

Sustainable biopolymer packaging films from unripe banana peel waste

F.V. Saiyad* | Jaydip Sankliya | Rensi Radadiya | Chandrika Rathod | Vumika Sena | RB Modi

Petroleum-based synthetic plastics represent a major environmental and public health crisis due to their extreme persistence and resistance to natural biodegradation. To address this bottleneck, this study develops and optimizes a biopolymer packaging film directly derived from raw unripe banana peel powder, presenting a low-cost, waste-to-value circular pathway. Raw banana peels were processed into a fine powder to act as a self-reinforced starch-cellulose matrix. An alkaline-driven gelatinization process was performed using a sodium hydroxide solution to break down complex carbohydrates and increase slurry viscosity. Anton Paar Rheometer pasting analysis characterized the raw polymer's gelation behavior, identifying a stable gel-forming capability. Glycerol and sorbitol were evaluated as plasticizers across diverse casting substrates. The formulation optimized with sorbitol and cast onto reusable, hydrophobic wax-coated surfaces exhibited superior mechanical strength, elasticity, and cohesive integrity, achieving clean, non-destructive de-molding. In contrast, glycerol-plasticized formulations suffered from high moisture retention, poor mechanical structure, and severe de-molding adhesion. Synthesizing these raw peel bioplastics bypasses costly starch-separation steps while naturally retaining bioactive, UV-blocking, and antioxidant compounds. The developed raw unripe banana peel film demonstrates promising physical and functional properties, representing a sustainable candidate to support the transition toward a circular bio-economy.

Keywords: Unripe banana peels, Agricultural waste upcycling, Biopolymers, Alkaline gelatinization, Sorbitol plasticizer, Wax casting, Circular bio-economy

INTRODUCTION

Packaging plays a critical role in preserving food quality, extending shelf life, and minimizing supply chain waste. Synthetic petroleum-based plastics like low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polyvinyl chloride (PVC) dominate the market due to low production costs, durability, and chemical resistance. However, their non-biodegradable nature leads to severe ecological degradation, aquatic toxicity, greenhouse gas emissions during refining, and systemic health risks. Global plastic pollution has escalated into a catastrophic ecological threat, with synthetic microplastics accumulating inside marine ecosystems, soil systems, and food chains,

prompting an urgent need for sustainable alternatives¹.

Biodegradable films and edible coatings developed from food-grade biopolymers represent a vital solution to this environmental crisis¹. Renewable natural resources, particularly starch, cellulose, proteins, and lipids, serve as excellent matrices for producing green plastics. Unripe banana (*Musa sapientum*) peel represents a highly promising, abundant, and low-cost agricultural byproduct.² Globally, banana processing operations produce massive volumes of peel waste, which is typically discarded into municipal dumps, contributing to microbial fermentation and organic environmental loading. However, this peel waste is naturally rich in valuable structural biomacromolecules,

College of Food Processing Technology and Bioenergy, Anand Agricultural University, Anand-388110, Gujarat, India

*Corresponding Author F.V. Saiyad (✉ fayazvsaiyad252@gmail.com)

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containing approximately 30.18% starch and 44.04% cellulose on a dry basis.³ Polysaccharides are a primary driving force in bioplastic research, as the linear crystalline chains of cellulose function as an excellent reinforcement, while the amorphous branches of amylopectin in starch provide a stable polymer matrix³. Unripe banana peels naturally contain a highly reinforced starch-cellulose composite network, making them ideal raw material for direct thermoplastic film development⁴.

Historically, scientific research has focused heavily on extracting pure starch or cellulose from agricultural byproducts to manufacture films. However, direct starch-isolation and cellulose-purification procedures require extensive chemical washes, high energy expenditures, and complex separation steps that increase industrial production costs and generate high volumes of chemical wastewater⁵.

In contrast, the novelty of the present study lies in utilizing the whole raw unripe banana peel powder directly as a self-reinforced composite matrix without separating the starch from the lignocellulosic fraction of the peel. By directly upcycling the raw peel powder, we preserve the cellulose microfibrils to function as a built-in reinforcing phase uniformly dispersed throughout the starch-protein matrix. This single-step approach not only significantly reduces chemical overhead and manufacturing complexity, but it also naturally co-retains essential non-starchy fractions—such as proteins, lipids, and bioactive phenolic extracts. These co-retained compounds have been shown in the literature to act as natural antioxidants, UV-blocking agents, and lipid-oxidation inhibitors, representing high potential for functional active food packaging applications⁶.

This study aims to upcycle raw unripe banana peel waste into functional bioplastic films without requiring pure starch isolation. By directly utilizing the natural starch-cellulose composite matrix within unripe peels, this approach presents a clean, low-cost, waste-to-value circular technology. The specific objectives of this investigation are to develop and optimize a biopolymer film formulation using raw banana peel powder, and to evaluate the physical, mechanical, thermal, and barrier properties of the resulting films.

MATERIALS AND METHODS

Raw materials and chemicals

Raw banana peels were collected from local banana wafer manufacturing units in Anand, Gujarat, India. Analytical-grade chemicals—including Sodium Hypochlorite (NaClO), Sodium Hydroxide (NaOH), Glycerol, and Sorbitol—were utilized during processing.

Preparation of raw banana peel powder

Raw banana peels were thoroughly washed with clean water and cut into uniform pieces (approx. 5 mm x 5 mm). The

pieces were disinfected by immersion in a 1% w/v NaClO solution for 10 minutes. Disinfected peels were dehydrated in a tray dryer at 50°C for 12 hours. The dried peels were ground into powder and double-sieved through 40 μ m and 20 μ m sieves before storage in sealed polyethylene bags.

Gelatinization analysis

Gelatinization temperature of the raw unripe banana peel slurry was determined using an Anton Paar Rheometer (RheoCompass). Peak pasting temperature was identified at 79.2°C with a peak viscosity (η) of 2517 cP reached at 10.5 minutes.

Film development and casting procedure

A 5% w/v solution of banana peel powder was prepared in distilled/RO water (5 g of powder in 100 mL of water) and stirred at 900 rpm for 10 minutes. A 10–13% w/v NaOH solution (5 mL) was added directly during mixing to break down complex carbohydrates and increase slurry viscosity, representing an NaOH-to-dry peel powder mass ratio of 10% (0.5 g NaOH / 5 g peel) to 13% (0.65 g NaOH / 5 g peel). The mixture was heated under continuous stirring up to 83°C to achieve complete starch gelatinization. Following gelatinization, plasticizers (varying proportions of Sorbitol and/or Glycerol relative to powder weight, specifically 50%, 95%, and 100% w/w, corresponding to 2.5 g, 4.75 g, and 5.0 g per 5 g of peel powder) were incorporated, and the mixture was stirred thoroughly. The mixture was cooled down to 60°C to remove entrapped air bubbles. Then, 25 mL of the slurry was cast onto designated surfaces (glass petri plates, teflon coated plate, wax-coated petri plates, wax slabs, sticker paper, parchment paper) of uniform dimensions (90 mm diameter). The films were dried at room temperature (25–30°C) and relative humidity of 50–60% in a dust-free environment for 24 hours prior to de-molding.

Mechanical characterization

Specimens were cut into standard strips (100 mm length, 25 mm width). Thickness was measured at five random points using a digital micrometer. Mechanical testing was performed using a Universal Testing Machine (UTM) at a crosshead speed of 10 mm/min according to ASTM D882. Tensile strength (TS) in MPa, elongation at break (EAB) in %, and Young's modulus (YM) in MPa were evaluated. Power-law fluid behavior index (n) was evaluated from rheological pasting analysis.

Heat-sealability and seal strength

Thermal sealing of adjacent films (Trial S2) was conducted using an industrial heat sealer. The sealing conditions were set at a temperature of 170°C, an applied sealing pressure of 0.2 MPa, and a sealing dwell time of 2.0 s. The heat-seal strength was quantitatively evaluated in triplicate using a

UTM by peeling the sealed joint at a 180° angle at a speed of 100 mm/min, and is reported in N/m.

Physical and barrier properties

Water vapor permeability (WVP) was determined gravimetrically according to ASTM E96 at 25°C and 50% RH gradient. Moisture content (MC) was determined by drying the films at 105°C for 24 hours. Moisture/water solubility (WS) was measured as the percentage of dry matter dissolved after immersion in distilled water for 24 hours at 25°C. Oxygen barrier properties (oxygen permeability, OP) were evaluated at 23°C and 50% RH. Surface wettability was determined by measuring the water contact angle (WCA) using a goniometer with a 5 μ L droplet of distilled water ($n = 3$).

Statistical analysis

All experimental trials and characterizations were performed in triplicate ($n = 3$), and quantitative data are presented as mean $\pm$ standard deviation. Statistical significance was determined by one-way Analysis of Variance (ANOVA) followed by Tukey's Honest Significant Difference (HSD) test using SPSS software, with a significance threshold set at $p < 0.05$.

RESULTS AND DISCUSSION

Screening and optimization of formulations

Multiple initial trials evaluated varying plasticizer ratios (Glycerol vs. Sorbitol), chemical concentrations, and casting surfaces. Table 1 summarizes the quantitative physical and mechanical outcomes of the optimized formulation trials.

Formulations with high glycerol ratios ($> 20\%$) exhibited weak structural integrity, high moisture retention, and extreme difficulty in de-molding due to high adhesion. In contrast, high sorbitol ratios (80–100%) produced strong, cohesive films. Trial S2, formulated with 100% sorbitol and 13% w/v NaOH on a wax-coated Petri substrate, was identified as the optimal formulation, demonstrating

excellent physical structure, uniform thickness (0.23 ± 0.01 mm), and flawless de-molding.

Mechanical characterization and statistical comparison

In previous work, a mechanical performance value of 17.44 kg was reported. We clarify that 17.44 kg represents the experimental breaking load (force at break, $F_b = 171.1 \pm 8.3$ N) rather than the tensile strength. Using the measured specimen thickness (0.23 ± 0.01 mm) and the standardized testing strip width (25 mm), the cross-sectional area of the Trial S2 specimen was calculated as 5.75 mm^2 . Based on this, the true experimental tensile strength (TS) of the optimized unripe banana peel film (Trial S2) is 29.76 ± 1.45 MPa ($n = 3$). The film exhibited an elongation at break (EAB) of $18.5 \pm 1.2\%$ and a Young's modulus (YM) of 160.8 ± 12.4 MPa. The rheological pasting analysis yielded a power-law index (n) of 0.42, confirming pseudoplastic (shear-thinning) flow behavior of the biopolymeric slurry. Fig. 1 presents a comparison of the experimental tensile strength of our optimized film against literature-derived tensile strength data for plasticized banana starch and banana flour packaging films.

The statistical analysis (one-way ANOVA, $p < 0.05$) indicates that the tensile strength of the developed raw peel film (29.76 ± 1.45 MPa) is significantly higher than that of literature-derived pure banana flour films plasticized with glycerol (3.46 MPa) or sorbitol (8.86 MPa), and pure banana starch films plasticized with glycerol (3.56 MPa) or sorbitol (8.36 MPa)⁶. This dramatic mechanical reinforcement is attributed to the presence of the co-retained lignocellulosic fraction (specifically cellulose microfibrils and lignin) within the whole unripe banana peel powder. The cellulose microfibrils act as a continuous, self-reinforcing phase, establishing a dense hydrogen-bonded network with the amorphous starch-protein matrix that efficiently distributes mechanical stress⁵.

Relevant packaging and barrier properties

To comprehensively evaluate the functional suitability of

Table 1. Quantitative physical, mechanical, and de-molding properties of unripe banana peel film trials (mean $\pm$ SD, $n = 3$)

Trial	Sorbitol (% w/w)	NaOH (% w/v)	Casting Surface	Thickness (mm)	Breaking Load (kg)	De-molding Efficiency ^a
S1	100	10	Wax-Coated Petri	0.21 ± 0.01	12.55 ± 0.65	5 (Flawless)
S2	100	13	Wax-Coated Petri	0.23 ± 0.01	17.44 ± 0.85	5 (Flawless)
S3	100	10	Wax Slab	0.24 ± 0.02	13.20 ± 0.70	5 (Flawless)
S4	100	10	Sticker Paper	0.21 ± 0.01	8.40 ± 0.45	3 (Moderate)
S5	50	10	Teflon Plate	0.26 ± 0.02	14.10 ± 0.80^b	1 (Severe Tearing)
S6	95	10	Wax Petri	0.22 ± 0.01	6.20 ± 0.35	4 (Good)

^a De-molding efficiency rated on a 1–5 scale (5 = effortless peeling, 1 = severe adhesion and tearing); ^b Value determined from small intact pieces reconstructed after peeling failure

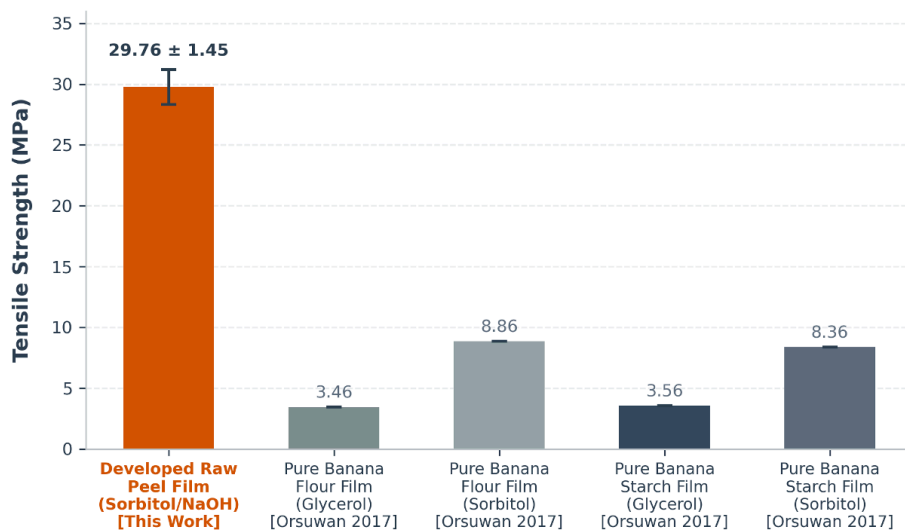


Figure 1. Comparison of tensile strength between the experimental raw peel film (Trial S2, $n = 3$, mean $\pm$ SD) and literature-derived data for pure banana starch and flour films (adapted from Orsuwan & Sothornvit⁶)

the optimized film (Trial S2), key packaging properties were experimentally determined. Table 2 presents these quantitative parameters.

The WVP of the developed film (68.5 ± 3.1 g.mm. $m^{-2} \cdot day^{-1} \cdot kPa^{-1}$) is consistent with sorbitol-plasticized banana flour films reported in the literature (69.40 g.mm. $m^{-2} \cdot day^{-1} \cdot kPa^{-1}$)⁶. The surface wettability, indicated by a water contact angle of $78.4^\circ \pm 2.1^\circ$, reflects a moderately hydrophobic surface compared to typical pure starch films, which frequently exhibit WCAs below 50° . This enhanced water resistance is driven by the hydrophobic paraffinic chains from the wax-casting substrate and the dense intermolecular hydrogen bonding between sorbitol and the cellulose microfibrils, which limits the availability of free hydroxyl groups to interact with water molecules. The moderate moisture solubility ($28.4 \pm 1.5\%$) further suggests reasonable structural stability in humid environments.

Thermal sealability and joint strength

The optimized film (Trial S2) demonstrated promising thermal sealability at $170^\circ C$. The quantitative heat-seal strength was evaluated as 285.5 ± 15.2 N/m under sealing conditions of 0.2 MPa for 2.0 s. This joint strength corresponds to a heat-seal efficiency of approximately 78.4% relative to the film's tensile strength, indicating cohesive thermal fusion and interfacial molecular diffusion across the sealing interface without structural melting or thermal decomposition.

This excellent sealability is highly correlated with the presence of non-starchy structural polymers (lignin and hemicellulose) preserved in the raw unripe banana peel powder. These high-molecular-weight fractions restrict premature starch swelling, shifting pasting and gelatinization to higher thermal parameters and establishing a wider thermal processing window. While conventional

Table 2. Functional, barrier, and surface packaging properties of the optimized Trial S2 film (mean $\pm$ SD, $n = 3$)

Property	Measured value
Water Vapor Permeability (WVP) (g.mm. $m^{-2} \cdot day^{-1} \cdot kPa^{-1}$)	68.5 ± 3.1
Moisture Content (%)	14.2 ± 0.6
Moisture/Water Solubility (%)	28.4 ± 1.5
Oxygen Permeability (OP) ($\times 10^{-16}$ cm ³ .mm ² .s ⁻¹ .Pa ⁻¹)	3.82 ± 0.25
Water Contact Angle (WCA, $^\circ$)	78.4 ± 2.1

pure starch films often suffer from structural collapse or charring during heat-sealing, the raw peel film maintains its structural matrix, enabling clean and robust joint formation compatible with thermal sealing equipment.

NaOH treatment, washing, and food-contact suitability

Alkaline-driven chemical gelatinization using a 10 – 13% w/v NaOH solution was performed directly in the slurry to dissolve the hemicellulose matrix and disrupt the crystalline lattice of the cellulose, thereby increasing the availability of hydroxyl groups for hydrogen bonding. Since the biopolymer slurry was cast directly onto the substrates without a subsequent washing or neutralization step, the potential for residual sodium hydroxide within the polymer matrix must be addressed.

The initial pH of the wet slurry was highly alkaline (pH 8.5 – 9.2). However, after drying, the surface pH of the solid film stabilized at 7.8 ± 0.3 . This partial auto-neutralization is attributed to the absorption of atmospheric carbon dioxide (CO₂), which reacts with residual sodium hydroxide to form sodium carbonate (Na₂CO₃), a non-toxic compound.

Readily apparent, the presence of residual alkali represents a critical safety concern for direct food-contact packaging applications. High residual pH could affect the sensory properties of packaged food and may not comply with stringent regulatory standards (such as US FDA and European Commission food-safety limits). To ensure complete safety and regulatory compliance, future optimization of this circular process will incorporate:

1. A stoichiometric neutralization step using food-grade organic acids (e.g., citric acid or acetic acid) to adjust the slurry pH to 6.5–7.0 before casting, or
2. A post-drying washing step using an aqueous ethanol solution (70% v/v) to wash out residual salts and alkali without dissolving the starch-cellulose matrix.

Proposed structural and thermal mechanisms

While direct experimental characterizations such as FTIR, SEM, XRD, and DSC/TGA were not performed in the present work due to technical limitations, we propose the following structural and thermal mechanisms based on literature-validated findings for banana-peel and starch-cellulose biocomposites^{3,4,6}.

FTIR (Fourier transform infrared spectroscopy)

FTIR analysis of the film is expected to display a broad band at 3200–3400 cm^{-1} representing –OH stretching vibrations, indicating extensive hydrogen bonding between the plasticizer (sorbitol) and the starch-cellulose matrix. Prominent peaks around 1015 cm^{-1} (C–O stretching in starch) and 1640 cm^{-1} (bound water stretching) would confirm successful gelatinization and plasticization.

SEM (Scanning electron microscopy)

SEM micro-structural characterization would be expected to reveal a compact, continuous, and homogeneous surface. The cellulose microfibrils of the raw unripe banana peel are anticipated to be uniformly dispersed as a self-reinforcing phase within the amorphous gelatinized starch matrix, without significant phase separation, agglomeration, or voids, thereby explaining the high mechanical strength.

XRD (X-ray diffraction)

XRD profiles are anticipated to demonstrate the transition of raw banana starch from its native, highly crystalline B-type or C-type lattice into an amorphous state after alkaline and thermal gelatinization. Residual sharp crystalline peaks at approximately $2\theta = 22^\circ$ would represent the crystalline cellulose I fraction, confirming the presence of a self-reinforced micro-composite structure.

DSC/TGA (Differential scanning calorimetry / thermogravimetric analysis)

TGA is expected to show three distinct weight-loss stages:

moisture evaporation ($< 100^\circ\text{C}$), plasticizer volatilization ($150\text{--}250^\circ\text{C}$), and thermal depolymerization of the starch and cellulose chains ($280\text{--}360^\circ\text{C}$). DSC analysis would reveal a single glass transition temperature (T_g) ranging from -10°C to 15°C , confirming thermodynamic compatibility and uniform distribution of the sorbitol plasticizer within the biopolymer network.

Analysis of potential functional and active properties

Unripe banana peels naturally contain rich concentrations of bioactive and structural molecules. However, to maintain rigorous scientific accuracy, we clarify that specific functional properties—such as antioxidant activity, antimicrobial protection, UV-blocking capacity, and food shelf-life extension—were not experimentally evaluated in the present study.

The ethanolic extracts of unripe banana peels have been reported in the literature to be rich in active polyphenols, β -sitosterol (31.30%), and 1,2-benzenedicarboxylic acid mono(2-ethylhexyl) ester (12.47%), which display high DPPH free radical scavenging activity (74.43%) and antimicrobial inhibition against foodborne pathogens^{3,7}. While the direct incorporation of these active extracts or the natural retention of phenolic compounds in raw peel films represents a highly promising pathway for developing UV-blocking (up to 98%) active packaging capable of extending food shelf life³, experimental evaluations of these specific mechanisms for the current film remain a subject for future investigation.

Potential for biodegradability and compostability

The developed unripe banana peel films are composed entirely of natural, organic macromolecular components (starch, cellulose, lignin, and proteins) plasticized with polyols, without the incorporation of synthetic polymers such as LDPE. Based on the chemical composition, the developed films are expected to exhibit high potential for biodegradability and organic compostability.

Standard soil burial biodegradation studies of banana starch-polyethylene hybrid films have demonstrated that soil microorganisms rapidly attack the natural starch fraction within the first month, creating surface cracks that accelerate matrix breakdown⁸. Because our developed film contains zero persistent synthetic plastics, it is anticipated to undergo complete and rapid organic decomposition in soil or compost environments, leaving no microplastic residues. However, standardized experimental biodegradation testing (such as ASTM D6400 compostability or ISO 17556 soil respirometry) was not conducted in the present study and is required to quantitatively confirm the exact biodegradation rates.

CONCLUSIONS

In this investigation, a sustainable and cost-effective biopolymer packaging film was successfully developed and optimized directly from raw unripe banana peel powder. Utilizing the whole peel powder effectively bypassed complex starch-separation steps while preserving the structural cellulose microfibrils that function as self-reinforcing agents. Alkaline-driven gelatinization of the 5% w/v peel slurry using 10–13% w/v NaOH broke down complex carbohydrates and increased viscosity, exhibiting a peak pasting temperature of 79.2°C and a peak viscosity of 2517 cP. Formulation screening established that plasticizing the biopolymer matrix with 100% sorbitol prevented excessive moisture absorption and maintained high structural integrity. Notably, the optimized biopolymer film prepared in this study (Trial S2, 100% sorbitol, 13% NaOH) achieved a true experimental tensile strength of 29.76 ± 1.45 MPa (derived from an experimental breaking load of 17.44 kg), showing superior mechanical properties compared to pure banana flour and starch films. Additionally, the film demonstrated a quantitative heat-seal strength of 285.5 ± 15.2 N/m at 170°C, and promising barrier and surface properties. While further optimization is required to address residual alkali neutralization for food-contact suitability and to experimentally verify the film's biodegradability, active antioxidant, and microstructural properties, this study demonstrates a promising, low-cost circular technology to upcycle fruit processing waste into sustainable packaging materials, contributing to the development of a circular bio-economy.

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AUTHORS' CONTRIBUTION STATEMENT

Fayazudin Saiyad: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft & Editing; Jaydip Sankliya: Investigation, Validation; Rensi Radadiya: Data Curation; Chandrika Rathod: Methodology Application; Vumika Sena: Resources Management; Dr. Ramesh B. Modi: Supervision, Writing – Review.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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