

Comparative performance of tapioca-starch bioplastics reinforced with pandan and grass jelly extracts

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Highlights:

- A first systematic comparison is presented between lignocellulosic- and hydrocolloid-reinforced tapioca-starch bioplastics under identical processing conditions.
- Pandan-derived extract produced mechanically stronger and thermally more stable films, likely due to the presence of lignocellulosic constituents and a denser microstructure.
- Grass-jelly-derived extract promoted greater flexibility and faster biodegradation, which may be associated with water-soluble polysaccharide constituents, higher hydrophilicity, and a more porous morphology.

Abstract

The development of biodegradable plastics with tunable performance is critical for replacing petroleum-based polymers in engineering applications. This study systematically compares tapioca-starch-based bioplastics reinforced with *Pandanus amaryllifolius* (PA) and *Cyclea barbata Miers* (CBM) extracts to elucidate their structure–property–degradation relationships. Bioplastic films were fabricated via solution casting and characterized through mechanical testing, Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), soil-burial biodegradation tests, and scanning electron microscopy (SEM). The results show that pandan–tapioca films (PTF) exhibit higher tensile strength and Young’s modulus, which are likely associated with the presence of lignocellulosic constituents in the pandan-derived extract and a more

compact microstructural organization. In contrast, grass-jelly–tapioca films (GTF) demonstrate higher elongation at break, which may be related to the presence of water-soluble polysaccharide constituents in the CBM-derived extract that promote greater polymer-chain mobility. Differences in intermolecular interactions and morphology directly govern thermal resistance and degradation behavior, with PTF showing controlled degradation and GTF exhibiting rapid environmental breakdown. These findings establish a comparative materials-design framework for tailoring starch-based bioplastics toward specific mechanical durability and service-life requirements.

Keywords: Tapioca starch; *Pandanus amaryllifolius*; *Cyclea barbata* Miers; Bioplastics; Lignocellulosic reinforcement; Hydrocolloids; Biodegradation

1. Introduction

The persistent accumulation of petroleum-based plastics continues to intensify environmental concerns and has accelerated the search for renewable and biodegradable alternatives for short-service-life applications, particularly packaging [1], [2]. Among the available bio-based polymers, starch remains one of the most attractive candidates because it is abundant, low-cost, widely available, and readily processable into films [3]. However, native starch films still suffer from major limitations, including high moisture sensitivity, limited mechanical strength, and insufficient thermal and barrier stability, which restrict their broader practical use unless the polymer network is modified through blending, reinforcement, or functional additives [4], [5].

Recent research has therefore shifted from neat starch films toward more advanced composite and multifunctional systems [4], [6]. Current studies show that cellulose and cellulose-derived reinforcements can effectively improve the structural integrity, stiffness, and strength of starch-based films, while other natural modifiers are used to tune flexibility, interfacial interactions, and application-specific functionality [2], [5]. At the same time, recent packaging research has emphasized that the final performance of starch films is governed not only by the starch source itself, but also by the chemistry of the co-biopolymer phase, the strength of intermolecular hydrogen bonding, and the resulting film microstructure [7], [8].

In parallel, plant-derived polysaccharides and extracts have gained increasing attention as sustainable modifiers for starch-based films, particularly in edible and active packaging research [1], [9]. Recent developments in starch packaging systems indicate that natural additives can do more than simply replace synthetic ingredients; they can also tune mechanical behavior, water affinity, thermal response, barrier performance, and biodegradation-related functionality through changes in intermolecular interactions and film microstructure [10], [11]. Nevertheless, much of the recent literature still focuses on optimizing one modifier family at a time, including cellulose-reinforced starch films [11], [12], starch–pectin systems [13], [14], and extract-loaded cassava starch films [10], [15]. As a result, the evidence base remains fragmented by modifier class, with recent reviews and experiments still being organized largely around individual additive families rather than direct head-to-head comparisons under matched formulation and casting conditions [10], [14]. This fragmentation limits the rational selection of plant resources for designing starch-based bioplastics with targeted strength, flexibility, and service life, because current reviews continue to emphasize the need for structure–property-guided formulation and processing optimization [16], [17].

In this context, *Pandanus amaryllifolius* and *Cyclea barbata* Miers represent two regionally abundant plant resources in Asia with potentially contrasting functions in a tapioca-starch matrix [18]. Pandan leaves are expected to contribute a crude lignocellulosic phase because *P. amaryllifolius* fibers contain substantial cellulose, hemicellulose, and lignin fractions [19], whereas *C. barbata* leaves are associated with pectic and water-soluble polysaccharide constituents that exhibit spontaneous gel-forming behavior and pronounced hydration-related functionality [20]. Although both plant materials have been explored individually in food or biomaterial related contexts *P. amaryllifolius* in food-quality and utilization studies and fiber-reinforcement work, and *C. barbata* in pectin/gelation studies and membrane-based biomaterials their roles as modifiers in tapioca-starch bioplastics have, to the best of our knowledge, not yet been systematically compared within a unified formulation and casting framework [21], [22]. Therefore, this study presents a direct comparative evaluation of tapioca-starch bioplastic films reinforced with pandan and grass-jelly extracts prepared under equivalent processing conditions. By combining mechanical testing, FTIR, TGA, SEM, and biodegradation analysis, this work aims to establish clearer structure property degradation relationships and to provide a materials design basis for tailoring starch-based bioplastics toward application-specific durability and environmental lifetime.

2. Materials and Method

2.1. Materials

Fresh *Pandanus amaryllifolius* (PA) and *Cyclea barbata* Miers (CBM) leaves were collected from local agricultural sources in East Java, Indonesia. Leaves with uniform appearance, no visible physical damage, and comparable freshness were selected to minimize variation in biochemical composition. Immediately after collection, the leaves were washed thoroughly under running tap water to remove soil, dust, and other surface impurities, and were then rinsed with distilled water.

Food-grade tapioca starch with high amylose content was used as the primary film-forming polymer because of its good gelatinization behavior, wide availability, and compatibility with natural biopolymer systems. Glycerol (Merck) was used as a plasticizer to improve film flexibility by reducing intermolecular forces between polymer chains, whereas glacial acetic acid (Merck) was added in small amounts to assist starch swelling and improve matrix homogeneity. Distilled water was used as the solvent in all formulations to avoid interference from dissolved ions or contaminants. No synthetic fillers, crosslinking agents, or chemical modifiers were introduced, so that all prepared films remained fully biodegradable and derived exclusively from renewable resources.

2.2. Formulation Design and Raw Material Characteristics

The formulation of each bioplastic system was defined explicitly to improve methodological reproducibility. For the pandan–tapioca film (PTF), the film-forming mixture consisted of tapioca starch (5 g; 76.9 wt%), glycerol (1.5 g; 23.1 wt%), pandan extract (80 mL), and distilled water adjusted to a final total volume of 100 mL. For the grass-jelly–tapioca film (GTF), the film-forming mixture consisted of tapioca starch (5 g), glycerol (1.5 g), CBM extract (80 mL), acetic acid (1 mL, 1%), and distilled water adjusted to the same final total volume of 100 mL.

To ensure comparability between the two systems, the total starch content, glycerol content, total casting volume, mixing temperature, stirring duration, casting area, and drying conditions were kept constant for all formulations. The only intentional difference between the two formulations was the type of plant-derived extract incorporated into the tapioca matrix, namely pandan extract for PTF and *Cyclea barbata* Miers extract for GTF. Acetic acid was introduced only into the GTF system because the CBM extract formed a more viscous plant-derived medium that required acid-assisted homogenization during gelatinization and film formation. In contrast, the PTF mixture produced a stable and homogeneous film-forming solution under the same thermal and mixing conditions without acetic acid addition.

Regarding raw-material characteristics, fresh pandan leaves were cut into segments of approximately 1–2 cm before blending, while fresh CBM leaves were cut into small pieces before thermal extraction. The blended pandan slurry was filtered, and the resulting liquid phase was used directly for film preparation without drying or powdering. Therefore, the pandan-derived phase used in this study is more appropriately described as a crude lignocellulosic extract rather than a purified cellulose fraction. For the GTF system, the CBM extract was prepared at an extraction ratio of 100 g leaves per 200 mL distilled water, producing a CBM-derived filtrate used immediately after filtration. All extracts were prepared on the same day as film casting to minimize compositional variation due to storage.

2.3. Preparation of PTF

Fresh *Pandanus amaryllifolius* leaves were thoroughly washed with running water, rinsed with distilled water, and drained to remove surface impurities. The cleaned leaves were then cut into small segments of approximately 1–2 cm. A total of 100 g of fresh leaves was blended with 200 mL of distilled water for 3 min until a uniform slurry was obtained. The slurry was filtered sequentially through muslin cloth and a fine mesh sieve to remove coarse insoluble residues, yielding a crude lignocellulosic pandan extract containing soluble and finely dispersed plant-derived components.

For film preparation, 5 g of tapioca starch and 1.5 g of glycerol were gradually added to 100 mL of pandan extract under continuous stirring to avoid agglomeration and improve matrix homogeneity. The mixture was heated at 70–80 °C and stirred at 500 rpm for 20 min until starch gelatinization was complete and a homogeneous viscous gel had formed. The resulting hot film-forming solution was poured onto a flat acrylic plate with a casting area of 20 cm × 20 cm and spread evenly to control film thickness. Drying was carried out at 25–30 °C for 24–48 h under dust-

free conditions to allow gradual solvent evaporation and reduce defect formation. After drying, the films were carefully peeled from the casting surface and conditioned at room temperature for 24 h before further characterization.

2.4. Preparation of GTF

Fresh *Cyclea barbata* Miers leaves were thoroughly washed, drained, and cut into small pieces prior to extraction. A total of 100 g of fresh leaves was extracted in 200 mL of distilled water by heating at 90–95 °C for 15 min to obtain a viscous plant extract. The hot extract was then filtered to remove fibrous residues, producing a smooth CBM-derived filtrate that likely contained water-soluble polysaccharide constituents reported for *Cyclea barbata* Miers leaves.

Subsequently, 5 g of tapioca starch, 1.5 g of glycerol, and 1 mL of acetic acid at 1% concentration were added into 80 mL of CBM extract under continuous stirring. The mixture was heated at 70–80 °C and stirred at 500 rpm for 20 min until complete gelatinization occurred and a homogeneous gel-like film-forming solution was obtained. The solution was then cast onto a flat tray using the same casting area, total casting volume, and drying conditions as those applied for PTF in order to maintain equivalent preparation conditions between both systems. Drying was conducted at 25–30 °C for 24–48 h, and the dried films were conditioned at room temperature for 24 h before characterization.

Although both PTF and GTF were fabricated under the same starch content, glycerol content, mixing temperature, stirring duration, casting area, and drying conditions, the two film-forming systems differed fundamentally in the way the plant-derived phase was generated. In PTF, the pandan phase was obtained through direct blending followed by filtration, which likely retained soluble compounds together with finely dispersed lignocellulosic components from the leaf tissue. In contrast, the GTF system was based on a hot aqueous extraction of *Cyclea barbata* leaves, followed by filtration, which more likely yielded a smoother filtrate enriched in water-soluble polysaccharide constituents. Under otherwise comparable casting conditions, this difference in extract-preparation route was expected to influence intermolecular interactions, chain mobility, and the final compactness of the dried film matrix, and therefore had direct implications for the subsequent FTIR, TGA, SEM, mechanical, and biodegradation results [23], [24].

2.5. Mechanical Testing

Mechanical properties were evaluated according to ASTM D638 (Type V) standards. The bioplastic films were cut into dumbbell-shaped specimens using a standardized cutting die to ensure uniform geometry. Prior to tensile testing, the thickness of each specimen was measured using a digital micrometer at five different points, and the average value was used for stress calculation.

Tensile tests were performed using a universal testing machine (UTM) equipped with a calibrated load cell. Specimens were mounted vertically between pneumatic grips and stretched at a constant crosshead speed of 50 mm min⁻¹ until failure. Tensile strength was calculated by dividing the maximum load by the initial cross-sectional area and is reported in MPa. Elongation at break is reported as %, and Young's modulus is reported in MPa, calculated from the initial linear region of the stress–strain curve. For each formulation, at least three specimens were tested, and the results are presented as mean ± standard deviation to describe the variation among replicate specimens.

2.6. Fourier Transform Infrared (FTIR) Spectroscopy

FTIR analysis was carried out using a Shimadzu Fourier Transform Infrared Spectrometer equipped with an attenuated total reflectance (ATR) accessory. Spectra were recorded over the mid-infrared range of 4000–400 cm⁻¹ at room temperature. Each sample was scanned multiple times to improve the signal-to-noise ratio. The obtained spectra were analyzed to identify characteristic functional groups, including O–H and C–H stretching vibrations, carbonyl (C=O) groups, and polysaccharide-related C–O and C–O–C vibrations. This analysis provided insight into intermolecular interactions, hydrogen bonding, and structural differences between the two bioplastic systems.

2.7. Thermogravimetric Analysis (TGA)

Thermal stability was assessed using a Shimadzu thermogravimetric analyzer operated under a nitrogen atmosphere. Approximately 5–10 mg of each bioplastic sample was placed in a platinum

pan and heated from room temperature to 600 °C at a controlled heating rate. Changes in mass were continuously recorded to identify moisture evaporation, polymer decomposition, and char formation stages. The onset degradation temperature, maximum degradation rate, and residual mass were used to compare the thermal resistance of PTF and GTF.

2.8. Biodegradation Test

Biodegradation behavior was evaluated using a soil-burial method in natural soil under ambient environmental conditions, as this approach is widely used for comparative assessment of biodegradable starch-based films under post-disposal conditions [25], [26]. Prior to burial, the bioplastic film samples were pre-weighed to obtain their initial mass. The samples were then buried in the soil at a fixed depth, while soil moisture was monitored and maintained throughout the test period. The biodegradation test was conducted over 7 days, and the samples were retrieved at predetermined daily intervals for mass-loss evaluation.

After retrieval, the film specimens were gently cleaned to remove adhering soil particles, dried, and reweighed. The percentage of weight reduction was used to quantify the degradation behavior of each film. In addition to weight reduction, qualitative visual changes such as surface erosion, fragmentation, and discoloration were also observed during the burial period to support interpretation of the degradation process. Recent studies have likewise combined weight-loss measurements with visual, morphological, and structural observations to better interpret degradation pathways in biodegradable films [25], [27]. Although visible changes were monitored during burial, no photographic documentation of the buried samples was retained in the final dataset; therefore, the biodegradation analysis presented here relies primarily on weight-loss data and descriptive visual observation. The percentage of weight reduction was calculated using Eq. (1).

$$\text{Weight reduction (\%)} = \frac{W_0 - W_t}{W_0} \times 100 \quad (1)$$

where W_0 is the initial weight of the film sample before burial and W_t is the weight of the sample after burial for a given exposure time.

2.9. Scanning Electron Microscopy (SEM)

Surface morphology and microstructural features of the bioplastic films were examined using a FESEM FEI QUANTA 650. Film samples were cut into small sections and sputter-coated with a thin layer of gold to enhance electrical conductivity. SEM images were captured at various magnifications to observe surface smoothness, porosity, phase distribution, and interfacial adhesion between tapioca starch and plant-derived polymers. In the present study, SEM was also used to support interpretation of biodegradation behavior by identifying initial morphological features that may influence water penetration, microbial accessibility, and structural disintegration during soil burial, particularly differences in matrix compactness and surface porosity between PTF and GTF [28], [29].

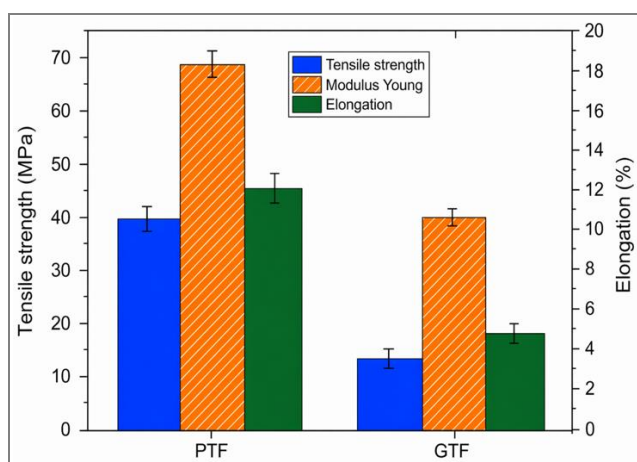
3. Results

3.1. Mechanical Properties

The tensile behavior of PTF and GTF highlights the strong influence of plant-matrix chemistry on mechanical performance (Figure 1). In this study, tensile strength and Young's modulus are reported in MPa, while elongation at break is reported as %. The average film thickness used for tensile testing was 0.09 ± 0.02 mm for PTF and 0.09 ± 0.02 mm for GTF. The results are presented as mean values with their corresponding standard deviations based on replicate measurements. Across all formulations, PTF exhibited higher tensile strength and Young's modulus, whereas GTF showed higher elongation at break [30].

Quantitatively, the tensile strength of PTF was approximately 40 MPa, which was higher than that of GTF at approximately 13 MPa. A similar trend was observed for Young's modulus, where PTF exhibited a value of approximately 68 MPa, indicating a stiffer polymer network, while GTF showed a lower modulus of approximately 40 MPa. In contrast, GTF demonstrated higher elongation at break (approximately 18%) compared with PTF (approximately 12%), indicating a

Figure 1. Tensile strength (MPa), Young's modulus (MPa), and elongation at break (%) of PTF and GTF films. Values are presented as mean $\pm$ standard deviation ($n = 3$)



optimum value reported for empty-fruit-bunch-cellulose/chitosan/starch bioplastics by Waluyo et al. (2024), which reached 6.84 MPa with a Young's modulus of 21.94 MPa, indicating that the pandan-derived lignocellulosic phase in the present system provided a markedly stronger reinforcement effect under the current formulation conditions [31]. In contrast, the tensile strength of GTF (approximately 13 MPa) remained lower than the highest values reported for compatible starch/pectin blend films, where tensile strength could reach 52.2 MPa and Young's modulus 1837 MPa depending on pectin structure, but it still exceeded the strength level commonly reported for more weakly structured hydrocolloid-dominant films [32]. Moreover, the general trend observed in the present study, namely higher tensile strength and lower elongation in the lignocellulosic system and greater flexibility in the polysaccharide-rich system, is consistent with previous cassava-starch films reinforced with lignocellulosic nanofibers, where tensile stress increased while elongation at break decreased after reinforcement addition [33]. These comparisons place the present PTF and GTF films within a broader mechanical-performance spectrum and more clearly demonstrate how plant-derived modifiers can be selected to prioritize either stiffness and strength or flexibility and degradability according to application requirements.

3.2. FTIR Analysis

The FTIR spectra of PTF and GTF provide molecular-level insight into the chemical interactions governing film formation and performance (Figure 2). Both spectra display characteristic absorption bands of polysaccharide-based materials, confirming that the films are dominated by starch and plant-derived biopolymers. However, differences in band shape and intensity indicate distinct hydrogen-bonding environments and network organization in the two systems.

A broad O–H stretching band between 3200 and 3400 cm^{-1} is observed in both films, reflecting hydrogen-bonded hydroxyl groups in starch-based matrices together with water molecules strongly coupled to the polymer network [34]. In PTF, this band appears sharper and more intense, suggesting a relatively more organized hydrogen-bonding environment that may involve interactions between starch chains and lignocellulosic constituents from the pandan-derived extract, since *Pandanus amaryllifolius* fibers contain cellulose, hemicellulose, and lignin and starch–cellulose systems are known to form strong interfacial hydrogen bonds [19]. This

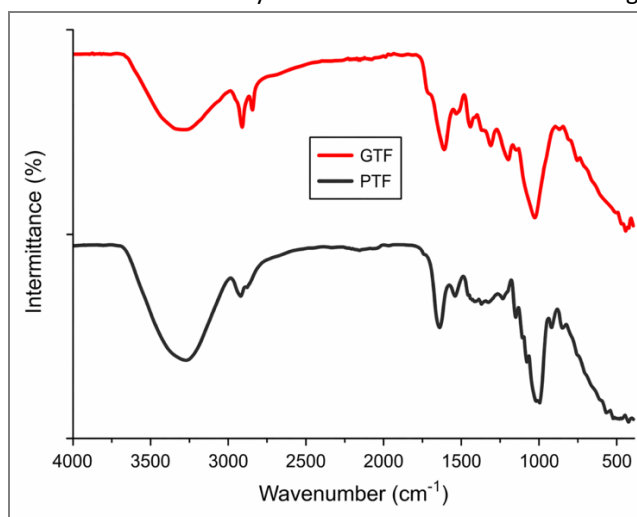


Figure 2. FTIR spectra of PTF and GTF films

more flexible and ductile matrix that may be associated with the presence of water-soluble polysaccharide constituents in the CBM-derived extract.

When benchmarked quantitatively against relevant starch-based bioplastics reported in the literature, the present PTF films showed comparatively strong mechanical performance. The tensile strength of PTF (approximately 40 MPa) was substantially higher than the

interpretation is consistent with the higher stiffness and tensile strength observed in mechanical testing, because cellulose-containing reinforcements in starch films commonly reduce polymer-chain mobility and increase tensile strength and modulus relative to unreinforced films [4], [35].

In contrast, GTF exhibited a broader O–H band, which is compatible with a more heterogeneous and hydrated bonding environment and may reflect the predominance of water-soluble pectic polysaccharides in the

CBM-derived extract, because the polysaccharide fraction of *Cyclea barbata* leaves has been reported to consist mainly of pectin and its aqueous extract is known to undergo spontaneous gelation through hydration- and cation-mediated interactions [18]. This feature is consistent with the higher elongation at break and greater flexibility observed for GTF, since pectin-containing starch films commonly exhibit strong water affinity and can preserve or improve film extensibility depending on pectin structure and film composition [32]. Its more hydrophilic and hydrated network may also help explain the faster biodegradation behavior of this system, as pectin-based films are intrinsically biodegradable and their water-sensitive character generally facilitates environmental disintegration [36].

Differences are further evident in the fingerprint region ($900\text{--}1200\text{ cm}^{-1}$), where PTF show more pronounced bands that are consistent with cellulose- and hemicellulose-related contributions, supporting the presence of lignocellulosic constituents in the pandan-derived phase. The presence of carbonyl-related bands in GTF suggests the contribution of carboxyl-containing polysaccharide components, which may enhance hydrophilicity and promote plasticization.

These spectral differences are also consistent with the different preparation routes used for the two plant-derived phases. Because PTF was prepared from a directly blended and filtered pandan slurry, the resulting film likely contained a broader distribution of lignocellulosic constituents capable of interacting with starch through multiple hydroxyl-rich contact points. This may explain the relatively sharper O–H band and the more pronounced fingerprint-region features associated with cellulose- and hemicellulose-related vibrations. By contrast, the hot aqueous extraction route used for GTF was more likely to favor dissolved or highly dispersed polysaccharide constituents, producing a more hydrated and less structurally constrained network after casting. Since the starch content, glycerol content, and drying conditions were kept constant between both systems, the FTIR differences are more reasonably attributed to plant-phase chemistry and network organization than to processing variation alone [37], [38].

3.3. Thermal Stability (TGA)

The Thermogravimetric analysis reveals distinct thermal degradation behaviors for PTF and GTF that reflect differences in polymer network structure and plant-matrix chemistry (Figure 3). Overall, PTF exhibit higher onset degradation temperatures and greater residual mass, indicating superior thermal stability compared to GTF.

For both PTF and GTF, three main thermal events can be recognized, corresponding to initial moisture loss, primary decomposition of the starch-rich polymer matrix, and final degradation/char formation at higher temperature. Quantitatively, PTF exhibited a higher onset degradation temperature ($T_{\text{onset}} = 293.44^\circ\text{C}$) than GTF ($T_{\text{onset}} = 242.78^\circ\text{C}$), indicating that the pandan-containing system was more resistant to the beginning of thermal decomposition.

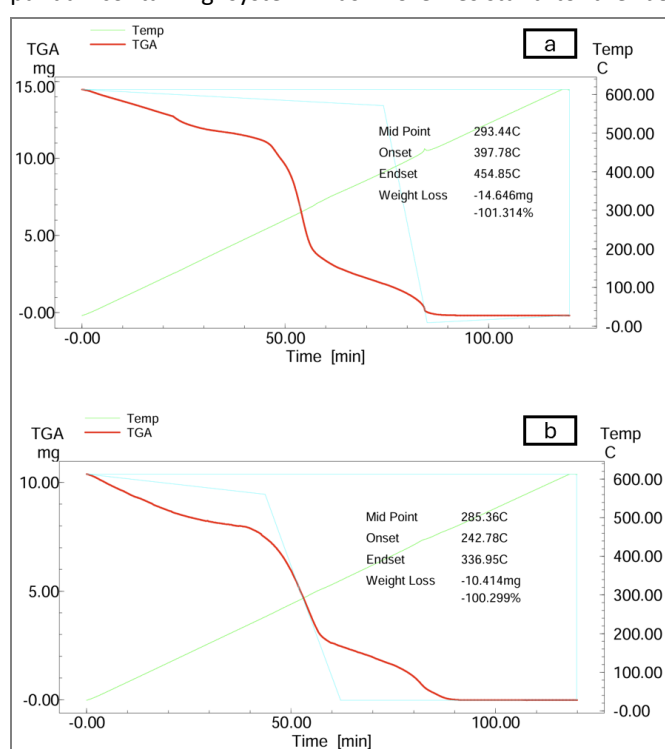


Figure 3.
TGA thermograms of:
(a) PTF;
(b) GTF films

Likewise, the maximum degradation temperature (T_{max}) of PTF (397.78°C) was markedly higher than that of GTF (285.36°C), showing that the main decomposition stage of PTF occurred at a substantially higher temperature. At 600°C , both films showed negligible residual mass under the present test conditions, indicating near-complete decomposition.

This difference in thermal behavior can be linked to the distinct preparation routes and the resulting film organization. In PTF, the directly blended pandan phase likely introduced a crude lignocellulosic fraction that contributed to stronger intermolecular restriction and a denser matrix after solvent evaporation, thereby delaying

thermal breakdown. In contrast, the GTF film was formed from a hot aqueous CBM extract that likely favored a more soluble and hydrated polysaccharide-rich phase, which may have promoted higher chain mobility and earlier thermal decomposition. Recent studies on starch-based composite films consistently report that lignocellulosic reinforcement tends to increase stiffness and delay thermal degradation when compatibility with the starch matrix is adequate, whereas more weakly packed and highly hydrated systems often decompose earlier [37], [38]. Therefore, in the present manuscript, the TGA results are interpreted as evidence of different thermal-degradation behavior arising from different plant-phase chemistry and matrix organization, rather than as direct proof of crystallinity.

3.4. Biodegradation Behavior

The soil-burial test revealed distinct biodegradation profiles for PTF and GTF over the 7-day observation period (Figure 4). Both films exhibited progressive weight reduction, confirming that both starch-based systems are biodegradable under the tested soil conditions [24], [26], [27]. However, the degradation pattern was not identical throughout the burial period. During the early stage of burial, PTF showed a higher initial weight reduction than GTF. The weight reduction of PTF increased gradually from approximately 15% on day 1 to about 21% on day 7, whereas GTF increased from approximately 6% on day 1 to about 29% on day 7.

A more detailed examination of the degradation trend indicates that PTF underwent a relatively steady and moderate increase in weight reduction throughout the test period. In contrast, GTF showed a slower initial reduction during days 1–3, followed by a sharper increase after day 4, and eventually surpassed PTF after day 5. By day 6 and day 7, GTF reached approximately 22% and 29% weight reduction, respectively, while PTF remained lower at approximately 20% and 21%. This behavior suggests that GTF became more susceptible to rapid soil-induced disintegration in the later stage of burial, which is consistent with recent soil-burial studies showing that biodegradable starch-based films can display non-linear mass-loss behavior depending on matrix composition, water accessibility, and reinforcement type [24], [25], [26].

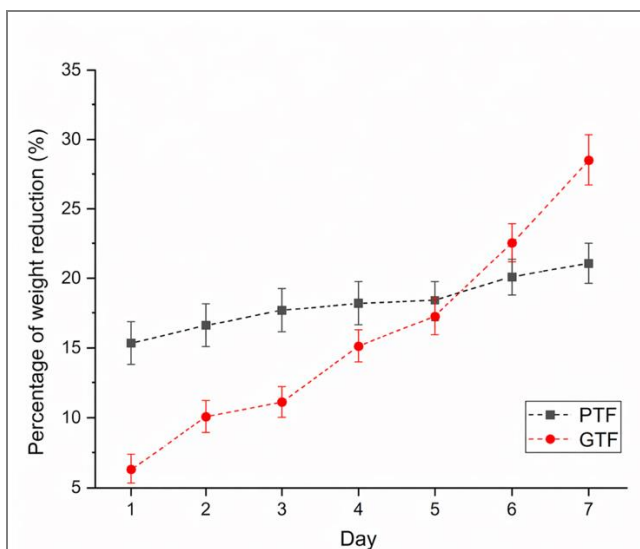
The different degradation patterns can be interpreted in terms of moisture-assisted structural weakening followed by microbial attack on the starch-rich matrix. In GTF, the more heterogeneous and porous morphology observed by SEM likely facilitated earlier water penetration into the film interior. Once the matrix became more hydrated, the polymer network would have loosened, allowing easier microbial access to biodegradable domains and accelerating mass loss during the later burial stage. This interpretation is also consistent with the broader O–H absorption band observed in the FTIR spectrum of GTF, which suggests a more hydrated intermolecular environment [10], [27].

In contrast, the smoother and more compact morphology of PTF likely reduced the rate of water diffusion and delayed microbial penetration into the interior of the film. As a result, although initial weight loss still occurred, the structural breakdown of PTF progressed more gradually over the burial period. The relatively higher early-stage weight reduction of PTF may be associated with the release of loosely bound moisture or easily leachable low-molecular-weight components, but because no post-burial chemical or surface characterization was conducted, this interpretation should be considered cautiously. Overall, the combined evidence indicates that the biodegradation

behavior of the two films was governed not only by starch biodegradability itself, but also by differences in matrix compactness, hydrophilicity, and accessibility to environmental moisture and microorganisms [7], [24], [25], [26].

In this study, the role of SEM in the biodegradation analysis should be understood as indirect but structurally meaningful support rather than direct post-burial evidence. Because SEM imaging was performed on the as-prepared films and not on the buried specimens after soil exposure, the SEM results are used here to interpret how the

Figure 4.
Weight loss of PTF and
GTF films during soil
burial



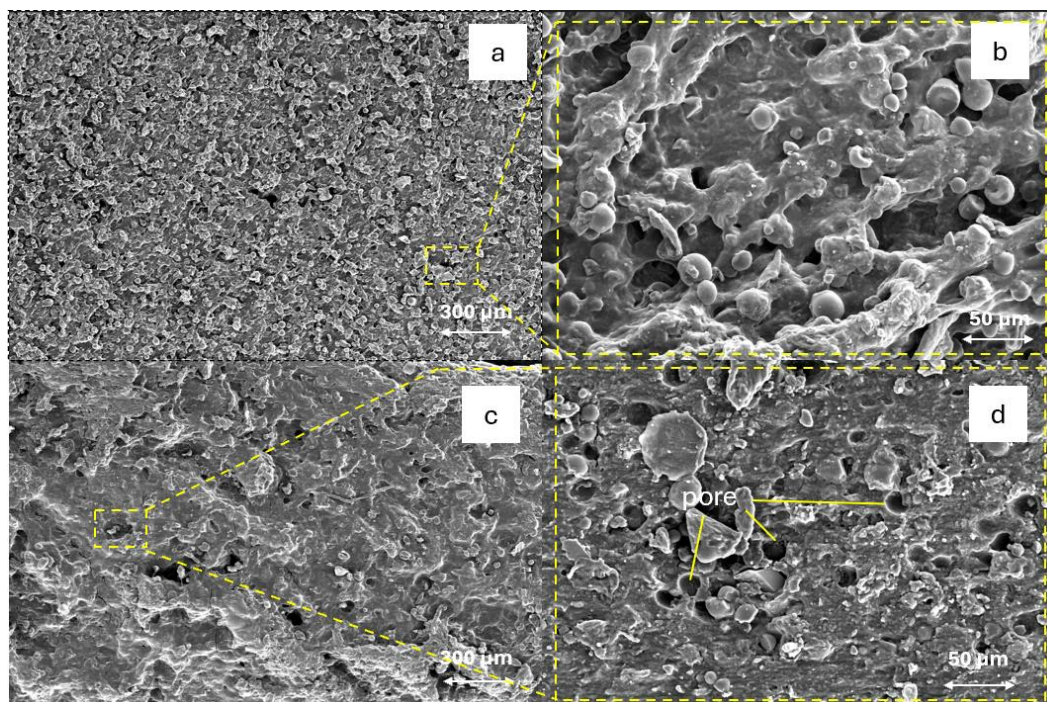
initial morphology of each film may have affected its degradation pathway. The smoother and more compact surface of PTF suggests fewer accessible pathways for moisture diffusion and microbial penetration, which is consistent with its slower late-stage weight-loss profile. In contrast, the more heterogeneous and porous morphology of GTF indicates a matrix with greater initial accessibility to water and microorganisms, which helps explain its stronger late-stage degradation under the same soil-burial conditions [39], [40].

A limitation of the present biodegradation analysis is that no photographic documentation of the buried films was retained, so the degradation process could not be supported by direct visual comparison between the initial and final burial stages. Accordingly, the present interpretation relies primarily on weight-loss data together with indirect structural evidence from SEM and FTIR. Even so, the available results consistently support the conclusion that GTF underwent faster late-stage degradation because of its more porous and moisture-accessible matrix, whereas PTF retained a slower and more gradual degradation profile under the same burial conditions.

3.5. Morphological Characteristics (SEM)

SEM micrographs provide visual evidence of the different matrix organizations generated by the two preparation routes and also offer indirect structural support for interpreting the distinct biodegradation tendencies observed during soil burial [41]. PTF exhibited a smoother, more compact, and more homogeneous surface, suggesting that the directly blended pandan-derived phase was incorporated into the starch matrix without producing extensive voids or severe phase separation (Figure 5). This type of morphology is commonly associated with better stress transfer, reduced local defect concentration, and improved resistance to water penetration, which is consistent with the higher tensile strength, higher Young's modulus, and slower late-stage biodegradation observed for PTF [24], [42]. From a biodegradation perspective, this compact morphology also suggests lower initial accessibility of moisture and soil microorganisms to the interior of the film matrix, thereby supporting the more gradual degradation profile observed for PTF during burial [28], [43].

Figure 5.
SEM surface
morphology of:
(a, b) PTF and
(c, d) GTF
films at 100× and 500×
magnifications



In contrast, GTF displayed a more heterogeneous and porous morphology characterized by microvoids and irregular gel-like domains. This morphology is consistent with a film formed from a hot aqueous extract containing more soluble and highly hydrated plant-derived constituents, which may have limited the compact packing of the matrix during drying. In starch-based films, a more heterogeneous or porous morphology can be associated with lower mechanical strength and a more deformable structure, because higher porosity and weaker interfacial polymer interactions tend to reduce mechanical resistance in starch-based composites [44]. Increased free volume in starch film networks is likewise known to enhance molecular mobility, which facilitates segmental

motion of polymer chains and can contribute to greater flexibility [45]. The SEM observations therefore support the interpretation that GTF developed a less densely packed and more moisture-accessible structure, which helps explain its lower strength, higher elongation at break, and faster degradation tendency under soil burial [37], [38], [46]. Thus, in the present study, SEM supports the biodegradation discussion by showing that the initial porous and heterogeneous morphology of GTF would be more favorable to water uptake, microbial access, and subsequent matrix loosening during soil exposure.

3.6. Discussion

Taken together, the mechanical, FTIR, TGA, SEM, and biodegradation results show that the behavior of the present tapioca-based films was governed not only by the presence of plant-derived additives, but also by how those additives were generated and incorporated into the starch matrix. In the present work, both systems were prepared under matched starch loading, glycerol loading, thermal mixing, casting area, and drying conditions, which reduces the likelihood that the observed differences arose simply from processing variability. Instead, the main distinction lies in the plant-phase preparation route: PTF was derived from a directly blended and filtered pandan slurry, whereas GTF was obtained from a hot aqueous extraction of *Cyclea barbata* leaves. Recent literature on starch-based blends and polysaccharide films emphasizes that such differences in feed-phase chemistry and compatibilization route strongly influence hydrogen bonding, morphological evolution, interfacial adhesion, and ultimately the structure–property relationship of the final film [23], [38], [46], [47].

Within that framework, PTF can be interpreted as a starch film containing a crude pandan-derived lignocellulosic phase. Because the pandan leaves were blended directly prior to filtration, the film-forming phase likely retained not only soluble compounds but also finely dispersed lignocellulosic components capable of reinforcing the matrix through hydrogen-bond-assisted restriction of chain mobility. This interpretation is supported consistently by the sharper O–H absorption profile in FTIR, the smoother and denser morphology in SEM, the higher tensile strength and modulus, and the delayed thermal decomposition seen in TGA. Recent reviews and structure–property studies on starch–cellulose and starch–lignocellulosic systems similarly report that improved compatibility and denser morphology are typically associated with enhanced stiffness and thermal resistance [24], [37], [48].

By contrast, GTF can be interpreted as a starch film modified by a CBM-derived extract generated through hot water extraction, a route that is more likely to favor water-soluble polysaccharide constituents. Under solution-casting conditions, such a phase may contribute to a more hydrated and less tightly packed film network. This interpretation is supported by the broader O–H band in FTIR, the more heterogeneous and porous morphology in SEM, the lower tensile strength, the higher elongation at break, and the earlier thermal decomposition observed in TGA. In other words, the GTF system appears to have favored ductility and degradability at the expense of stiffness and thermal robustness. Rather than treating these differences as isolated observations, the present data support a coherent process–structure–property relationship in which extract-preparation route governs matrix organization, and matrix organization in turn governs mechanical performance, thermal stability, and degradation behavior [17], [38], [42], [46].

More broadly, the integrated results reveal a consistent structure–property–degradation relationship linking molecular interactions to macroscopic performance. Stronger and more ordered hydrogen bonding, together with denser polymer packing, favored higher mechanical strength, improved thermal stability, and slower degradation. In contrast, a more heterogeneous bonding environment and a more porous morphology promoted greater flexibility and faster biodegradation. The TGA results support this interpretation by showing that the PTF system decomposed at higher temperatures than the GTF system, indicating greater thermal resistance under the present test conditions. Because no direct crystallinity analysis was performed, these differences are interpreted here as evidence of distinct thermal-degradation behavior rather than as proof of semi-crystalline or amorphous network structures. Taken together, the findings provide a practical comparative basis for selecting plant-derived modifiers in tapioca-starch bioplastics according to the desired balance between strength, flexibility, thermal resistance, and degradation rate. Nevertheless, because no photographic record of the buried films was retained, the biodegradation interpretation in this study should be understood as being supported primarily by weight-loss data and indirect structural evidence rather than direct visual documentation of surface deterioration.

4. Conclusion

This study presents a direct comparative evaluation of lignocellulosic- and hydrocolloid-dominant plant-derived modifiers within the same tapioca-starch film system under equivalent processing conditions. The main novelty of this work lies not only in comparing two abundant tropical plant resources, namely *Pandanus amaryllifolius* and *Cyclea barbata* Miers, but also in demonstrating how differences in extract-preparation route and plant-phase chemistry generate distinct matrix organizations and, consequently, different property profiles.

The key contribution of this study is the establishment of a clear process–structure–property–degradation relationship for tapioca-based bioplastics. The directly blended pandan-derived phase produced films with a denser morphology, higher tensile strength, and greater thermal resistance, whereas the hot-water-extracted grass-jelly-derived phase produced films with higher flexibility and faster biodegradation. These contrasting behaviors show that plant-matrix selection can be used deliberately to tune not only mechanical performance, but also degradation tendency and functional lifetime.

From a practical perspective, the present findings provide a comparative materials-design basis for selecting natural modifiers in starch-based bioplastics according to application needs. Pandan-derived reinforcement is more suitable when greater strength and thermal stability are required, whereas grass jelly derived modification is more advantageous when flexibility and faster post-use degradation are prioritized. Accordingly, this work contributes a useful design framework for the development of application-specific biodegradable films based on renewable tropical resources.

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Authors' Declaration

Authors' contributions and responsibilities – The authors made substantial contributions to the study's conception and design. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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