based materials as alternatives to conventional

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plastics has been driven by mounting concern for environmental sustainability. The primary advantage of utilising such waste materials is that the raw materials are sourced from renewables and are characterised by their biodegradability [4]. The utilisation of biomass derived from renewable resources, including environmental waste and aquatic organic waste, represents a promising approach. The utilisation of organic waste materials, such as water hyacinth (*Eichhornia crassipes*), for the purpose of bio-based polymer material synthesis, has been demonstrated to present a potential strategy for the mitigation of the environmental problems associated with conventional petroleum-based plastics [5].

Water hyacinth (WH) has been identified as a potential industrial crop, exhibiting a number of distinctive characteristics. However, research into the application of WH in the development of new materials appears to be in its infancy [6]. As demonstrated in the relevant literature, the presence of WH has been shown to disrupt aquatic ecosystems. A number of mechanisms through which this disruption occurs have been identified, including the reduction of oxygen levels and the limitation of sunlight. In addition, disturbance has been observed in the native species inhabiting these environments [7]. This disruption can lead to a deterioration in water quality and biodiversity, which has significant ecological consequences. The economic implications of its rapid spread are significant, impacting sectors such as agriculture, fisheries and navigation, and resulting in substantial costs to the local economy and the livelihoods of individuals [8]. The WH plant presents a promising source of renewable biomass for degradable plastic applications due to its high cellulose content. The biomass of WH contains cellulose, hemicellulose and lignin, properties which make it a promising material for use in the synthesis of degradable plastics. Cellulose is a material of considerable concern due to its potential for biodegradation and durability [9]. However, its low dissolubility in water is a challenge.

The decomposition of degradable plastics is strongly governed by variables such as moisture uptake and the availability of terminal carboxyl or hydroxyl groups [10].

The mounting requirement for green materials has resulted in the innovation of degradable plastics derived from cellulose and polylactic acid (PLA), with the objective of substitute for synthetic polymers in industrial and commercial applications [11]. Among the biopolymers that have been discovered, PLA is special because it comes from natural sources, it is compatible with living things, and it works well compared to other plastics like polystyrene (PS) and polyethylene terephthalate (PET) [12]. Various studies continue to seek to optimize the compatible properties in hydrophilic biomass and hydrophobic PLA. A typical initial stage is to adjust the biomass substance to improve its interfacial compatibility with PLA, thus successfully dealing with the drawbacks of PLA [13]. The combination of PLA with specific types of cellulose has been shown to improve the thermal, mechanical and physical properties of the polymeric compounds, making them suitable for a wide range of products [14].

In a study conducted by Termizi et al. [15], it was noted that PLA-cellulose blends exhibit better tensile strength and Young's modulus than pure PLA. Conversely, the addition of cellulose to the PLA blend was found to reduce elongation, and the surface morphology of pure PLA is relatively smoother than that of the PLA/cellulose blend. Costa et al. [16] conducted a study to evaluate the biodegradability and ecotoxicity of PLA-based biocomposites. These biocomposites contained 30-40% microfibre cellulose. The material under scrutiny has been determined to adhere to the limits set by the European Union with regard to fluorine and heavy metal content. The biodegradability of the material was determined through respirometric testing conducted under thermophilic conditions, which revealed a degradation rate of 81% within a period of 155 days.

Ferreira et al. [17] investigated the compatibility of PLA/BioPE blends with PP-g-MA. Compared with pure PLA, these blends were found to improve mechanical properties as well as mechanical and thermal stability. The incorporation of the polypropylene-grafted maleic anhydride (PP-g-MA) into degradable plastics has been identified as a potential solution to enhance the morphology of the uniformly dispersed phase, thereby improving the processability of the resultant material. In consideration of the efficacy of the PP-g-MA compound in the context of its utilisation as a linkage agent within synthetic composite and polymeric applications, it is anticipated that the compound will exhibit performance that meets the requisite standard of optimality [18,19].

Although previous studies, such as Termizi et al. [15], have successfully demonstrated the basic mechanical benefits of embedding cellulose into PLA, a critical research gap remains regarding the processing window and industrial moldability of these biocomposites. Traditional PLA-cellulose blends frequently suffer from severe phase separation and structural vulnerability due to the inherent incompatibility between the highly hydrophobic PLA matrix and raw hydrophilic cellulose fibers. Furthermore, most prior research relies on highly purified, expensive commercial cellulose networks. There is a notable lack of comprehensive insight into the utilization of unpurified, highly abundant agricultural waste fibers when regulated via a multi-component compatibilization mechanism.

To bridge this research gap, the innovative aspect of this research lies in the use of cellulose fibres from water hyacinth stem, specifically modified using a formulation of PLA and PP-g-MA compatibiliser, which fundamentally expands the material boundaries discussed in prior single-matrix works. Water hyacinth stems (WHS), otherwise referred to as petioles, have been found to contain elevated levels of cellulose. The composition of the material is as follows: 25% cellulose, 33% hemicellulose, and 10%

lignin. Chemical analysis of WHS indicates that cellulose constitutes 23–57% of their dry weight. WH is a readily available resource that can be utilised as a source of cellulose with minimal financial cost [20]. A number of studies have indicated that WH contains elevated levels of cellulose, accompanied by comparatively low levels of lignin when compared with other lignocellulosic materials such as rice, wood, bamboo, and sugarcane [21].

The issue with degradable plastics is that they remain challenging to mould, which poses a significant obstacle for industrial production. They are also not as strong as synthetic plastics, thus limiting their applications [22]. This means that novel solutions that can address these issues are essential. This research addresses these challenges by processing WHSC-based degradable plastics using thermopressing, utilizing PLA as a filler and PP-g-MA as a compatibilizer for degradable plastics made from water hyacinth stem cellulose (WHSC). To produce cellulose-based degradable plastics with optimal mechanical properties, the use of PLA has been identified as the appropriate approach. This is supported by the properties of PLA as a degradable organic polymer [23]. An evaluation of the effect of PLA blends on degradable plastics made from WHSC was carried out by varying the concentrations of PLA (3, 5, 8, and 7 g) and WHSC (1.5, 2.5, and 3.5 g) to achieve optimal mechanical, thermal, and physical properties.

2. RESEARCH METHODS

This section outlines the comprehensive methodology employed to develop and evaluate the water hyacinth-based degradable plastic films. The research process is systematically structured into two primary phases: materials acquisition and the experimental procedures. The experimental work details the preparation of raw biomass, the chemical extraction of pure cellulose, and the subsequent synthesis of the composite films using a hot-press technique. Finally, the analytical framework used to characterize the

resulting films' physical, mechanical, and environmental properties is presented.

2.1. Materials

The main material used in this study was water hyacinth (*Eichhornia crassipes*), an invasive weed species collected from rice fields and water bodies in Nisam Sub-district, North Aceh Regency. The plant stems were extracted to obtain cellulose as a raw material for the production of degradable plastic. Xylene (Merck Supelco 108297, Burlington, MA, USA), maleic anhydride (MA) 99% (Sigma-Aldrich-8.00408.1000), and polypropylene (PP) were used as matrix components. Additional chemical reagents included hydrogen peroxide (H₂O₂) 30% 500 mL (Merck-1.07209.0500), Polylactic Acid (PLA) C₃H₆O₃, 90.08 g/mol, Sigma-Aldrich – 38534 – 1G), Sodium Hydroxide (NaOH, Merck-1310-73-2), and Sodium Hypochlorite (NaOCl, Merck-2828 90 00). Distilled water was procured from PT Bratachem, Surabaya, Indonesia.

2.2. Experimental Procedure

The experimental process comprised three core stages: preparation of the water hyacinth stem powder, chemical extraction of the cellulose, and the synthesis of the degradable plastic films. To evaluate the performance and quality of the developed films, the final products were characterized based on their mechanical properties, chemical composition, thermal stability, water absorption capacity, and biodegradation rate.

2.2.1. Preparation of Water Hyacinth Stem (WHS) Powder

The preparation process began by washing the water hyacinth stems with clean water until they were free of dirt, followed by cutting them into small segments measuring 1–3 cm. These pieces were subjected to a continuous sun-drying process for 3 consecutive days, accumulating approximately 24 hours of direct sunlight exposure under a typical tropical ambient temperature ranging between 31 and 33°C. Drying was terminated once the biomass

achieved a stable, constant weight, ensuring the thorough removal of unbound moisture. Following the drying stage, the stems were ground using a commercial blender, and the resulting powder was sieved through a 50-mesh screen to yield uniform WHS powder ready for utilization.

2.2.2. Water Hyacinth Stem Cellulose (WHSC) Extraction

The cellulose extraction process was initiated by mixing the dried WHS powder with distilled water at a volume ratio of 1:10 (w/v). The mixture was stirred until homogeneous and heated at 100°C for 60 minutes. The suspension was filtered to separate and remove the solid fractions, which were subsequently dried in an oven at 105°C until a constant weight was reached. Next, the treated solids were fully immersed in a 5% NaOH solution and digested using an autoclave at 121°C for 60 minutes. The process continued with a bleaching stage, where the solids were mixed with 3% H₂O₂ and heated at 70°C for 30 minutes. After filtration, the resulting solids were reacted with 2% NaOCl under heating for another 30 minutes. In the final stage, the solids were washed repeatedly with distilled water until a neutral pH was achieved, followed by oven-drying at 105°C to obtain pure, dry WHSC powder. For film preparation, the dry WHSC powder was systematically passed through a 50-mesh sieve; the fine fraction (≤ 0.3 mm) was collected for formulation, while the larger retained particles were discarded to ensure structural uniformity.

2.2.3. Synthesis of WHSC-Based Degradable Plastic (WHSC-DP) Films

The degradable plastic (DP) synthesis began by dissolving 3 g of PLA, 3 g of PP, and 0.5 g of MA in 10 mL of xylene inside a glass beaker. These initial polymer matrix components were dissolved under continuous magnetic stirring at a controlled speed of 350 rpm for 30 minutes to ensure complete macromolecular dissolution at a temperature of 125°C. Next, 1.5 g of WHSC was

integrated directly into the solvent-based solution without any acid addition, and the mechanical agitation was systematically increased to 500 rpm for an additional 45 minutes at 150°C until a macroscopically uniform and viscous mixture was obtained. The resulting mixture was then molded using the hot press method at 120°C with a pressure of 130 kg/cm² and a dwell time of 15 minutes. The final degradable plastic film was allowed to cool to ambient temperature before being removed from the mold. This procedure was repeated with specified variations in the PLA and WHSC ratios. Finally, the characteristics of the resulting WHSC-DP films were evaluated through mechanical property testing, chemical analysis, water absorption testing, and biodegradability testing.

2.3. Characterization and Analysis

2.3.1. Mechanical Properties

The mechanical properties of the WHSC-DP films, including tensile strength, elongation at break, and Young's modulus, were determined using a ZwickRoell universal testing machine in accordance with the ASTM D-638 Type I standard [24]. The test specimens were prepared with a total length of 165 mm, a gauge length of 50 mm, and a thickness of 3.2 mm. This specific thickness was selected to represent the bulk material properties and to enhance the accuracy of the strain data captured during testing [24].

2.3.2. Chemical Properties

Fourier-transform infrared (FTIR) spectroscopy was performed to characterize the chemical functional groups and identify the molecular composition of the WHSC-DP films, which is essential for evaluating their potential biodegradability. The spectral analysis was conducted using a Shimadzu 8400S FTIR spectrometer operating within the wavenumber range of 550–4000 cm⁻¹.

2.3.3 Thermal Properties

The thermal stability of the WHSC-DP films was evaluated using thermogravimetric analysis (TGA). This analysis monitored changes in sample weight as a function of

temperature during programmed heating, cooling, and isothermal processes under a controlled atmosphere. The measurements were carried out using a TGA-50 SrC30025100553 model instrument (New Orleans, LA, USA).

2.3.4. Water Absorption

The water resistance and swelling behavior of the WHSC-DP films were evaluated via a swelling test in accordance with the ASTM D2765 standard [25]. The initial mass of each sample was recorded prior to immersion in water for 24 hours. Subsequently, the mass of the swollen sample was measured before it was oven-dried to a constant final weight. The swelling degree, which reflects the volume expansion and structural distortion caused by water penetration into the polymer matrix, was calculated using Equation (1):

$$\text{Swelling Degree (\%)} = \frac{W_s - W_i}{W_i} \cdot 100\% \quad (1)$$

Where W_s is the weight of the swollen sample (g) and W_i is the initial weight of the sample before immersion (g).

2.3.5. Biodegradability Rate

The decomposition rate of the WHSC-DP films was determined through a soil burial test following the ASTM D5988 standard to evaluate the degradation kinetics [26]. Specimens were cut into dimensions of 5 × 2 cm, and their initial mass M_0 was recorded. The samples were then buried in soil at a depth of 30 cm. The specimens were retrieved periodically at four-day intervals, carefully cleaned of soil residues, and weighed to determine the final remaining mass M_f . The weight loss percentage, representing the biodegradability rate, was calculated using Equation (2):

$$\text{Biodegradability (\%)} = \frac{M_0 - M_f}{M_0} \cdot 100\% \quad (2)$$

In this equation, M_0 is the initial mass of the sample (g) and M_f is the final mass of the WHSC-DP (g). This biodegradation test aims to evaluate the degradation kinetics of the

material and estimate the time required for the WHSC-DP to biodegrade in the soil.

3. RESULTS AND DISCUSSION

This section presents a comprehensive evaluation and discussion of the experimental results obtained from the characterization of the water hyacinth stem cellulose-based degradable plastic (WHSC-DP) films. The performance of the developed composite films is systematically analyzed across five key performance indicators: mechanical robustness, chemical structural composition, thermal degradation stability, water absorption resistance, and environmental biodegradability behavior. The correlations between varying formulation ratios of WHSC and PLA are thoroughly discussed to establish the optimal composition required for sustainable food packaging or alternative degradable film applications.

3.1. Mechanical Properties Analysis

The tensile strength characteristics of the material in this study were evaluated using a texture analysis approach. The optimization of these tensile properties aims to ensure that the material can withstand external loads to the maximum extent possible before the WHSC-DP undergoes deformation or failure. Such failures are generally caused by cracks resulting from excessive strain, or, conversely, by deformation of the structure [27].

Based on Table 1, there is a clear trend of increasing mechanical properties for the WHSC-DP composite as the amount of PLA mixed with a constant 1.5 g of WHSC increases. The tensile strength and elongation

at break reached their highest values at 7 g of PLA, yielding 10.993 MPa and 84.10%, respectively. This result confirms that incorporating a higher mass fraction of PLA effectively enhances the mechanical properties of WHSC-DP, steering them closer toward the threshold of pure PLA.

However, the Young's modulus of the WHSC-DP composites across all formulations (232.92–381.95 MPa) remains significantly lower than that of pristine pure PLA (3600 MPa) [28]. This sharp decrease compared to the pure matrix is primarily driven by the fundamental chemical incompatibility at the phase boundary. The hydrophilic cellulose molecules in WHSC possess abundant surface hydroxyl (–OH) groups, which lack chemical affinity for the hydrophobic, non-polar backbone of the PLA matrix [29]. Consequently, instead of forming strong covalent or hydrogen bonds across the interface, the components only interact via weak Van der Waals forces. During solidification, this poor thermodynamic compatibility prevents molecular interdiffusion, leading to the formation of micro-voids, interfacial gaps, and localized stress concentration points under tensile load [30].

When an external load is applied, these weak interfaces fail to facilitate efficient shear stress transfer from the continuous PLA matrix to the rigid WHSC fibers [31]. Rather than acting as reinforcing agents, the poorly bonded cellulose particles act as structural defects that readily delaminate, leading to premature yielding and a drastically reduced collective stiffness (Young's modulus) [32].

Table 1. Mechanical properties of WHSC-DP.

WHSC (g)	PLA (g)	Tensile Strength (MPa)	Elongation (%)	Young's modulus (MPa)
1.5	3	4.7983	39.90	232.92
	5	8.8483	71.80	291.04
	7	10.993	84.10	381.95
-	Pure PLA*	60	430	3600

*Note: Discrete representative baseline values for pristine PLA obtained from Ref. [28].

Interestingly, within the composite series, the Young's modulus increases from 232.92 MPa to 381.95 MPa as the PLA content rises. This intra-composite phenomenon occurs because a higher polymer matrix ratio provides better encapsulation of the cellulose fibers, reducing local fiber-fiber agglomeration and restricting the localized mobility of the polymer chains near the fiber interface [33].

Additionally, the absolute tensile strength and elongation of the biocomposite are substantially influenced by the incorporation of cellulose into the PLA matrix. Previous literature indicates that an increased cellulose content relative to a pure polymer matrix typically results in reduced tensile strength and elongation at break due to poor stress transfer across the phase boundary, while the Young's modulus often shows inconsistent trends. Similarly, Gregor-Svetec et al. [34] observed that while the Young's modulus of cellulose-filled PLA blends remained relatively stable, both elongation at break and tensile strength were severely compromised upon fiber addition compared to the pristine polymer.

However, the structural performance of the WHSC-DP composite in this study successfully counteracts this traditional declining trend through targeted chemical and physical adjustments, revealing an opposite, positive reinforcement behavior within its stable limits. The fundamental divergence between this work and the system reported by Gregor-Svetec et al. [34] lies in the integration of the multi-component PP-g-MA compatibilizer and a highly controlled particle geometry. In uncompatibilized reference systems, crude natural fibers act as incompatible voids that trigger early micro-cracking. Conversely, in our formulation, the maleic anhydride (MA) groups of the compatibilizer undergo robust esterification and hydrogen bonding with the free surface hydroxyl (–OH) groups of the WHSC, while the hydrophobic backbone successfully interlocks with the matrix. Furthermore, refining the WHSC powder through a 50-mesh sieve (<0.3 mm) vastly expands the

effective surface area for mechanical interlocking. This synergistic combination prevents local macro-agglomeration and facilitates efficient shear stress transfer, thereby allowing the embedded water hyacinth cellulose to actively support tensile loads rather than acting as a structural defect. To assess the commercial viability of WHSC-DP, studies on the optimal composition must balance mechanical thresholds with environmental and economic benefits. For degradable packaging applications, rigid containers or structural films generally require a minimum tensile strength of 5–10 MPa to withstand loads during transport [35]. As shown in Table 1, the formulation containing 7 g of PLA and 1.5 g (17.6 wt%) of cellulose successfully met these structural requirements, achieving a tensile strength of 10.993 MPa and an impressive elongation at break of 84.10%.

From a sustainability perspective, replacing up to 20 wt% of synthetic PLA with WHSC derived directly from raw waste reduces the production costs of the material and decreases reliance on petroleum-based processing energy. Furthermore, the abundance of hydroxyl groups on the exposed cellulose surface significantly accelerates microbial colonisation and enzymatic hydrolysis, thereby drastically increasing the overall biodegradability rate of the packaging material once it has been discarded [36]. Therefore, despite a compromise in overall stiffness compared with pure PLA, formulations containing 10–20 wt% cellulose emerge as the optimal performance range, offering an environmentally friendly, cost-effective and mechanically adequate matrix for sustainable packaging design [37].

3.2. Chemical Properties Analysis

The composition of the sample materials was determined by employing Fourier transform infrared (FTIR) spectroscopy in this study. Absorption features at specific wavelengths reflect the molecular structure of the materials. The FTIR analysis was conducted over a wavenumber range of 550 to 4000

cm^{-1} . Table 2 and Figure 1 show the results of FTIR testing on the WHSC-DP sample, which was prepared using a mixture of 1.5 g of WHSC and 7 g of PLA.

Figure 1 presents the FTIR spectrum of the WHSC-DP composite, displaying the characteristic absorption bands inherited from its constituent phases. The absorption bands in the region of $4000\text{--}3200\text{ cm}^{-1}$ primarily represent the O–H hydroxyl stretching vibrations. In the composite spectrum, broad peaks are observed at 3502.73 cm^{-1} and 3404.36 cm^{-1} , which are characteristic of the extensive intra- and intermolecular hydrogen bonding inherently

present within the linear cellulose chains of WHSC [38]. The slight shift and broadening of these peaks compared to raw cellulose suggest potential interfacial hydrogen bonding between the hydroxyl groups of WHSC and the oxygen atoms in the PLA chains. Meanwhile, the sharp peak at 3743.83 cm^{-1} indicates free, unbonded –OH groups located on the outer surface of the cellulose microfibrils.

The aliphatic C–H stretching vibrations constituting the main organic framework of WHSC are clearly detected at 2993.52 and 2902.87 cm^{-1} , corresponding to the –CH₂– and –CH– groups, respectively [39].

Table 2. FTIR Spectrum of WHSC-DP.

Bonding	Compound Type	Wave Numbers (cm^{-1})
O–H	Hydroxyl	$4000\text{--}3200$
C–H	Aliphatic	$3000\text{--}2800$
C=O	Carbonyl	$1740\text{--}1750$
C=C	Alkenes	$1650\text{--}1300$
C–O	Ethers or Esters	$1300\text{--}1000$

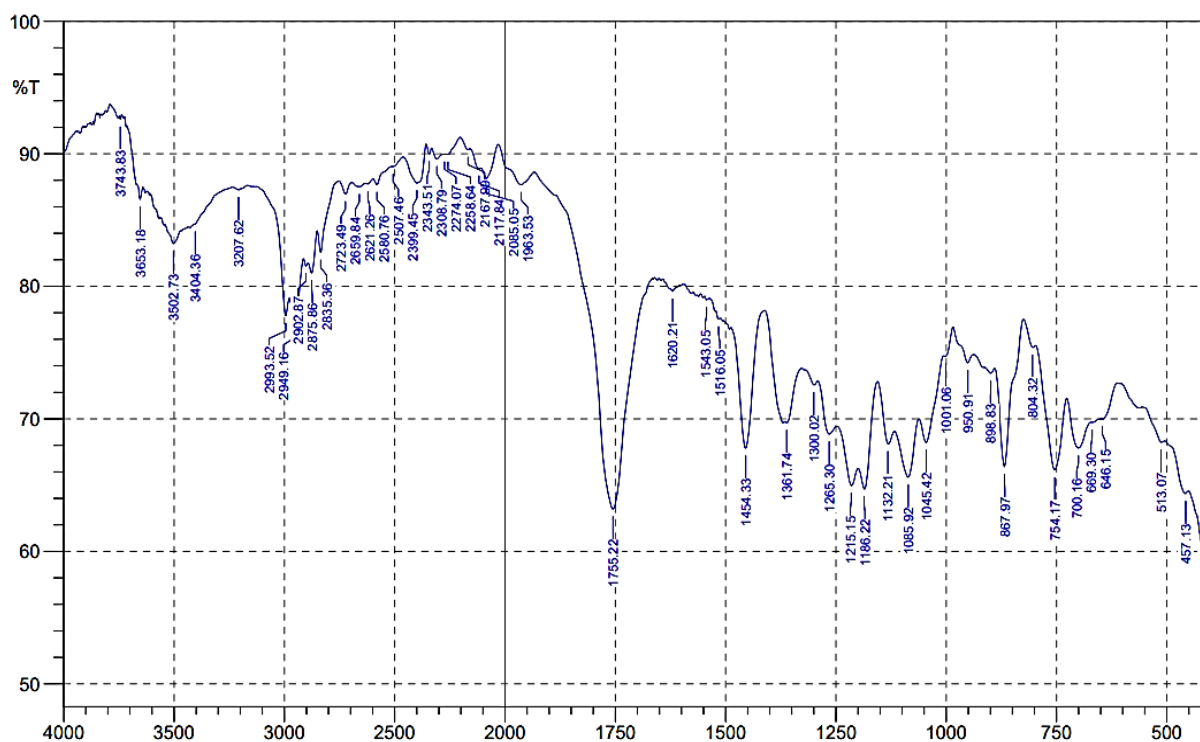


Figure 1. FTIR of WHSC-DP.

The successful incorporation of the PLA polymer into the composite matrix is primarily confirmed by the appearance of a very sharp and intense peak at 1755.22 cm^{-1} . This band corresponds to the carbonyl group ($\text{C}=\text{O}$) stretching vibration, which is a distinct fingerprint of neat PLA. This presence is further corroborated by the bending and stretching peaks in the 1454.33 to 1361.74 cm^{-1} region, representing the asymmetric and symmetric deformations of $-\text{CH}_3$ groups from the PLA backbone [40]. Additionally, the strong bands stretching from 1265.30 to 1186.22 cm^{-1} correspond to the $\text{C}-\text{O}$ ester bonds, serving as another characteristic signature of the PLA matrix [41]. The retention of these prominent peaks in the WHSC-DP spectrum verifies the chemical coexistence of both natural cellulose fibers and the PLA polymer within the biocomposite. While these FTIR data confirm the presence of both phases and hint at localized interfacial interactions, further complementary characterizations (such as SEM and DSC) are utilized to fully evaluate the morphological phase blending and homogeneity of the composite.

3.3. Thermal Properties Analysis

The water absorption capacity and swelling behavior reflect the physical water-resistance performance of the developed WHSC-DP films. Figure 2 presents the comprehensive water absorption profiles of the composites. This swelling test was systematically conducted by varying the mass of the WHSC reinforcement (1.5, 2.5, and 3.5 g) combined with various matrix concentrations of PLA (3, 5, and 7 g) to observe the effects of hydrophilic natural fibers on matrix distortion.

The thermal degradation behavior of the WHSC-DP composite is presented in Figure 2. The thermogram reveals that the thermal decomposition process occurs in a single main stage, starting from an initial test stage of 30°C . The major weight loss initiates at an onset temperature (T_{onset}) of 342.43°C and concludes at an endset temperature (T_{endset}) of 417.06°C . The maximum degradation rate T_{max} is recorded at the midpoint temperature of 379.47°C . This single-stage decomposition profile reflects the overlapping degradation windows of the organic polymer matrices and the lignocellulosic components within the evaluated temperature range [42].

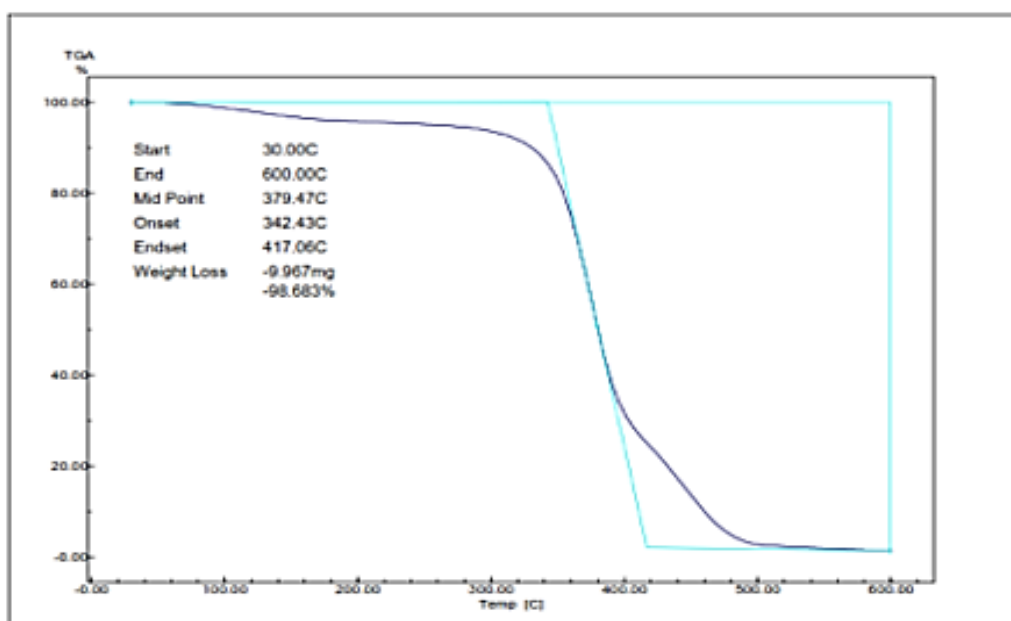


Figure 2. TGA of WHSC-DP.

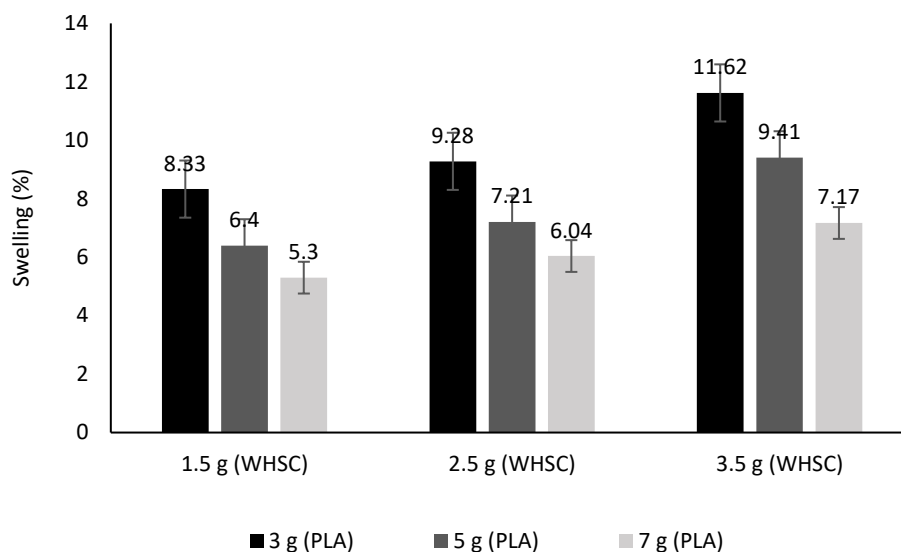


Figure 3. Swelling of WHSC-DP.

The main decomposition stage involves the thermal cleavage of carbon-carbon bonds, depolymerization, and advanced decomposition within the polymer matrices and cellulose structure [43]. The total mass loss during this stage reaches 98.683%, leaving a solid carbonaceous residue of 1.317% at the final test temperature of 600°C, which is primarily attributed to the char formation from the WHSC component.

Furthermore, the thermal stability of the composite is demonstrated by its relatively high initial degradation onset (342.43°C). Given that isolated pure cellulose and starch structures typically exhibit thermal weight loss at a lower temperature range (200–300°C), the shifted degradation onset of WHSC-DP above 300°C indicates that the composite exhibits enhanced thermal resistance against early heat exposure. This thermal profile confirms that the WHSC-DP composite can safely withstand standard manufacturing conditions, as the typical processing window for PLA-based blends ranges between 180 and 200°C, falling substantially below the material's thermal decomposition threshold [44].

3.4. Water Absorption Analysis

The water absorption capacity and swelling behavior reflect the physical water-resistance performance of the developed WHSC-DP

films. Figure 3 presents the comprehensive water absorption profiles of the composites. This swelling test was systematically conducted by varying the mass of the WHSC reinforcement (1.5, 2.5, and 3.5 g) combined with various matrix concentrations of PLA (3, 5, and 7 g) to observe the effects of hydrophilic natural fibers on matrix distortion.

A swelling test was conducted to determine the resistance of WHSC-DP to water absorption, which is a key parameter in assessing the structural stability of degradable plastics. As shown in the graph (see Figure 3), the swelling percentage of WHSC-DP is significantly influenced by the mass ratio of the hydrophobic (PLA) to the hydrophilic (WHSC). An increase in WHSC mass from 1.5 to 3.5 g resulted in a rise in the swelling percentage for all PLA variants. At a PLA mass of 3 g, the swelling value increased from 8.33% to 11.62%. A similar trend occurred in the 5 and 7 g PLA variations. This is due to the inherent characteristics of water hyacinth stem cellulose (WHSC), which contains free hydroxyl (–OH) groups. These functional groups are highly hydrophilic and tend to form hydrogen bonds with water molecules; thus, the more WHSC added, the more water is absorbed into the film matrix, causing the WHSC-DP structure to swell [45].

As seen in the WHSC-DP results, increasing the PLA content was shown to effectively reduce the rate of water absorption. In each group of the same WHSC, increasing the PLA content from 3 to 7 g significantly reduced the swelling value. The most significant reduction was observed in the 3.5 g WHSC group, where the swelling value decreased from 11.62% (3 g PLA) to 7.17% (7 g PLA). The highest water resistance (lowest swelling value) was achieved with a combination of 1.5 g of WHSC and 7 g of PLA, with an absorption value of 5.3%. In contrast, the WHSC-DP blend, with a concentration of 3.5 g of WHSC and 3 g of PLA, exhibited the poorest water resistance, with the highest swelling value reaching 11.62%. The hydrophobic nature of PLA makes it a highly versatile polymer [22].

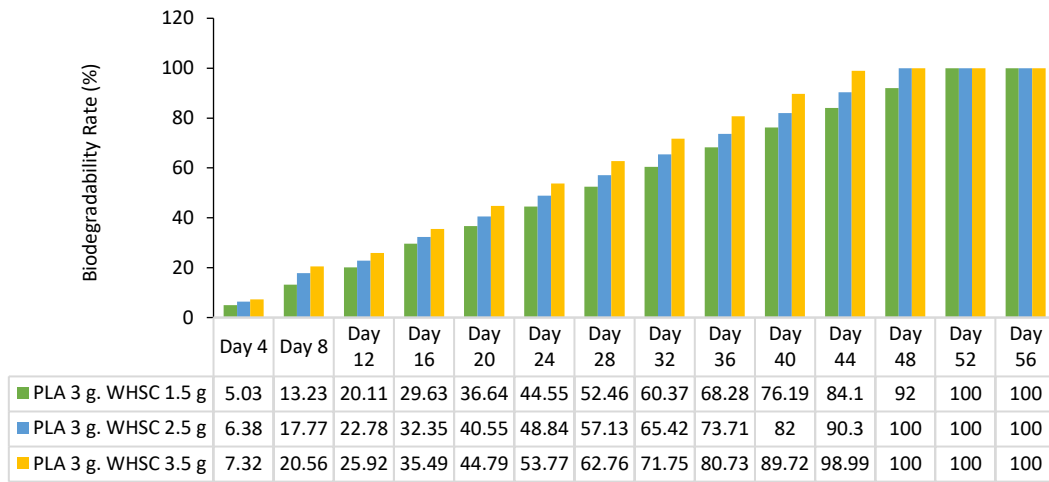
When compared to previous studies on similar biocomposites, the swelling values of WHSC-DP (5.3% to 11.62%) are highly comparable to and in some configurations outperform other PLA-cellulose matrices. For instance, similar PLA composites reinforced with natural fibers or agricultural waste typically exhibit water absorption or swelling values ranging from 6% to 15% under comparable immersion intervals [22]. The relatively low swelling value of 5.3% achieved in this work indicates a favorable structural stability. For short-term biodegradable packaging applications, industrial benchmarks and structural criteria generally target a maximum swelling threshold of below 10% to prevent premature mechanical failure or severe warping during service [46]. Consequently, the formulations with higher PLA content (5 and 7 g) meet these favorable benchmarks, making them highly suitable for moisture-resilient packaging. Conversely, formulations with

higher swelling (e.g., 11.62%) might be less ideal for direct food contact but remain viable for agricultural mulch films where higher initial water uptake is preferred to initiate rapid degradation.

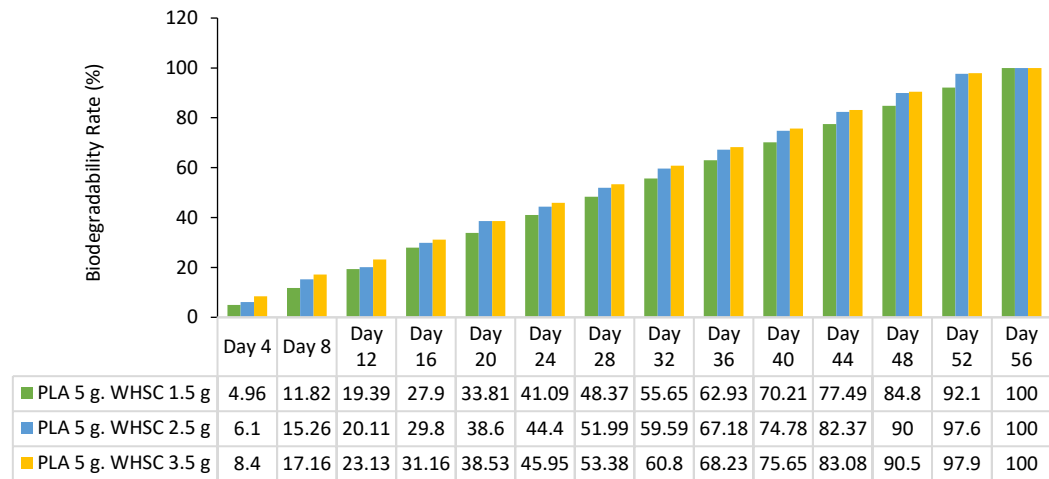
In soil burial tests, the addition of cellulose was found to accelerate the biodegradation of the plastic by increasing its water absorption capacity. The results of the water absorption tests confirm that a higher water absorption capacity of the degradable plastic accelerates the degradation rate of the PLA-cellulose blend, as water absorption promotes polymer chain cleavage via hydrolysis [47]. The findings indicate that water absorption capacity is highly dependent on the structure and interfacial compatibility between PLA and cellulose. The potential use of compatibilizing agents such as PLA-g-MA could further reduce the volume of water absorbed into the material's surface by improving interfacial adhesion. Conversely, weak interfacial bonds lead to the formation of micro-voids that serve as pathways for water penetration, thereby increasing water accumulation within the material [48].

3.5. Biodegradability Rate Analysis

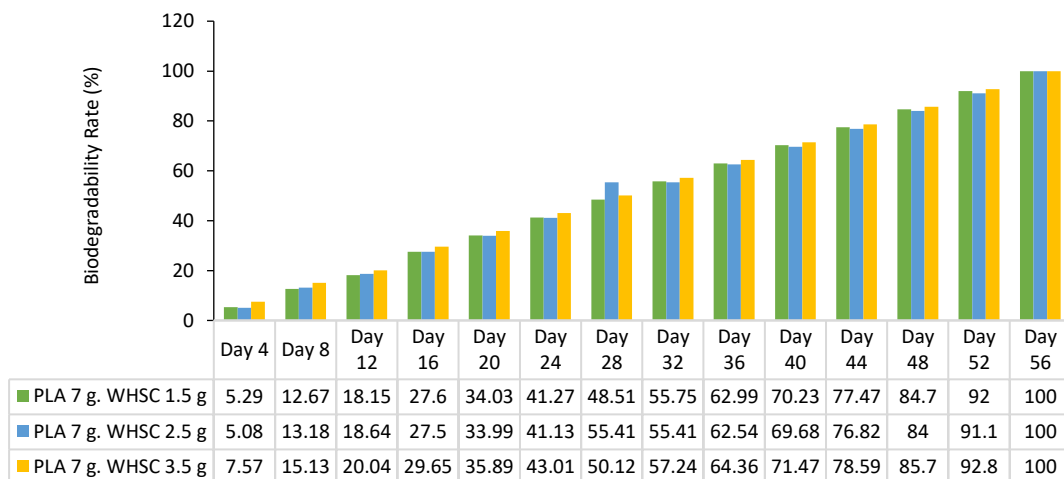
Biodegradation analysis was conducted to measure the degradation kinetics of the degradable plastics and to estimate the time required for the material to completely break down under specific soil conditions. The biodegradability profile of the WHSC-DP films is presented in Figure 4. The data summarizes the results of the soil burial tests obtained by varying the mass of WHSC (1.5, 2.5, and 3.5 g) combined with various concentrations of PLA (3, 5, and 7 g), highlighting the role of cellulose in accelerating environmental decomposition.



(a)



(b)



(c)

Figure 4. Biodegradability Rate of WHSC-DP: (a) PLA 3 g; (b) PLA 5 g; and PLA 7 g with WHSC (1.5; 2.5; and 3.5 g).

The soil burial biodegradation profiles of the various WHSC-DP formulations are illustrated in Figure 4. To ensure test reliability and experimental reproducibility, the specific soil burial conditions were closely monitored: the testing environmental temperature was maintained at an average of 32°C, the soil pH was recorded at 6.2, and the soil moisture level was systematically kept within the range of 40–50%, fostering an active native microbial environment.

Based on the research results, all tested composite samples exhibited a progressive increase in weight loss and biodegradation rate over the 56-day evaluation period. In the initial phase (days 4 to 16), the degradation process proceeded relatively slowly across all configurations. A sharp acceleration in the biodegradation rate was observed after day 20. By day 56, the peak values demonstrated that all composite variations had completely degraded, achieving a 100% mass loss. This total degradation capability demonstrates that the addition of WHSC can significantly enhance the biodegradable properties of conventional bio-based plastics. These findings align with a study by Rasheed et al. [49], who demonstrated that incorporating cellulose nanocrystals (CNC) into a poly(lactic acid)/poly(butylene succinate) (PLA/PBS) polymer composite enabled full degradation in soil, reinforcing its viability as a sustainable alternative to conventional packaging materials.

To contextualize this performance without an in-lab neat polymer, the degradation rates of the WHSC-DP formulations were benchmarked against established literature data for pure PLA under similar soil burial environments. Standard pure PLA films are highly semi-crystalline and hydrophobic, which severely restricts initial microbial attack and moisture penetration, typically resulting in less than weight loss after 45 to 60 days of soil burial [50]. In stark contrast, the WHSC-DP formulation containing 3 g PLA + 3.5 g WHSC achieved complete biodegradation (100%) much faster, specifically on day 48. Meanwhile, WHSC-DP blends with higher PLA contents, such as

the 7 g PLA + 1.5 g WHSC variant, delayed total biodegradation until day 56.

This behavior is governed by the structural variations between the hydrophobic matrix and the hydrophilic filler. Higher PLA concentrations yield denser, more tightly packed polymer chain structures that repel water [51]. As a highly common bio-based polymer representing approximately 25% of global bioplastics, pure PLA degrades primarily via a multi-step mechanism initiated by chemical hydrolysis, followed by microbial assimilation [52]. Incorporating hydrophilic WHSC particles breaks this hydrophobic barrier; a higher filler loading provides accessible pathways for moisture penetration via capillary action, expanding the surface area available for microbial colonization and accelerating subsequent polymer chain cleavage [53].

These experimental configurations meet the performance criteria outlined in the ASTM D-6002 standard (developed in conjunction with ASTM D-20.96) for naturally degradable plastics. The standard requires that a significant portion of organic carbon converts to CO₂ within a 180-day window under controlled conditions (ASTM). Under the optimized environmental parameters of 32°C and a neutral-to-slightly acidic pH, the structural disruption caused by the water hyacinth cellulose effectively compresses this degradation timeline, ensuring rapid environmental assimilation [54]. A similar accelerated assimilation behavior was also observed in areca nut shell cellulose-based bioplastics, which successfully demonstrated rapid degradation within 45 to 96 days depending on the plasticizer concentration, aligning well with the ASTM bioplastic standards [55].

4. CONCLUSION

A homogeneous degradable plastic has been synthesized using water hyacinth stem cellulose (WHSC) and polylactic acid (PLA) as raw materials. FTIR analysis confirmed the presence of hydrogen bonding interactions between the –OH and carbonyl (C=O) groups. The synergy between WHSC

and PLA resulted in a material with high thermal stability (T_{onset}) = 342.43°C), making it safe to process within the standard temperature range of (180–200°C). The optimal formulation was obtained with a combination of 1.5 g WHSC and 7 g PLA, yielding optimal mechanical properties with a tensile strength of 10.993 MPa, an elongation of 84.10%, and the best water resistance with the lowest swelling value of 5.3%. Although the Young's modulus of this degradable plastic is still lower than that of pure PLA due to limitations in interfacial bonding, this material exhibits rapid biodegradability and has significant potential for commercialization as an eco-friendly plastic. For further research and development, additional chemical modifications to the water hyacinth cellulose surface (such as acetylation or silanization) are necessary to enhance interfacial bonding with the PLA matrix, thereby improving the material's Young's modulus. More specific mechanical and physical tests, such as puncture resistance or water vapor transmission rate (WVTR) tests, are also required if this material is intended for commercial products.

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AUTHOR CONTRIBUTIONS

R.D.: Conceptualization, methodology, resources, project administration, writing – original draft, review & editing. **N.S.:** Methodology, investigation, formal analysis, writing – original draft. **M.S.:** Investigation, data curation, formal analysis. **M.R.:** Formal analysis, validation, supervision. **B.S.K.:**

Visualization, investigation, validation. **A.A.:** Writing – review & editing, resources. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no competing financial interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

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