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Development of sustainable packaging films using hybrid food-processing waste starches reinforced with recycled cotton cellulose fibers

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Abstract

This study demonstrates a sustainable, multi-waste-derived approach to fabricating biodegradable composite biofilms by simultaneously valorizing three independent household and industrial waste streams: potato peel waste, industrial rice milling residue, and short recycled textile cotton fibers. Using a scalable solution gelatinization and compression molding technique assisted by a food-grade glycerol and acetic acid system, a hybrid starch matrix was developed and reinforced with varying fiber concentrations. The structural and functional properties of the resulting biofilms were profoundly dictated by the fiber loading level. The integration of 10% recycled cotton fiber established an optimal reinforcement network, boosting the tensile strength by over 240% to a peak of 5.2 MPa compared to the unreinforced matrix. Furthermore, strong matrix-fiber interfacial hydrogen bonding locked the hydrophilic polymer chains, reducing water solubility from 45% down to 12% at maximum loading. While the unreinforced thermoplastic starch films underwent rapid aqueous disintegration within 36 hours, the high-density fiber mesh successfully acted as a structural cage, maintaining macrostructural integrity for up to 120 hours. Finally, soil-burial testing confirmed exceptional environmental compatibility, with all films undergoing heavy microbial fragmentation and achieving full metabolic consumption within 28 to 35 days, presenting a highly viable, closed-loop packaging alternative aligned with circular bioeconomy goals.

Keywords: Starch Bio-composites; Potato Peel Waste; Recycled Cotton Fiber; Biodegradable Packaging; Circular Bioeconomy

1. Introduction

The extensive use of petroleum-based plastics has revolutionized modern society because of their low cost, excellent mechanical performance, and ease of processing [1]. However, the widespread consumption of single-use plastics has created one of the most pressing environmental challenges of the twenty-first century, leading to continuous plastic waste accumulation in terrestrial and aquatic ecosystems [2, 3]. Traditional waste management strategies, including landfilling and incineration, face severe space and emissions limitations, while mechanical recycling is restricted by sorting constraints and material degradation [4, 5]. Consequently, replacing conventional plastics with sustainable materials derived from renewable resources has become a global priority [6]. Within the framework of a circular bioeconomy, biodegradable packaging derived from agricultural and industrial by-products provides an effective pathway to mitigate plastic pollution while reducing reliance on fossil resources [7, 8]. Starch-based biomaterials have attracted exceptional attention due to their low cost, renewability, non-toxicity, and excellent film-forming properties [9, 10]. Nevertheless, native starch films suffer from high brittleness, low tensile strength, and severe moisture sensitivity, which restrict their widespread industrial and packaging application [11].

Starch is a naturally occurring polysaccharide composed of linear amylose and highly branched amylopectin, where the amylose-to-amylopectin ratio fundamentally dictates its film structural properties [12]. Converting native starch into a

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functional continuous matrix requires a thermal gelatinization process in excess water to disrupt its crystalline granular architecture [13]. To alleviate inherent brittleness, plasticizers like glycerol are typically integrated to establish hydrogen bonds with starch chains, increasing free volume and improving flexibility [14]. However, excessive plasticizer loading often induces high moisture absorption and a drastic drop in tensile strength [15]. To overcome this, organic acids such as acetic acid are widely utilized as processing aids to optimize starch dispersion, facilitate structural uniformity, and enhance the overall stability of the resulting polymeric network [16]. Despite these modifications, unreinforced starch-based films remain inadequate under mechanical stress and humid conditions, driving intense research into natural fiber reinforcement [17].

Shifting away from commercial food-grade starches, the current focus is moving toward the valorization of industrial food-processing waste streams [18]. Potato peel residue represents an abundant, carbohydrate-rich industrial by-product that contains substantial amounts of recoverable starch possessing film-forming traits comparable to virgin tuber starch [19, 20]. Similarly, rice milling operations continuously generate low-value, broken rice and starch-rich processing powders [21]. Extracting and utilizing starch from these waste sources not only mitigates agro-industrial disposal burdens but also avoids competition with human food resources [22]. Furthermore, blending potato-derived and rice-derived starches offers a complementary hybrid system, where variations in granule morphology and amylose contents can be optimized to build a more cohesive, homogeneous biopolymer matrix with enhanced mechanical functionality [23].

To effectively upgrade the mechanical resistance and dimensional stability of these waste-derived starch films, the introduction of high-strength natural lignocellulosic fibers is highly essential [24]. Cellulose fibers possess remarkable specific mechanical properties, low density, and outstanding structural rigidity due to their highly ordered molecular structures [25]. Cotton fiber is exceptionally suited for biopolymer reinforcement because it consists of up to 95% pure cellulose with minimal lignin or hemicellulose impurities [26]. When incorporated into a gelatinized starch matrix, the abundant surface hydroxyl groups of the cellulose fibers interact closely with starch molecules through robust interfacial hydrogen bonding [27]. This allows efficient mechanical stress transfer from the starch matrix to the stronger fiber skeleton, effectively bridging microcracks, restricting polymer chain mobility, and maintaining the structural integrity of the composite film even under aqueous exposure [28].

To optimize environmental performance and follow circular manufacturing principles, utilizing recycled cotton fibers recovered from textile manufacturing waste provides significant technological advantages over virgin fiber resources [29]. Textile waste represents a vast, underutilized reservoir of high-purity cellulose that is conventionally discarded in landfills or incinerated. Processing these short, recycled cotton fibers directly into bioplastics minimizes the energy, water, and chemical purification steps typically required for nanocellulose or virgin fiber isolation, making the production process highly sustainable and cost-effective [30].

Despite growing research into starch biocomposites, a significant scientific gap remains. Most existing literature focuses on commercially refined starches combined with newly harvested or heavily chemically modified fibers. Studies evaluating the combined utilization of multiple waste streams specifically blending potato peel waste starch and rice milling starch reinforced with recycled textile cotton fibers remain exceedingly scarce. The simultaneous integration of these three independent waste fractions into a singular bio-based material system presents a highly unique opportunity to address food, agricultural, and textile industrial waste challenges concurrently.

The central hypothesis of this research is that incorporating short recycled cotton fibers into a blended potato peel-rice starch matrix will create an interconnected cellulose reinforcing network, thereby significantly improving the tensile performance and water resistance of the films. However, it is also hypothesized that an optimal fiber loading threshold exists, beyond which fiber agglomeration and inadequate matrix wetting will induce stress concentration sites and diminish mechanical performance. Consequently, the specific objectives of this study are to extract and prepare biodegradable biofilms from blended potato peel and rice milling waste starches, to reinforce this hybrid matrix with varying concentrations of short recycled cotton fibers, to evaluate the direct effects of fiber loading on film thickness, tensile strength, elongation at break, water solubility, and moisture absorption, and to analyze the soil-burial biodegradation dynamics of the composite materials. Ultimately, this work seeks to establish an environmentally responsible, fully waste-derived packaging film aligned with global circular bioeconomy goals.

2. Materials and Methods

2.1. Materials

Potato peel waste, collected from local household kitchens, served as the primary source of starch. Rice starches another primary matrix was extracted from rice powder obtained as a by-product from a local automatic rice mill. Recycled cotton fibers were gathered from local textile waste and utilized as the reinforcing phase. Before composite preparation, these textile fibers were cleaned to remove visible impurities and manually chopped into lengths of approximately 5 mm to promote uniform dispersion within the biopolymer matrix. Food-grade glycerol was used as the plasticizer, distilled water as the solvent, and 5% (v/v) acetic acid as the gelatinization medium and processing aid. All chemicals were used as received without further purification.

2.2. Preparation of Starch Matrix

For the extraction of potato peel starch, fresh potato peels were thoroughly washed with tap water followed by distilled water to remove adhering soil and dirt. The cleaned peels were mechanically crushed with distilled water to generate a starch slurry. This slurry was filtered to remove coarse fibrous materials, and the filtrate was left undisturbed to facilitate starch sedimentation. After decanting the supernatant, the sedimented potato starch was collected, dried at 60 °C until achieving a constant weight, ground into a fine powder, and stored in airtight containers (Fig. 1A).

For the preparation of rice starch, the collected industrial rice mill powder was dispersed in distilled water to obtain a suspension. The mixture was filtered to isolate insoluble particles, and the resulting filtrate was allowed to settle. After sedimentation, the supernatant was removed, and the recovered rice starch was dried at 60 °C, ground into a fine powder, and kept in sealed containers (Fig. 1B).

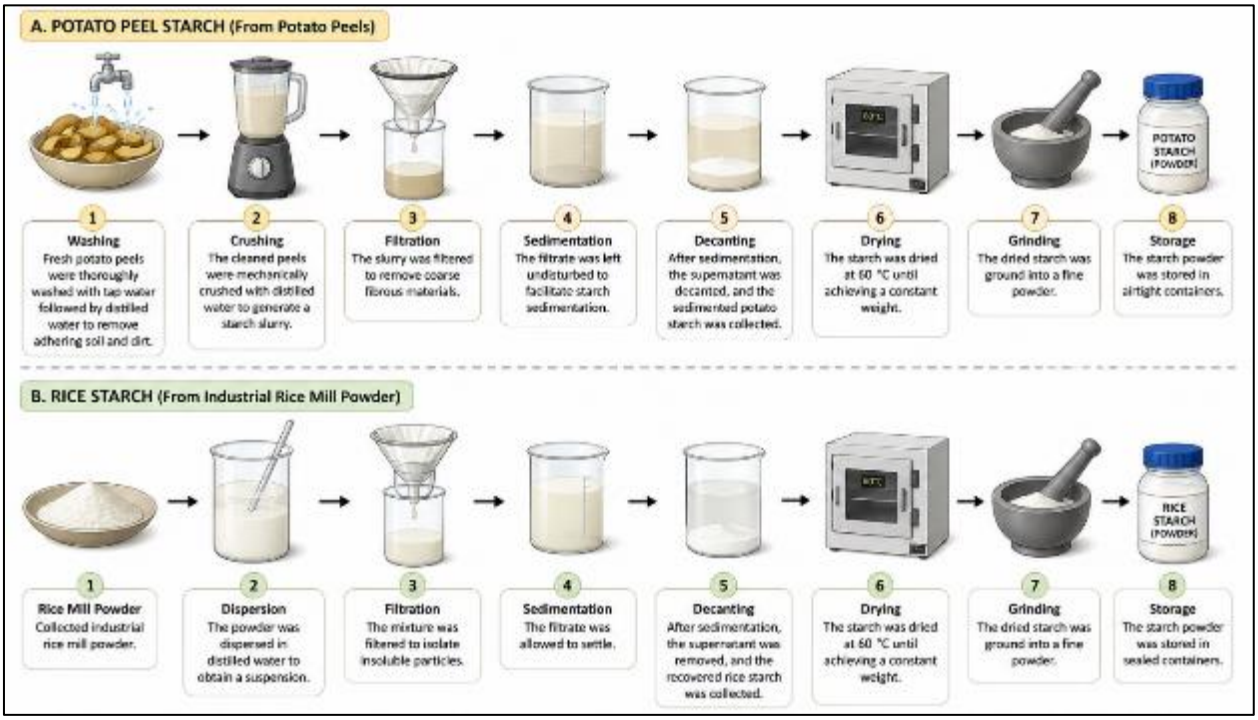

Figure 1 Process flow diagram detailing the synthesis of the biopolymer matrices: (A) extraction workflow from potato peel waste, and (B) preparation process from industrial rice milling powder by-products

2.3. Preparation of Starch Composite Biofilms

Three distinct film formulations were prepared by varying the content of recycled cotton fiber while keeping the amounts of starches, plasticizer, and solvent constant (Table 1) and illustrated the process in Fig. 2.

Table 1 Formulation of starch biofilms

Sample	Potato Starch (g)	Rice Starch (g)	Cotton Fiber (g)	Glycerol (g)	Water (mL)	5% Acetic Acid (mL)
PR	10	10	0	10	30	10
PRC-1	9	9	2	10	30	10
PRC-2	8	8	4	10	30	10

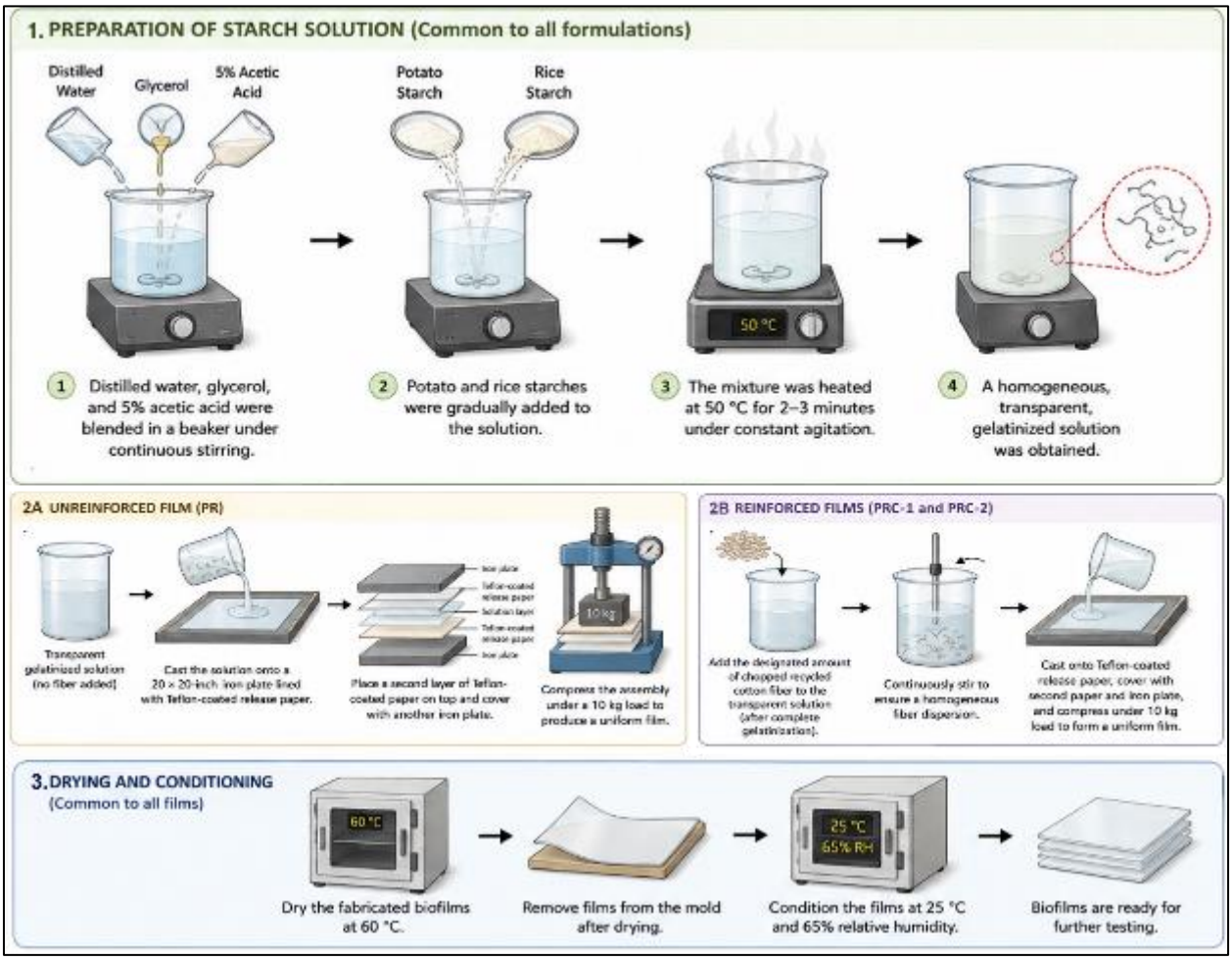

Figure 2 Schematic illustration of the experimental workflow for biofilm fabrication: (1) preparation of the blended starch solution; (2A) compression molding process for the unreinforced neat starch film (PR); (2B) fiber integration process for the reinforced composite films (PRC-1 and PRC-2); and (4) subsequent oven-drying and environmental conditioning of the fabricated biofilms

Initially, distilled water, glycerol, and 5% acetic acid were blended in a beaker under continuous stirring. The potato and rice starches were then gradually added to the solution. The mixture was heated at 50 °C for approximately 2–3 minutes under constant agitation until a homogeneous, transparent, gelatinized solution was formed (Fig. 2.1).

For the unreinforced, neat starch film (PR), the transparent gelatinized solution was immediately cast onto a 20 × 20-inch iron plate lined with Teflon-coated release paper. A second layer of Teflon-coated paper was placed over the upper surface, followed by another iron plate. This entire assembly was compressed under a 10 kg load to produce a uniform film (Fig. 2.2A). For the reinforced formulations (PRC-1 and PRC-2), the designated amount of chopped recycled cotton fiber was gradually incorporated into the transparent solution immediately following complete starch gelatinization. The mixture was continuously stirred to ensure a homogeneous fiber dispersion prior to plate pouring and compression

molding under identical conditions (Fig. 2.2B). All fabricated biofilms were dried at 60 °C before mold removal and were subsequently conditioned at 25 °C and 65% relative humidity before further testing (Fig. 2.3).

2.4. Characterization of Biofilms

2.4.1. Thickness Measurement

The total thickness of the composite biofilms was measured using a digital thickness gauge. To minimize local variations and ensure statistical reliability, measurements were taken at five random locations on each film specimen, and the calculated average value was reported.

2.4.2. Water Solubility

Water solubility was determined gravimetrically. Film specimens (2.5 × 2.5 cm^2) were dried in a hot-air oven to a constant mass to record their initial dry weight (W_0). Each specimen was then immersed in 100 mL of distilled water and continuously agitated using a magnetic stirrer at 180 rpm for 3 hours at 25 °C. After immersion, the remaining insoluble film fragments were carefully removed, dried again in an oven to a constant weight, and weighed to obtain the final dry weight (W_f). The percentage of water solubility was calculated using Eq. (1):

$$Water\ Solubility\ (\%) = \frac{W0-Wf}{W0} \times 100 \qquad (1)$$

2.4.3. Water Absorption

Water absorption behavior was evaluated in accordance with the ASTM D570 standard. Film specimens were oven-dried to a constant weight to establish their initial dry weight W_0 and then fully immersed in a distilled water bath maintained at 25 °C for a total duration of 120 hours. At periodic intervals of 12 hours, the specimens were temporarily removed, gently blotted with absorbent paper to eliminate excess surface water, weighed immediately, and returned to the immersion bath. The water absorption percentage was calculated using Eq. (2):

$$Water\ Absorption(\%) = \frac{Wt-W0}{W0} \times 100 \qquad (2)$$

where W_t represents the weight of the specimen at immersion time t.

2.4.4. Tensile Properties

The mechanical performance of the prepared biofilms was evaluated using a Universal Testing Machine (UTM) according to the ASTM D882 standard for thin plastic sheeting. Rectangular specimens were cut from the conditioned films and tested under ambient laboratory conditions. Tensile strength and elongation at break were derived directly from the generated experimental stress–strain curves.

2.4.5. Soil-Burial Biodegradation

The environmental degradation kinetics of the composite films were investigated via a soil-burial method. Film specimens measuring 5 × 5 cm^2 were oven-dried to a constant weight to record their initial dry weight (W_0). Each specimen was buried at a depth of approximately 5 cm beneath the surface of 500 g of moist, nitrogen-rich soil under controlled laboratory conditions for 35 days. At 7-day intervals, the films were carefully retrieved, gently rinsed with distilled water to remove adhering soil particles, and dried in a hot-air oven to record their dry weight (W_t) before being reburied. The percentage weight loss was calculated using Eq. (3):

$$Weight\ Loss\ (\%) = \frac{W0-Wt}{W0} \times 100 \qquad (3)$$

3. Results and Discussion

3.1. Thickness and Physical Appearance

The thickness of the fabricated biofilms increased progressively with the incorporation and loading level of short recycled cotton fibers, as illustrated in Fig. 3. The neat starch film (PR) exhibited the lowest thickness at 0.6 ± 0.03 mm. Upon reinforcing the matrix, the film thickness increased substantially to 1.1 ± 0.04 mm for PRC-1 (10% fiber loading) and reached a maximum of 1.5 ± 0.03 mm for PRC-2 (20% fiber loading). This pronounced increment in thickness is primarily attributed to the physical space occupied by the bulky three-dimensional lignocellulosic fiber networks within

the compression-molded matrix. As fiber loading scales up, the total volume of solid content increases, expanding the structural gap between the mold plates during compression [17]. Furthermore, higher fiber contents elevate the slurry viscosity and create a stiffer, less compressible wet compound that resists deformation during the pressing phase [31].

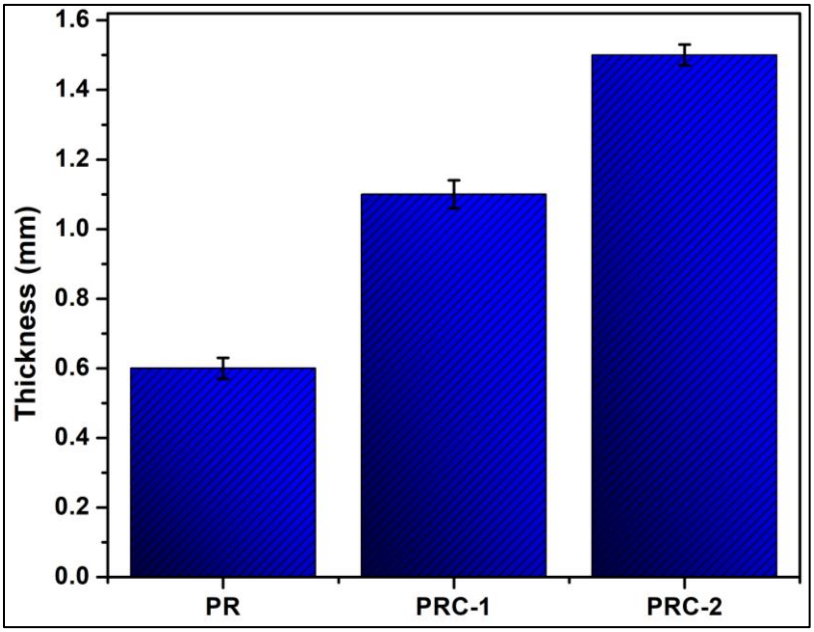

Figure 3 Mean thickness of the unreinforced (PR) and recycled cotton fiber-reinforced (PRC-1 and PRC-2) starch composite biofilms

In terms of physical appearance, the unreinforced film (PR) appeared highly homogeneous, translucent, and smooth. The addition of 10% fiber (PRC-1) yielded a slightly textured film surface with fibers visually well-distributed across the structural domain, signaling favorable interfacial compatibility facilitated by the glycerol–acetic acid solvent system [16]. However, at 20% loading (PRC-2), the composite film displayed visible superficial roughness, localized fiber bundling, and micro-voids. This threshold effect occurs because excessive fiber inclusion drives mechanical entanglement, limiting the ability of the gelatinized starch to wet the dense cellulose networks thoroughly [27].

3.2. Tensile Strength and Elongation at Break

The mechanical performance profile revealed that the addition of recycled cotton fibers drastically reshaped both the tensile strength and molecular flexibility of the biofilms, as illustrated in Fig. 4. The neat starch film (PR) showed an intrinsically low tensile strength of 1.5 MPa coupled with a high elongation at break of 42%. The incorporation of 10% fiber (PRC-1) triggered an outstanding reinforcement effect, boosting the tensile strength by over 240% to a peak of 5.2 MPa, while reducing elongation to 18%. This significant mechanical upgrade highlights efficient stress transfer across the fiber-matrix boundary, driven by strong hydrogen bonding between the highly abundant hydroxyl groups on the cotton cellulose surfaces and the hydroxyl blocks of the gelatinized amylose-amylopectin matrix [26, 28]. The short fibers establish a skeletal backbone that restricts the localized sliding of starch chain domains, resulting in a stiffer and significantly stronger composite material [32].

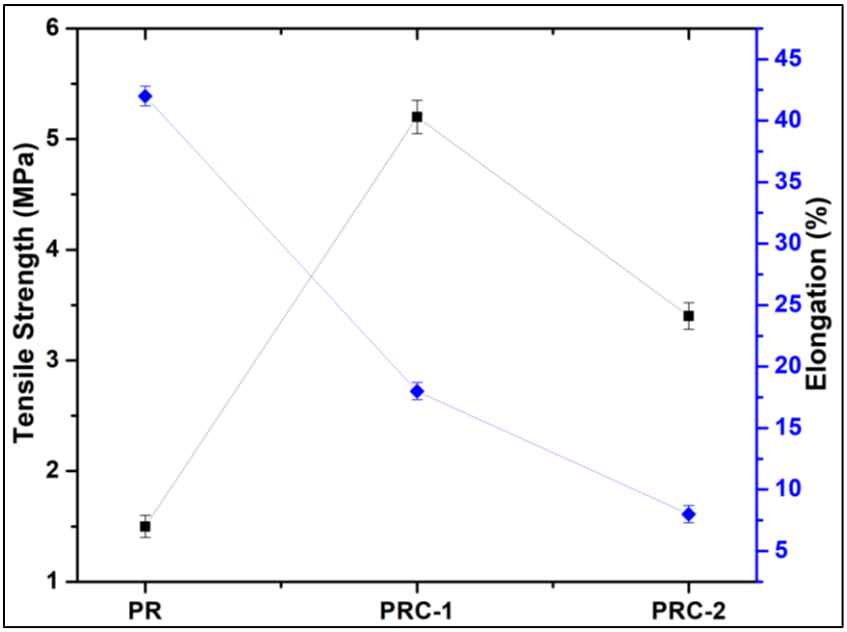

Figure 4 Tensile strength and elongation at break of the unreinforced (PR) and recycled cotton fiber-reinforced (PRC-1 and PRC-2) starch composite biofilms

When the fiber volume was doubled to 20% (PRC-2), the tensile strength dropped markedly from the peak to 3.4 MPa, and the elongation further plummeted to 8%. This performance degradation at higher loadings confirms the central hypothesis regarding reinforcement thresholds. At 20% loading, the volume of the starch matrix becomes insufficient to coat the vast cumulative surface area of the chopped cotton fibers entirely [17]. This creates un-plasticized fiber agglomerations and interfacial structural defects which function as intense stress concentration sites, causing premature micro-cracking and structural breakdown under mechanical loading [33].

3.3. Water Solubility

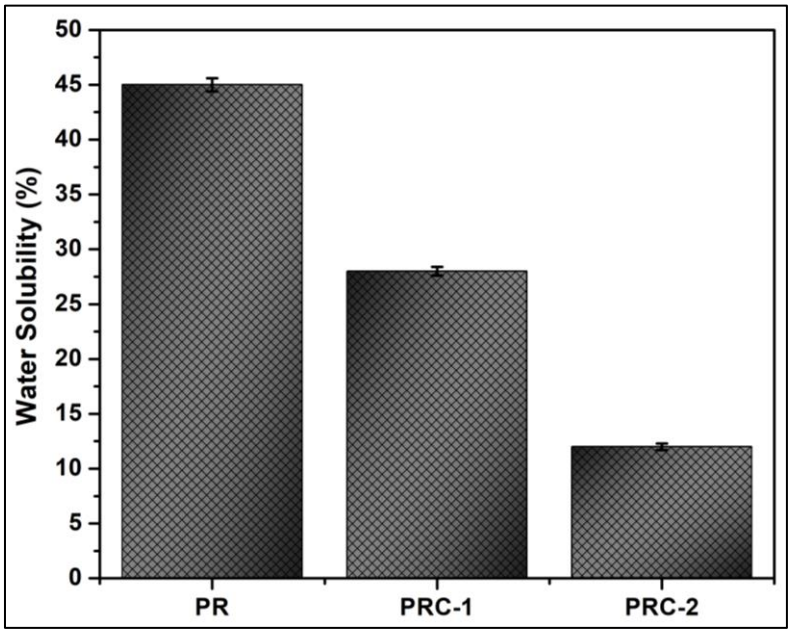

Figure 5 Comparative water solubility profiles of the formulated biofilms as a function of recycled cotton fiber loading level (0%, 10%, and 20%)

Water solubility provides a vital indicator of a bio-based film's structural endurance under moisture exposure, as shown in Fig. 5. The gravimetric test demonstrated a steep decline in film solubility as a function of fiber loading. The

unreinforced PR matrix displayed the highest water solubility at 45%, highlighting the highly hydrophilic character of starch macromolecules, which readily absorb water molecules, disrupting the native intermolecular hydrogen-bonded network [34]. For the composite formulations, the percentage of water solubility dropped to 28% for PRC-1 and reached a minimum of 12% for PRC-2.

This sharp drop in solubility indicates that the structural introduction of cotton fibers locks the starch matrix into an interconnected network. Lignocellulosic fibers possess a highly crystalline cellulose core that is fundamentally insoluble in water under ambient conditions [25]. When dispersed uniformly, these fibers function as structural anchoring webs that physically restrict the swelling, swelling-driven detachment, and subsequent dissolution of the surrounding starch matrix fragments [17]. Additionally, the strong matrix-fiber interfacial bonding reduces the availability of free hydrophilic hydroxyl pathways on the starch chains to bond with external water molecules, effectively acting as an anchor that locks the polymer matrix in place [27].

3.4. Water Absorption

Table 2 Long-term water immersion and swelling dynamics of the biofilms

Immersion Time (Hours)	**Sample PR (0% Fiber)**	**Sample PRC-1 (10% Fiber)**	**Sample PRC-2 (20% Fiber)**
12	~ 200% (Highly swollen gel)	~ 150% (Soggy, structurally weak)	~ 110% (Swollen but intact)
24	Fragmented / Dissolving	~ 250% (Pulpy state)	~ 180% (Fiber mat holding gel)
36	Completely Dissolved	Severe fragmentation	~ 210% (Starch leaching out)
48	—	Completely Disintegrated	~ 200% (Starch matrix mostly gone)
60	—	—	~ 150% (Only fiber skeleton left)
72	—	—	~ 120% (Fiber skeleton)
84–120	—	—	~ 80%–90% (Pure wet cotton remnants)

The long-term water immersion profile over 120 hours revealed highly dynamic absorption, swelling, and physical erosion behaviors among the tested formulations, as depicted in Table 2. At the initial 12-hour mark, all samples underwent rapid moisture intake due to their hydrophilic nature. The PR film absorbed ~200% water, transforming into a highly swollen, structurally unstable gel. By 24 hours, the unreinforced film underwent fragmentation and dissolution, disappearing completely into the aqueous medium by 36 hours. This quick dissolution highlights that the hydrogen-bonded network of plasticized thermoplastic starch possesses no wet-strength and crumbles entirely as water molecules flood the free volume within the matrix [15].

The inclusion of recycled cotton fibers markedly prolonged the life of the biofilms in water. PRC-1 (10% fiber) reached a maximum absorption of ~250% at 24 hours in a pulpy, weakened state, before undergoing severe fragmentation at 36 hours and fully disintegrating by 48 hours. Conversely, PRC-2 (20% fiber) demonstrated superior structural stability, maintaining its mechanical shape up to 120 hours. PRC-2 absorbed ~110% at 12 hours, peaked at 210% by 36 hours as starch slowly leached out, and then showed a steady decline in apparent weight down to 80%–90% between 84 and 120 hours. This progressive weight loss corresponds to the structural leaching of the soluble starch portion, leaving behind a pure, intact wet cotton fiber skeleton. This pattern confirms that an extensive, high-density fiber mesh acts as a mechanical cage that resists total disintegration, offering structural integrity even after the surrounding biopolymer matrix has dissolved [28, 30].

3.5. Soil-Burial Biodegradability

The soil-burial evaluation established that all produced biofilms maintain high environmental compatibility, returning fully to the ecosystem within a 35-day window, as presented in Table 3. The degradation rate was closely coupled to the presence of the reinforcing fiber phase. The neat starch film (PR) degraded at the fastest rate, showing 30–40% weight loss by Day 7 alongside a highly swollen, slimy morphology. It advanced to heavy fragmentation (60–75%) by Day 14, left only minute traces by Day 21, and was completely metabolized (~100%) by Day 28. This accelerated degradation occurs because soil microorganisms (bacteria and fungi) easily secrete extracellular amylases to hydrolyze the accessible, amorphous glucose linkages of plasticized starch [35, 36].

The addition of recycled cotton fibers caused a controlled retardation of the biodegradation kinetics. PRC-1 reached complete metabolic consumption at Day 35, whereas PRC-2 retained minor trace fiber residues (90–98% weight loss) at the conclusion of the 35-day cycle. On Day 14, PRC-1 and PRC-2 exhibited weight losses of 45–55% and 35–45%, respectively, with the samples turning highly brittle and showing widespread microbial discoloration spots. The slower degradation path of the composites is governed by two factors: first, the highly crystalline nature of cellulose in cotton fibers requires a longer timeframe for specialized cellulolytic enzymes to break down compared to amorphous starch fractions [25]; second, the dense network structural configuration and reduced water solubility of the composites restrict moisture infiltration within the soil matrix, thereby slowing down the microbial colonization and subsequent enzymatic cleavage rates [30, 37].

Table 3 Soil-burial biodegradation kinetics (Weight Loss, %) and sample morphology

Burial Duration (Days)	**Sample PR (0% Fiber)**	**Sample PRC-1 (10% Fiber)**	**Sample PRC-2 (20% Fiber)**
7	30–40% (Swollen, slimy)	20–30% (Softening, microbial spots)	15–25% (Slight swelling)
14	60–75% (Heavy fragmentation)	45–55% (Breaking into pieces)	35–45% (Brittle, discolored)
21	85–95% (Traces remaining)	65–75% (Loose fibers/fragmented)	50–65% (Heavy fragmentation)
28	~100% (Completely gone)	85–95% (Only loose cotton remnants)	70–85% (Decaying fiber mats)
35	100% (Fully metabolized)	100% (Fully metabolized)	90–98% (Trace fiber residues)

4. Conclusion

This study has successfully demonstrated a sustainable, fully waste-derived approach to fabricating biodegradable composite biofilms by simultaneously valorizing three independent industrial and household waste streams: potato peel waste, rice milling residue, and recycled textile cotton fibers. By employing a simple, scalable solution gelatinization and compression molding technique utilizing a food-grade glycerol and acetic acid system, the research successfully shifted the paradigm away from using refined commercial starches and virgin reinforcements toward a closed-loop circular bioeconomy model. The experimental investigations confirmed the central hypothesis that the architectural introduction of short, recycled cotton fibers establishes a robust, interconnected reinforcing cellulose skeleton within the blended potato peel–rice starch matrix. The functional properties of the films were profoundly dictated by the fiber loading level, demonstrating a distinct performance threshold. The incorporation of 10% recycled cotton fiber achieved an optimal reinforcement effect, boosting the tensile strength by over 240% to a peak of 5.2 MPa compared to the unreinforced matrix, while maintaining an acceptable elongation at break of 18%. Furthermore, the structural integration of the crystalline cellulose network effectively locked the hydrophilic starch chains, leading to a critical drop in water solubility from 45% down to 12% at maximum loading. Long-term water immersion tests revealed that while unreinforced thermoplastic starch films underwent rapid fragmentation and disintegrated completely within 36 hours due to flooding of the polymer free volume, the high-density fiber mesh in the 20% loading formulation successfully maintained its macrostructural shape for up to 120 hours by acting as a structural cage that prevented complete

physical dissolution and left an intact wet cotton skeleton. Crucially, soil-burial testing established that all formulated composite films retain exceptional environmental compatibility, undergoing widespread microbial colonization, heavy fragmentation, and ultimate metabolic consumption within 28 to 35 days, with only a minor degradation delay observed at higher fiber contents due to the slower enzymatic cleavage of highly crystalline cellulose fractions by soil microorganisms.

Despite these highly promising outcomes, certain critical limitations must be acknowledged to guide future industrial implementation and material optimization. While the incorporation of recycled cotton fibers significantly prolonged the life of the biofilms in water and delayed macrostructural collapse, the films still exhibited highly hydrophilic moisture absorption profiles under extended aqueous immersion, which limits their immediate commercial application in high-moisture food packaging, damp environments, or direct liquid storage. Furthermore, the hand-chopping of the recycled cotton fibers into approximately 5 mm lengths introduces significant structural variability, labor costs, and challenges for industrial scalability, as manual processing cannot guarantee the absolute fiber length uniformity necessary for automated mass manufacturing. The high fiber loading of 20% also resulted in a notable increase in film thickness to 1.5 mm, visible superficial roughness, micro-void formation, and localized fiber agglomeration due to inadequate wetting by the gelatinized starch slurry, which inherently sacrificed the optical transparency, cosmetic uniformity, and flexibility of the composite packaging material, dropping elongation to a brittle 8%. Finally, the structural evaluation in this work was restricted to fundamental physical, mechanical, and degradation tests, leaving critical transport properties—such as water vapor transmission rates, oxygen permeability, and long-term thermal stability—completely unquantified.

To expand the industrial feasibility and functional performance of these waste-derived biofilms, several key research avenues should be explored in the future. Future research must focus on developing advanced pretreatments and mechanical processing scaling strategies, such as investigating industrial milling, enzymatic pre-treatment, or green chemical modifications like mild citric acid crosslinking for both the waste starches and recycled cotton fibers to optimize interfacial adhesion, minimize fiber agglomeration, and allow for automated extrusion processing. Additionally, comprehensive barrier and storage testing must be conducted to systematically evaluate the water vapor transmission rate (WVTR), oxygen transmission rate (OTR), and thermal stability of the composite films to precisely map their compatibility with specific dry, semi-moisture, or short-shelf-life food sectors. The introduction of functional additives represents another significant opportunity for research expansion, where incorporating active bio-compounds such as natural antimicrobial or antioxidant agents extracted from agricultural residues can transition these composites into active packaging systems capable of actively extending food shelf life and preventing spoilage. Ultimately, extensive life cycle assessments (LCA) and techno-economic analyses must be conducted to evaluate the true environmental footprint savings, carbon reduction metrics, and raw economic production costs of moving from small-scale laboratory compression molding to continuous industrial scale-up technologies like twin-screw extrusion or rolling mills.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no conflicts of interest.

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