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Valorization of Potato Peel Waste into Starch-Based Bioplastic Films using Glycerol and Sorbitol Plasticizers

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Abstract

The valorization of potato peel waste into biodegradable materials offers a sustainable approach to reducing plastic pollution. Starch extracted by wet sedimentation yielded 17.10% with high purity (ash 0.47%, moisture 14.00%, amylose 21.20%, amylopectin 78.80%). Bioplastic films prepared using glycerol, sorbitol, and a glycerol–sorbitol blend were evaluated for physical, mechanical, optical, structural, and biodegradation characteristics. Glycerol-plasticized films showed the greatest flexibility, highest swelling (47.0 ± 3.0%) and water absorption (48.6 ± 3.40%), and the fastest biodegradation, reaching 95.62 ± 9.78% weight loss after 20 days. Sorbitol films exhibited the highest tensile strength (38.11 ± 1.52 N/cm2) and lowest water absorption (28.8 ± 1.15%), while blend films demonstrated intermediate mechanical performance and slower degradation (64.16 ± 5.41%). FTIR confirmed preservation of the starch backbone with plasticizer-dependent hydrogen bonding, and XRD indicated a semi-crystalline structure (crystallinity index 91.6%) in glycerol films. Application trials showed strong adhesion of glycerol films as leak-proof paper cup coatings and successful moulding into 3D shapes. Overall, glycerol-plasticized potato peel starch films emerged as the most promising formulation due to their flexibility, rapid biodegradability, and practical applicability for sustainable packaging.

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Introduction

The urgent challenge of plastic pollution and the depletion of petroleum-based resources have intensified the search for sustainable, biodegradable alternatives.[1] Globally, an estimated 390 million tonnes of plastics are produced annually, of which only about 9% is recycled, while the remainder is incinerated or accumulates in landfills and natural

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ecosystems.[2] This growing crisis has led to stricter environmental guidelines, such as the European Union's Single-Use Plastics Directive (EU, 2019) and extended producer responsibility (EPR) frameworks in several countries, which mandate the reduction or replacement of non-biodegradable plastics in packaging and consumer goods.[3] Market forecasts project that the global bioplastics sector will grow from 2.22 million tonnes in 2023 to over 7 million tonnes by 2033, driven by consumer demand, legislative action, and the shift toward circular economy models.[4]

Among these, starch-based bioplastics have emerged as a leading contender due to their renewability, biodegradability, and cost-effectiveness.[1] Nevertheless, innatefilms from starch often posesweaker mechanical strength and water sensitivity, necessitating the use of additives such as plasticizers, nanofillers, or polymer blends to enhance performance.[5] Potato peel, a waste by-product from the food processing industry presents a low-cost and abundant source of starch. Despite its potential, only a few studies have explored bioplastic film development from potato peel starch. Starch extracted from white potato peels had produced bioplastic films using glycerol as a plasticizer, reporting enhanced tensile strength and water absorption with increasing glycerol content.[6] In this study, the term "bioplastic film" refers specifically to starch-derived, biodegradable films that do not contain petroleum-based plastics but mimic the functional properties of conventional plastic films. Study further demonstrated that glycerol-plasticized films from potato peel starch exhibit meaningful mechanical properties and structural integrity.[7]

Plasticizer selection critically influences bioplastic properties. Sorbitol, for example, imparts higher tensile strength and lowers moisture absorption compared to glycerol, which typically yields more flexible and hydrophilic films.[8] Yet few studies have rigorously compared the effects of glycerol, sorbitol, and their combination on potato peel starch films, leaving a gap in designing materials with tailored properties.Therefore, this study aims to:(i) Extract and characterize starch from potato peel, including yield, amylose content, and gelatinization temperature. (ii) Develop bioplastic films using glycerol, sorbitol, and a glycerol-sorbitol blend as plasticizers. (iii) Evaluate the physical (thickness, moisture content, density), mechanical (tensile strength, swelling, water absorption), and structural (transparency, FTIR, XRD) properties of the films to determine the influence of plasticizer type on performance. (iv) Assess the biodegradation behavior of the films through soil burial tests to determine their environmental degradability. (v) Explore the potential application of potato peel starch-based bioplastic films in sustainable packaging.

Materials and Methods

Fresh *Solanum tuberosum* tubers were purchased from a local market in Madurai, Tamil Nadu, India. The tubers were washed under running tap water, peeled using a stainless-steel peeler, and the peels were rinsed twice with distilled water to remove surface dirt and loose starch. The cleaned peels were stored at 4 °C in zip-sealed polyethylene bags until use. Analytical-grade reagents (sodium hydroxide, acetic acid, ethanol, potassium iodide, and iodine) were obtained from HiMedia Laboratories Pvt. Ltd. (Mumbai, India), while food-grade glycerol and sorbitol were sourced from Merck Life Sciences Pvt. Ltd. (Mumbai, India). All solutions were prepared using distilled water.

Starch Extraction from Potato Peel

Starch was extracted using a modified wet sedimentation method.[9,10] Fresh potato peels (≈260 g) were cut into ~1 cm^2 pieces and homogenized with 100 mL distilled water in a high-speed blender (Philips HL7756, Netherlands) at 15,000 rpm for 5 min to obtain a fine slurry. The slurry was filtered through a double-layer muslin cloth (~60 µm), and the filtrate was allowed to sediment at ~28 °C for 2 h. The supernatant was decanted, and the sediment was re-dispersed in 200 mL distilled water, stirred for 2 min, and left to settle for 30 min. This washing–settling cycle was repeated three times to remove soluble impurities. The final starch sediment was oven-dried at 55 °C for 24 h (Memmert UF55, Germany), ground, and sieved through a 100-mesh screen. The starch powder was stored in airtight amber glass containers at 4 °C until analysis. Starch yield (%) was calculated as:

Starch yield (%)=Wt. of dried starch (g)x 100 / Wt. of fresh potato peel (g)

Characterization of Extracted Starch

Microscopy

The morphology of the extracted potato peel starch granules was observed using a compound light microscope (Model: Olympus CX23, Manufacturer: Olympus Corporation, Tokyo, Japan) at 40x magnification under bright-field illumination. A small amount of dried starch was evenly sprinkled onto a clean glass slide, dispersed in a drop of distilled water, and covered with a coverslip. The granule shape, size, and surface texture were observed, and representative images were captured using a digital camera attachment (Model: Olympus LC30, Manufacturer: Olympus Corporation, Tokyo, Japan).

Organoleptic Evaluation

The extracted starch was visually inspected for color and clarity, and odor was assessed directly.

pH

One gram of starch was dispersed in 100 mL distilled water, and pH was recorded using a calibrated digitized pH meter (Eutech pH700, Thermo Fisher Scientific, Singapore).

Qualitative Confirmation Tests for Starch

Starch was qualitatively confirmed using standard phytochemical tests.[11]

- **Molisch's test for carbohydrates:** Formation of a reddish-violet ring indicated positive result.
- **Fehling's test for reducing sugars:** Absence of brick-red precipitate indicated negative result.
- **Benedict's test for reducing sugars:** Absence of red precipitate indicated negative result.
- **Iodine test for non-reducing sugars:** Development of blue color after cooling confirmed starch presence.

Physico-Chemical Properties

Ash

The ash content of the extracted potato peel starch was determined following AOAC guidelines.[12] 5 g of dried starch was weighed into a pre-weighed silica crucible and incinerated in a muffle furnace at 550 °C until a constant weight of white ash was obtained (about 4 h). The crucible was then cooled in a desiccator and reweighed. Ash content was calculated as:

Ash content (%)=Weight of ash (g)x100 / Weight of dry sample (g)

Moisture

Moisture content was measured according to AOAC (2016).[12] Five grams of starch was weighed into a pre-weighed moisture dish and dried in a hot air oven at 105 °C until a constant weight was achieved (approximately 4–6 h). The dried sample was cooled in a desiccator and weighed. Moisture content was calculated using:

Moisture content (%)=[Initial weight −Final weight] ×100 / Initial weight

Amylose and Amylopectin

Amylose content was estimated using the iodine-binding method.[13] Starch (20 mg) was dispersed in 10 mL of 1 N NaOH and heated in a boiling water bath for 10 min to ensure complete gelatinization. The solution was cooled to room temperature and neutralized with 1 N CH_3COOH. 2 mL of iodine–potassium iodide solution (0.2% I_2 in 2% KI) were added, and the volume was made up to 100 mL with distilled water. After thorough mixing, absorbance was measured at 620 nm using a UV–Vis spectrophotometer (Shimadzu UV-1800, Japan). Amylose content was determined from a calibration curve prepared using potato amylose standards (Sigma-Aldrich, USA). Amylopectin content (%) was calculated as 100 − amylose.

Functional Characteristics

Functional characteristics were determined following AOAC (2016) methods in comparision with commercial starch (laboratory grade).[12]

Solubility

Solubility was determined by heating 1 g starch in 100 mL distilled water at 60°C for 30 min, centrifuging at 3000 rpm for 10 min (Remi C-24BL, India), and drying the supernatant to a constant weight. Solubility was expressed as grams of soluble starch per 100 g (%) dry starch.

Starch

Determined by acid hydrolysis followed by titration with Fehling's solution.

Foam Capacity

Measured by whipping 2 g starch in 50 mL distilled water for 5 min in a high-speed blender and recording volume increase.

Swelling Power

Determined by heating 1 g starch in 50 mL water at its gelatinization temperature (72 °C for commercial starch, 71.33 °C for potato peel starch) for 30 min, centrifuging at 3000 rpm for 15 min, and calculating the weight of swollen sediment per gram of dry starch.

Gelatinization Temperature

A 2% starch suspension (w/v) was prepared in distilled water in a 250 mL beaker and stirred continuously with a magnetic stirrer. The suspension was heated at a rate of 2°C/min, and the temperature at which the suspension first exhibited a translucent, viscous consistency was recorded using a calibrated mercury thermometer.[14]

Bioplastic Film Formation

Bioplastic films were prepared using the solution-casting method.[15] Three formulations were preparedas illustrated in Table 1. Each mixture was heated to 70 °C on a magnetic stirrer hot plate, with continuous stirring at 500 rpm for ~15 min until a translucent gel formed. The hot gel was immediately poured into 14 cm diameter glass Petri dishes, levelled to ensure uniform thickness, and dried at ambient laboratory temperature (25 ± 2 °C) for 48 h. The dried films were peeled carefully and stored in desiccators (25% RH, silica gel) prior to testing.

Table 1: Formulations of potato peel starch bioplastic films prepared with glycerol, sorbitol, and glycerol–sorbitol blend as plasticizers

Formulation Code	Starch (g)	Distilled water (mL)	Acetic acid (mL)	Plasticizer (s)	Amount of plasticizer
A	2.5	25	3.4	Glycerol	2.1 mL
B	2.5	25	3.4	Sorbitol	2.0 g
C	2.5	25	3.4	Glycerol + Sorbitol	2.1 mL + 2.0 g

Physical Property Analysis

Thickness

Film thickness was measured using a digital micrometre screw gauge (Mitutoyo, Japan) at five randomly selected points across each film, and the mean value was recorded.[15]

Moisture Content

Film samples (2 × 2 cm²) were weighed (W_i) and dried in an oven at 105 °C until constant weight (Wf). Moisture content (%) was calculated as:

Moisture content(%) =[Initial weight- Final weight] x 100 / Initial weight

Density

Density was calculated by dividing the mass of the film by its volume (area x average thickness) as per the formula,

ρ=mvg/cm³

Where: ρ=density, m=mass, ndv=volume

Mechanical and Water Interaction Properties

Tensile Strength

Mechanical strength was evaluated according to ASTM D882 using a universal testing machine (Instron 3365, USA). Rectangular strips (10 mm x 50 mm) were clamped between grips and stretched at a crosshead speed of 10 mm/min until breakage. Tensile strength (N/cm²) was calculated from the maximum force divided by the initial cross-sectional area.[16]

Tensile strength = Maximum load at break (N) / Cross-sectional area (mm^2)

Swelling Capacity

Swelling capacity was determined by immersing pre-weighed (W_1) film specimens (2 cm x 2 cm) in 25 mL of distilled water at RT for 30 min. The swollen films were removed, gently blotted to remove surface water, and weighed again (W_2). Swelling capacity (%) was calculated using the formula:[17]

Swelling capacity=$[W_1 - W_2] \times 100 / W_1$

Water Absorption

Water absorption was measured by immersing pre-weighed dried film specimens (W_1) in distilled water at RT for 24 h. The films were removed, surface water was blotted off, and the samples were weighed (W_2). Water absorption (%) was calculated using:[18]

Water absorption=$[W_2 - W_1] \times 100 / W_1$

Optical Characterization

Transparency

Film transparency was measured using a UV–Visible spectrophotometer (Model: UV-1800, Shimadzu, Japan) according to ASTM D1746-15. Film strips (2 cm x 1 cm) were placed in the sample holder, and transmittance was recorded at 600 nm using air as the blank. Transparency (T600) was expressed as the percentage of light transmitted, where lower values indicated greater opacity.[19]

Biodegradability Test

The biodegradability of the potato peel starch-based bioplastic films prepared with different plasticizers (glycerol, sorbitol, and their combination) was evaluated using the soil burial method. Film samples of 2 x 2 cm with uniform thickness and initial weight were buried in moist garden soil maintained under controlled laboratory conditions. The test was carried out for 20 days, with observations recorded at 5-day intervals (Day 5, Day 10, Day 15, and Day 20). At each interval, the films were carefully retrieved, rinsed with distilled water to remove adhering soil particles, air-dried, and weighed to determine the weight loss. The percentage of biodegradation was calculated using the below formula, by comparing the initial and final weights of the samples, and the results were expressed as percentage degradation.

Biodegradability (%)=$[W_0 - W_t] \times 100 / W_0$

FTIR Spectroscopy

FTIR was used to identify functional groups in potato peel starch and in bioplastic films plasticized with glycerol, sorbitol, and their blend, with a commercial starch film as reference. Spectra were obtained using a Shimadzu IRTracer-100 equipped with a DLATGS detector. Film samples were cut into 1 cm^2 pieces, dried at 40 °C for 4 h, and analyzed directly in ATR mode. Spectra were recorded from 4000–400 cm^{-1} at a resolution of 4 cm^{-1} with 32 scans per sample. Background spectra were collected before each run and automatically subtracted.[20] The plasticizer producing stronger hydrogen bonding and greater chain mobility was selected for further XRD and application-based evaluation.

XRD

XRD analysis was performed on the glycerol-based starch bioplastic film to assess its crystalline and amorphous phases. Measurements were carried out using a PANalytical X'Pert PRO diffractometer with Cu-Kα radiation (λ = 1.5406 Å) operated at 40 kV and 30 mA. Film samples (2 x 2 cm^2) were mounted on a flat holder and scanned from 5° to 50° (2θ) with a 0.02° step size at 2°/min.[21] The instrument was calibrated with a silicon standard, and crystallinity (%) was calculated by peak deconvolution using OriginPro 2023.[22] Changes in peak intensity and position were compared to standard A- and B-type starch polymorphs to evaluate the effect of glycerol and sorbitol on the film's crystalline pattern.

Application Studies

Replacement of Wax Coating in Paper Cups

The coating procedure was adapted from Butkinaree *et al*., with minor modifications.[23] Potato peel starch (2.5 g) was dispersed in 25 mL distilled water, followed by the addition of 3.4 mL vinegar and 2.1 mL glycerol. The mixture was heated to 75 °C with continuous stirring until a homogeneous coating solution formed. Commercial paper cups were prepared by making three small holes at the inner base to facilitate penetration of the coating. Approximately 10 mL of the solution was applied evenly to the inner surface using a manual film applicator, and the coated cups were dried at 28 ± 2 °C for 24 h. Waterproofing performance was assessed by adding 5 mL distilled water to each cup and monitoring for leakage over a fixed period.

Moulding Test for Bioplastic Products

The moulding procedure was adapted from Kadam and Datta, with minor modifications.[24] A moulding solution was prepared by dispersing 2.5 g of potato peel starch in 25 mL distilled water, followed by the addition of 2.1 mL glycerol. The mixture was heated with continuous stirring until gelatinization occurred, after which 3.4 mL vinegar was added to enhance gel network formation. The molten bioplastic was poured into a pre-cleaned silicone keychain mould and allowed to set at ambient temperature (28 ± 2 °C) for 24 h. After demoulding, the formed products were examined for shape retention, dimensional accuracy, and surface smoothness.

Statistical Analysis

All experiments were conducted in triplicate, and results are reported as mean ± standard deviation. The effects of plasticizer type (glycerol, sorbitol, glycerol + sorbitol) on the physical, mechanical, and optical properties of the films were evaluated using one-way ANOVA. Biodegradation data were analyzed using two-way ANOVA with replication to assess the influence of plasticizer type, burial duration (5, 10, 15, and 20 days), and their interaction. Statistical significance was set at $p < 0.05$. All analyses were performed using SPSS Statistics v.26 (IBM Corp., USA).

Results

Starch Extraction and Physicochemical Properties

Starch extraction by wet sedimentation yielded 48.0 g of starch from 280 g of potato peel (17.10%). Microscopy revealed predominantly oval, smooth granules with occasional irregular shapes (Fig. 1). The starch was fine-textured, white, odorless, tasteless, and free from visible fiber or pigmentation. It showed a near-neutral pH (6.40 ± 0.32), a positive Molisch reaction, and a deep-blue iodine complex, while Fehling's and Benedict's tests were negative. Ash and moisture contents were 0.47 ± 0.02% and 14.00 ± 0.7%, respectively. The starch composition included 21.20 ± 1.27% amylose and 78.80 ± 3.94% amylopectin. A comparison of its physicochemical and functional properties with commercial starch is shown in Table 2.

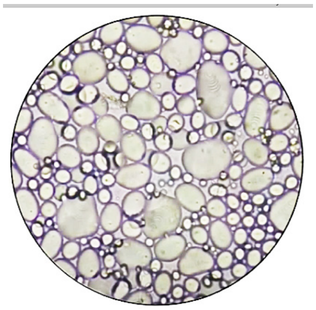


Fig.1: Light microscopy image (40x) of potato peel starch granules showing oval morphology and smooth surfaces(Scale bar = 20 µm)

Table 2: Physico-chemical and functional properties of extracted potato peel starch with commercial starch

Properties	Extracted potato peel starch	Commercial starch	Observations
Yield (%)	17.10 ± 0.0	—	Within reported range for potato peel starch (15–20%)
Ash content (%)	0.47 ± 0.02	—	Low mineral residue, indicating high purity
Moisture content (%)	14.00 ± 0.70	Similar	Stable for storage
Amylose (%)	21.20 ± 1.27	—	Typical for tuber starch; supports good gelation
Amylopectin (%)	78.80 ± 3.94	—	Higher fraction aids swelling and flexibility
Solubility (%)	1.83 ± 0.007	1.66 ± 0.009	Slightly higher in extracted starch due to minor surface irregularities
Starch content (%)	65.38 ± 2.62	72.50 ± 2.90	Slightly lower in extracted starch, possibly due to residual peel components
Foam capacity	Absent	Absent	Lack of surface-active proteins; prevents pore formation in films
Swelling temperature (°C)	71.33	72.00	Comparable; suitable for controlled gelatinization
Gelatinization temperature (°C)	~70	~70	Similar thermal behavior

Parameter not determined for commercial starch

Functional Properties of Extracted Starch

The extracted potato peel starch had a solubility of 1.83 ± 0.007%, slightly higher than the 1.66 ± 0.009% of commercial starch. Its total starch content (65.38 ± 2.62%) was marginally lower than the commercial value of 72.50 ± 2.9%. Neither sample produced foam. The starch showed a swelling temperature of 71.33 °C, close to the 72 °C noted for commercial starch, and initiated gelatinization at about 70 °C, forming a translucent gel.

Bioplastic Film Formation

The extracted starch was successfully converted into bioplastic films. The starch suspension was initially milky and gelatinized upon heating, and the incorporation of glycerol produced a uniform film-forming solution. The resulting dried films were smooth, flexible, and transparent. All three formulations, A (glycerol), B (sorbitol), and C (glycerol + sorbitol), were white, odorless, and evenly textured, with minor differences in appearance attributed to the plasticizer used and film thickness.

Physical, Mechanical, Water Interaction, and Optical Properties

Film thickness ranged from 0.143 ± 0.005 mm to 0.196 ± 0.05 mm, with Bioplastic C being the thinnest and Bioplastic B the thickest, while the polypropylene control measured 0.1 mm. Moisture content varied across formulations, highest in A (21.50 ± 2.20%) and lowest in B (11.23 ± 1.35%). Density values were 1.33 ± 1.5 g/cm^3 for A, 1.28 ± 1.2 g/cm^3 for B, and 1.48 ± 2.0 g/cm^3 for C, compared with 0.90 ± 1.0 g/cm^3 for the control. Sorbitol films showed the greatest tensile strength (38.11 ± 1.52 N/cm^2), followed by the control (27.55 ± 1.10 N/cm^2), the blend (25.05 ± 1.20 N/cm^2), and glycerol films (12.00 ± 0.72 N/cm^2). Swelling capacity was highest in A (47.0 ± 3.0%) and lowest in C (26.0 ± 2.5%), with similar patterns in water absorption, where A absorbed 48.6 ± 3.40% and B absorbed the least (28.8 ± 1.15%). Optical measurements showed greatest transparency in C (4.20 ± 0.21 mm^{-1}) and lowest in B (0.08 ± 0.02 mm^{-1}), while clarity ranged from 95.7 ± 1.8% in blend films to 99.2 ± 1.5% in sorbitol films. All mean values are summarized in Table 3.

The influence of three plasticizer formulations glycerol (A), sorbitol (B), and a glycerol–sorbitol blend (C) on potato peel starch bioplastic films was evaluated using one-way ANOVA (Table 4). Thickness, density, tensile strength, swelling capacity, water absorption, and transparency showed significant differences ($p < 0.05$), whereas moisture content and clarity did not.

Table 3: Physical, mechanical, water interaction, and optical properties of bioplastic films prepared with different plasticizers

Properties	Bioplastic A (Glycerol)	Bioplastic B (Sorbitol)	Bioplastic C (Glycerol + Sorbitol)	Polypropylene control
Thickness (mm)	0.183 ± 0.028	0.196 ± 0.050	0.143 ± 0.005	0.100 ± 0.002
Moisture content (%)	21.50 ± 2.20	11.23 ± 1.35	19.45 ± 8.39	20.58 ± 10.33
Density (g/cm^3)	1.33 ± 1.5	1.28 ± 1.2	1.48 ± 2.0	0.9 ± 1.0
Tensile strength (N/cm^2)	12.00 ± 0.72	38.11 ± 1.52	25.05 ± 1.20	27.55 ± 1.10
Swelling capacity (%)	47.0 ± 3.0	34.0 ± 2.8	26.0 ± 2.5	40.0 ± 2.0
Water absorption (%)	48.6 ± 3.40	28.8 ± 1.15	33.3 ± 1.99	1.5 ± 0.10
Transparency (mm^{-1})	2.344 ± 0.12	0.080 ± 0.02	4.202 ± 0.15	0.930 ± 0.05
Clarity (%)	97.7 ± 1.6	99.2 ± 1.5	95.7 ± 1.8	99.1 ± 1.5

Biodegradability Test

The soil burial test showed distinct biodegradation patterns based on plasticizer type (Fig. 2): glycerol-plasticized films degraded the fastest, increasing from 62.14 ± 27.28% (day 5) to 95.62 ± 9.78% (day 20), while sorbitol films degraded more gradually (41.28 ± 6.07% to 83.12 ± 9.79%), and glycerol–sorbitol blend films degraded the slowest (38.60 ± 26.85% to 64.16 ± 5.41%). Two-way ANOVA (Table 5) confirmed significant effects of plasticizer type ($F(2,24)=566.84$, $p<0.001$), burial duration ($F(3,24)=507.87$, $p<0.001$), and their interaction ($F(6,24)=19.86$, $p<0.001$), indicating different degradation trajectories among formulations.

Table 4: One-way ANOVA results showing the effect of plasticizer type on bioplastic film properties

Property	df (Between)	df (Within)	F-value	P-value	Significance*
Thickness (mm)	3	8	6.80	0.0136	Yes
Moisture content (%)	3	8	1.45	0.2986	No
Density (g/cm^3)	3	8	4.066	5.28×10^{-5}	Yes
Tensile strength (N/cm^2)	3	8	252.28	2.93×10^{-8}	Yes
Swelling capacity (%)	3	8	35.25	5.85×10^{-5}	Yes
Water absorption (%)	3	8	274.22	2.11×10^{-8}	Yes
Transparency (mm^{-1})	3	8	979.81	1.33×10^{-10}	Yes
Clarity (%)	3	8	3.11	0.0886	No

Df – degrees of freedom; *Significance considered at $p < 0.05$.

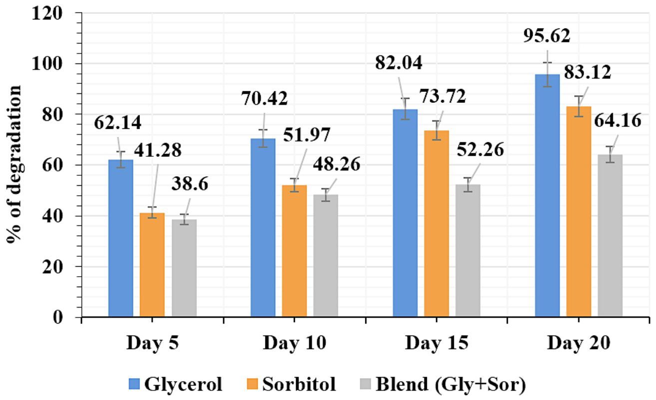


Fig.2: Biodegradation profiles of bioplastic films plasticized with glycerol, sorbitol, and glycerol–sorbitol blend during soil burial over 20 days

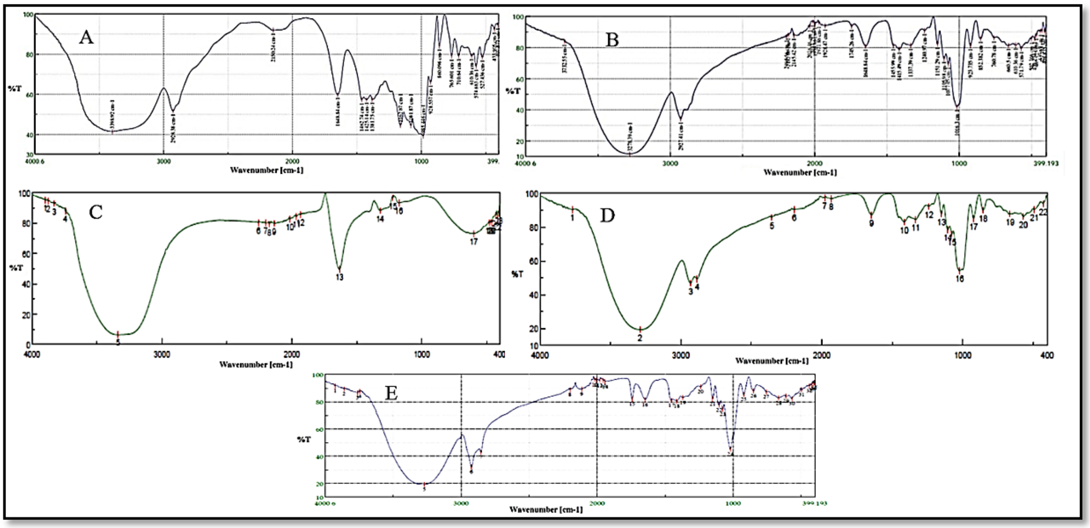
Table 5: Two-way ANOVA results for the effect of plasticizer type and burial duration on biodegradation of potato peel starch bioplastic films

Source of Variation	df	SS	MS	F	P-value	Significance
Group (Sample)	2	4312.12	2156.06	566.84	6.3×10^{-21}	***
Time (Columns)	3	5795.25	1931.75	507.87	7.4×10^{-22}	***
Interaction	6	895.34	149.22	19.86	3.2×10^{-8}	***
Within (Error)	24	180.79	7.53	–	–	–
Total	35	10651.93	–	–	–	–

Df – degrees of freedom; SS – Sum of squares; MS -Mean square; *Significance considered at $p < 0.001$.

FTIR

FTIR spectroscopy (Fig. 3, Tables 6 and 7) showed characteristic starch bands—O–H (~3420 cm^{-1}), C–H (~2920 cm^{-1}), O–H bending (~1650 cm^{-1}), C–O–C/C–O (~1160–985 cm^{-1}), and skeletal vibrations (~930–763 cm^{-1})—confirming that the polysaccharide backbone remained intact. Plasticization caused clear shifts in O–H and C–H stretching regions, indicating hydrogen bonding between starch and the plasticizers. Glycerol films displayed the largest O–H shift (~3260 cm^{-1}) and a distinctive C–H deformation (~859 cm^{-1}), suggesting stronger interactions and a more amorphous structure. Sorbitol films showed O–H shifts (~3280 cm^{-1}), while the blend films exhibited intermediate shifts (~3270 cm^{-1}).



(A) Potato Peel Starch, (B) Glycerol Bioplastic, (C) Sorbitol Bioplastic, (D) Glycerol + Sorbitol Bioplastic, and (E) Commercial Starch Bioplastic

Fig.3: FTIR Spectra of potato peel starch and plasticized bioplastic films

Table 6: FTIR absorption band assignments of potato peel starch and bioplastic films plasticized with glycerol, sorbitol, and glycerol–sorbitol blend

Sample	Wavenumber (cm^{-1})	Assignment	Functional Group / Source
Potato Peel Starch	~3420	O–H stretching	Hydroxyl groups, hydrogen bonding
	~2920	C–H stretching	Alkyl groups (CH_2, CH_3)
	~1650	O–H bending of water	Bound water in starch granules
	1160–985	C–O–C, C–O stretching	Glycosidic linkages, starch backbone
	930–763	Skeletal vibrations	Glucose ring structure
Glycerol Bioplastic	~3260	O–H stretching	Hydrogen-bonded hydroxyls (starch + glycerol)
	~2925	C–H stretching	Aliphatic CH_2 groups
	~1635	O–H bending / C=O stretching	Bound water, glycerol interaction
	1155–988	C–O, C–O–C stretching	Glycosidic linkages, starch backbone
	~859	C–H deformation	Amorphous starch phase
Sorbitol Bioplastic	~3280	O–H stretching	Hydrogen bonding (starch + sorbitol)
	~2920	C–H stretching	CH_2 groups
	~1640	O–H bending of water	Water + starch–sorbitol interaction

	1150–990	C–O–C stretching	Polysaccharide backbone
	<900	Skeletal vibrations	Glucose ring
Glycerol + Sorbitol Bioplastic	~3270	O–H stretching	Hydrogen bonding (starch + both plasticizers)
	~2920	C–H stretching	Aliphatic groups
	~1635	O–H bending / bound water	Plasticizer–starch interactions
	1150–985	C–O, C–O–C stretching	Glycosidic bonds
	<900	Skeletal vibrations	Glucose ring
Commercial Starch Bioplastic	~3400	O–H stretching	Hydroxyl groups, hydrogen bonding
	~2920	C–H stretching	CH_2, CH_3 groups
	~1650	O–H bending of water	Bound water
	1150–985	C–O, C–O–C stretching	Glycosidic linkages
	<900	Skeletal vibrations	Glucose ring

Table 7: Summary of spectral shifts observed in FTIR analysis of bioplastic films indicating starch–plasticizer interactions

Wavenumber (cm^{-1})	Assignment	Potato Peel Starch	Glycerol Bioplastic	Sorbitol Bioplastic	Glycerol + Sorbitol Bioplastic	Commercial Starch Bioplastic
~3420–3400	O–H stretching	✓	–	–	–	✓
~3260–3280–3270	O–H stretching (hydrogen-bonded, plasticizer interaction)	–	✓	✓	✓	–
~2920–2925	C–H stretching	✓	✓	✓	✓	✓
~1650–1635–1640	O–H bending / C=O stretching (bound water / plasticizer interaction)	✓	✓	✓	✓	✓
1160–1150–1155–988	C–O–C / C–O stretching	✓	✓	✓	✓	✓
~930–763 / <900	Skeletal vibrations (glucose ring)	✓	–	✓	✓	✓
~859	C–H deformation (amorphous starch)	–	✓	–	–	–

✓ – Presence of functional group/absorption band; – – Absence of functional group/absorption band.

XRD Crystallinity Profile

The XRD diffractogram of the potato peel starch–glycerol bioplastic film (Fig. 4A) showed a broad semi-crystalline pattern with major peaks at 2θ ≈ 17°–19° and minor shoulders at 22°-24°. The crystallinity index calculated using the Segal method was approximately 91.6% (Fig. 4B), indicating the dominance of crystalline domains and the coexistence of ordered and amorphous regions within the polymer matrix.

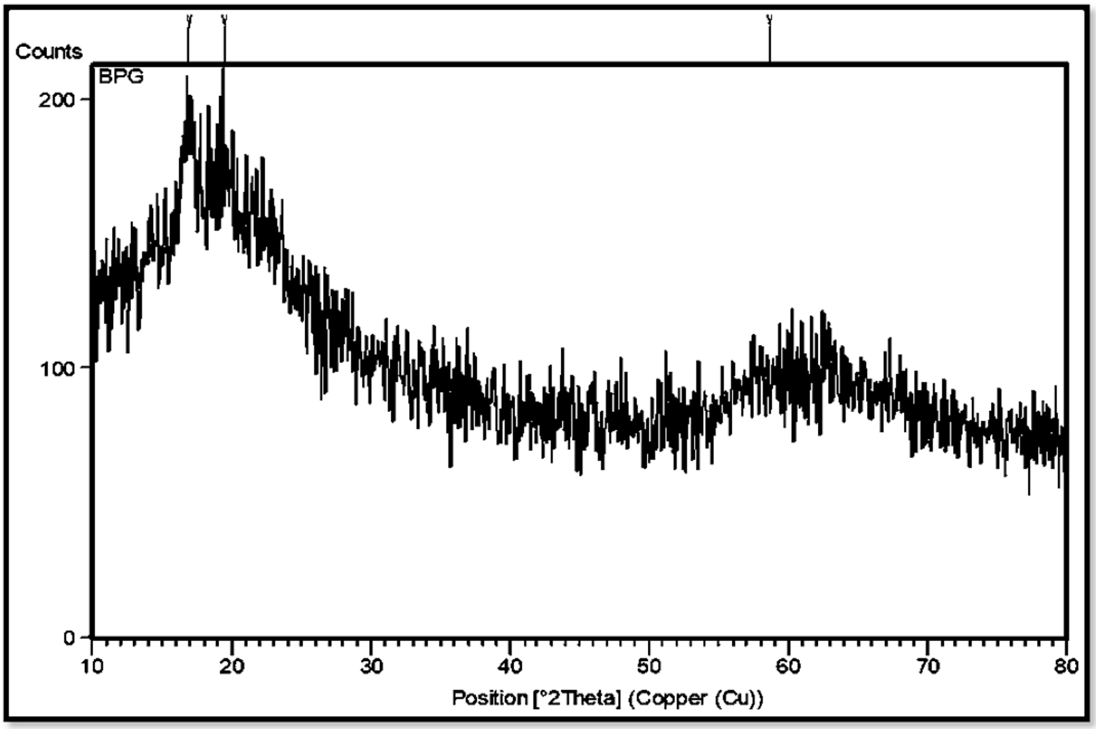


Fig. 4A: XRD diffraction pattern of glycerol-based potato peel starch bioplastic film

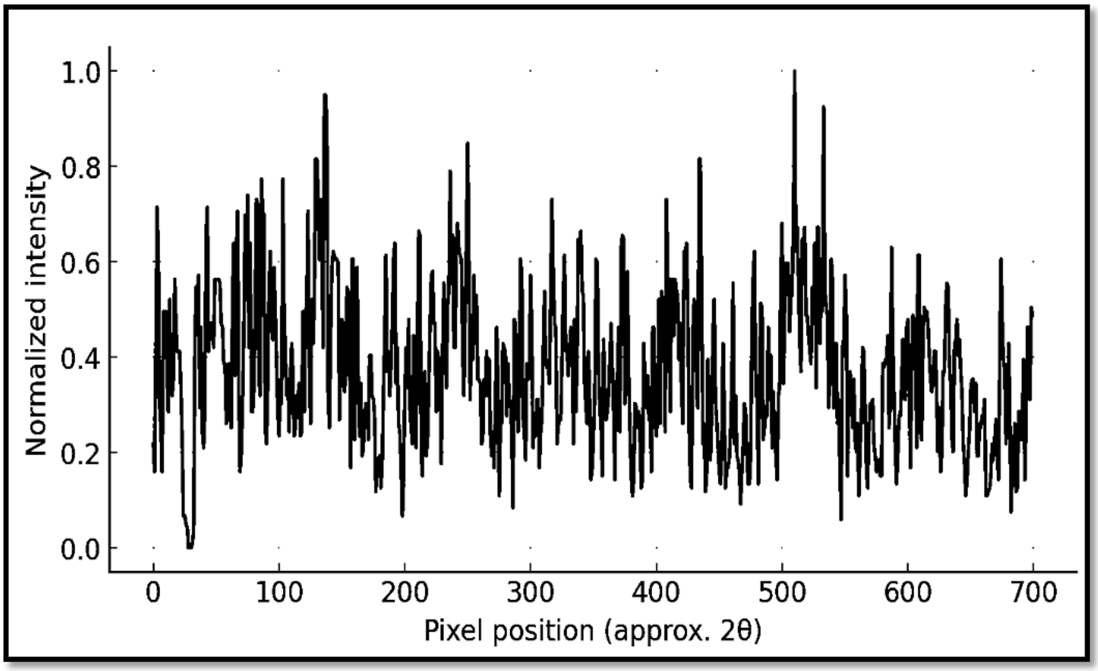


Fig. 4B: XRD intensity profile depicting crystalline structure of potato peel starch- glycerol based bioplastic film(Crystallinity Index: 91.6%)

Application Studies

The potato peel starch–glycerol bioplastic was evaluated as a sustainable coating for paper cups. The coating adhered uniformly, forming a continuous barrier without cracking or peeling. Cups filled with 100 mL of hot liquid (90 ± 2 °C) remained leak-proof for at least 10 min, demonstrating effective waterproofing. The mouldability of the potato peel starch–glycero"l bioplastic was evaluated by casting the molten material into silicone moulds. The bioplastic formed a keychain model with smooth surfaces and stable dimensions after cooling, indicating good thermal workability and shape retention. This suggests that the glycerol plasticizer provides sufficient flexibility and cohesiveness to prevent cracking or deformation during shaping.

Discussion

The starch yield of 17.10% fell within the typical 15–20% range reported for peel-derived starches,[25] with the comparatively lower value likely influenced by retained fiber and moisture in the peel matrix,[26] while studies using enzymatic or alkaline-assisted extraction have reported higher recoveries due to improved process efficiency.[27] The smooth, predominantly oval granules observed were consistent with earlier descriptions of peel starch,[28] and the absence of surface disruption indicated that wet sedimentation maintained native granule integrity, unlike harsher extraction methods that often produce irregular structures.[29] Preserving granule morphology is important, as it supports predictable gelatinization and swelling behavior.[30] The fine, white, odorless starch obtained in this study also agreed with previous reports on tuber waste starch purity,[31] with the lack of pigmentation or odor suggesting effective removal of peel-associated phenolics during extraction.[27]

The near-neutral pH of the starch (6.40 ± 0.32) agreed with values reported for purified tuber starch,[32] indicating removal of acidic components during extraction.[33] Qualitative test results were consistent with those described by Ramos *et al*., and the absence of reducing sugars matched earlier findings for purified potato peel starch.[34,35] The low ash content aligned with Namir *et al*., whereas studies reporting higher values attributed them to residual fibers or contamination.[36,37] The moisture content (14.00 ± 0.7%) fell within typical ranges for tuber starches,38 providing a balance between brittleness and microbial stability.[39] The amylose–amylopectin ratio was comparable to that reported by Maurya *et al*., with the high amylopectin fraction contributing to swelling and gel clarity as noted by Lemos *et al*., while variations among studies generally reflect botanical and maturity differences, as described by Wang *et al*.[40–42]

Solubility patterns matched those reported by Horison *et al*.,[43] with the slightly higher value likely due to mild granule disruption.[27] The reduced total starch content agreed with Rashwan *et al*., who attributed such decreases to residual fiber or pectin.[44] The lack of foam matched findings by Miller *et al*., indicating limited surface-active components.[28] Swelling and gelatinization behaviour reflected amylopectin-driven trends noted by Kumar *et al*.,[45] and the gelatinization temperature fell within previous potato starch ranges,[46] with minor differences linked to crystallinity.[47]

Film formation followed typical starch gelatinization and polymer mobility behaviour reported earlier, with glycerol increasing chain flexibility.[48–50] The flexible and transparent films obtained here were comparable to those produced from cassava and pea starch.[51] Variations in thickness, moisture content, density, and mechanical strength supported established plasticizer-dependent trends, with sorbitol imparting greater rigidity and density differences reflecting differences in polymer packing.[52–57]

Hydration properties followed expected trends, with glycerol increasing swelling and water absorption, while sorbitol reduced moisture sensitivity.[58,59] Optical behaviour also reflected established links between structural order and light transmission.[60–63] ANOVA results confirmed that plasticizer type had a significant effect on film characteristics,[8,64] and the differences in transparency were consistent with the microstructural influences described by Zhu *et al*.[65]

Biodegradation trends followed established observations, with glycerol-plasticized films degrading more rapidly due to their higher hydrophilicity and amorphous structure.[52,66] Sorbitol's stronger hydrogen bonding slowed microbial access, while blend films showed intermediate degradation. FTIR results were consistent with earlier findings indicating that glycerol produces more amorphous and flexible matrices,[8,67] whereas sorbitol contributes to greater thermal stability.[64] The XRD patterns, including a crystallinity index of ~91.6%, aligned with previous reports on tuber starch film crystallinity and supported the mechanical stability observed.[43,68–70]

The effective performance of starch–glycerol films as paper cup coatings aligned with polymer–cellulose adhesion previously documented,[18,71] and the leak-proof behavior may be attributed to partial retrogradation and matrix densification.[52] This strong adhesion is further explained by the high affinity of glycerol-plasticized starch for cellulose fibers, which promotes hydrogen bonding and formation of a continuous, defect-free barrier layer. The enhanced flexibility provided by glycerol also allows the film to conform closely to the paper substrate, improving coating integrity. Mouldability results supported earlier observations that plasticized thermoplastic starch systems exhibit sufficient chain mobility for accurate shape replication, highlighting their suitability for both packaging and molded applications.[72–75] The production of smooth, dimensionally stable molded forms reinforces that the glycerol formulation provides an optimal combination of flexibility and cohesiveness, supporting its identification as the most promising candidate among the tested bioplastic systems.

Conclusion

This study demonstrated that starch-rich potato peel waste could be effectively valorized into biodegradable films using a simple wet sedimentation and solution-casting process, highlighting a sustainable route for utilizing agro-industrial waste. The extracted starch possessed suitable physicochemical properties for film formation, and the resulting films showed plasticizer-dependent advantages: glycerol produced flexible films with rapid biodegradation, sorbitol increased tensile strength and reduced water sensitivity, and the glycerol–sorbitol blend provided an intermediate balance of properties. All formulations were biodegradable, with glycerol-based films degrading the fastest, indicating their suitability for applications requiring quick environmental breakdown. Although the work was limited to laboratory-scale processing and only three plasticizer systems, and glycerol films remained moisture-sensitive, the findings supported potato peel starch as a promising material for sustainable packaging. Future improvements through nanofillers, crosslinkers, and real-world packaging evaluations, along with scale-up and cost assessments, were recommended to advance its practical applicability.

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Conflict of Interest

The authors do not have any conflict of interest.

Data Availability

All datasets produced or examined in this study are contained within the manuscript.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to Reproduce Material from Other Sources

Not Applicable.

Author Contributions

- **Glory Jasmine Rani:** wrote whole paper,
- **Ramaiya Pillai Mallika:** review and editing

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