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Preparation and Characterization of Starch-Based Bioplastics from Custard Apple (Annona Squamosa) Peel

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Abstract
Growing environmental concerns over petroleum-based plastics have accelerated the development of biodegradable alternatives from renewable resources. This study reports the development of starch-based bioplastic films using custard apple (Annona squamosa) peel as an agro-waste raw material. Starch extracted from custard apple peel was blended with corn starch, glycerol (plasticizer), and vinegar (cross-linking agent) to prepare bioplastic films with varying starch concentrations. Biodegradability was evaluated using the soil burial method, and all formulations showed measurable degradation. Among them, Sample 3 exhibited the highest biodegradation rate of 59.58% and was selected for further characterization.
The optimized film showed an average thickness of 722.5 µm, low density (0.3223 g/cm³), and low grammage (0.025 g/cm²), indicating a lightweight and uniform structure. Solubility tests revealed low solubility in organic solvents (1.97–6.34%) and moderate solubility in hot and cold water (9.52–9.67%), reflecting the hydrophilic nature of starch-based polymers. The film also demonstrated minimal water absorption (0.1716%). These findings highlight the potential of custard apple peel starch for producing eco-friendly bioplastics suitable for sustainable applications.

Keywords: Custard apple peel, bioplastic, starch, biodegradability, agro-waste

1. Introduction

Custard apple (Annona squamosa), belonging to the family Annonaceae**,** is a tropical fruit widely cultivated in India and other subtropical regions. The fruit is commonly known as sharifa, sitaphal, or sugar apple and is valued for its pleasant flavour and nutritional richness. Several species of Annona exist, including A. squamosa, A. cherimola, and A. reticulata. The fruit possesses a waxy, light-green peel with an average thickness of approximately 0.5 cm [1].
Nutritionally, custard apple pulp is rich in carbohydrates, primarily glucose and fructose, contributing to its high energy value. It contains approximately 23.9 g of carbohydrates per 100 g of pulp, with moderate protein content (1.6 g/100 g) and low fat content (0.18 g/100 g) [4,5]. The fruit is also a good source of dietary fibre (3.1–11 g/100 g), vitamins A and C, potassium, magnesium, calcium, iron, and antioxidants [3,6]. During ripening, the starch present in the fruit is converted into sugars, enhancing sweetness and

palatability. The calorific value of custard apple (300–450 kJ/100 g) is significantly higher than that of commonly consumed fruits such as apple and orange [3].

Bioplastics are biodegradable or bio-based polymeric materials capable of decomposing into carbon dioxide, water, inorganic compounds, or biomass through microbial activity [9]. These materials may be derived directly from biomass sources such as starch and cellulose or synthesized through microbial fermentation processes, including polyhydroxyalkanoates (PHA) [10]. Starch-based bioplastics are particularly attractive due to their renewability, low cost, ease of processing, and biodegradability [11].

Corn starch is one of the most widely used raw materials for bioplastic production owing to its high availability and favourable amylose (≈27%) and amylopectin (≈73%) composition [15]. Amylose contributes to improved biodegradability, while amylopectin enhances plasticization, gel formation, and mechanical strength of the resulting films [16].

Fruit processing industries generate large quantities of peel waste, which poses serious disposal and environmental challenges. Custard apple peels are rich in natural polymers such as starch, cellulose, and pectin, making them suitable reinforcement materials for bioplastic formulations [2,12]. Utilization of such agro-waste not only adds value to underutilized biomass but also supports sustainable waste management and circular economy principles [13].

The present study focuses on the development of starch-based bioplastic films using custard apple peel starch blended with corn starch and evaluates their biodegradability and physicochemical properties for potential eco-friendly applications.

2. Review of Literature

2.1 Custard Apple

Custard apple has been extensively studied for its nutritional, medicinal, and industrial significance. Patil et al. reported that custard apple seed oil is rich in acetogenins, flavonoids, and essential fatty acids with antioxidant, anticancer, insecticidal, and wound-healing properties [15]. Gaddam et al. demonstrated significant antidiabetic and antimicrobial activity of A. squamosa leaf-based formulations, particularly against Gram-positive bacteria [5].

Custard apple is recognized as an underutilized arid-zone fruit with antioxidant, antidiabetic, anti-infective, and anti-dyslipidemic properties [12,13]. Despite its nutritional richness and traditional medicinal importance, its commercial exploitation remains limited [13].

2.2 Bioplastics

Bioplastics have emerged as sustainable alternatives to petroleum-based plastics due to increasing environmental concerns and legislative pressures [3,18]. Chen discussed their characteristics and applications, particularly in packaging [3]. Food-waste-derived bioplastics, such as those developed from orange peel, demonstrate promising biodegradability and material properties [19]. Bio-based plastics degrade more readily than conventional plastics, reducing long-term environmental impact [8,19].

3. Materials and Methods

3.1 Materials

Custard apple (Annona squamosa) fruits and corn flour were procured from a local market. Analytical-grade glycerol (propane-1,2,3-triol), vinegar (4.5% acidity), and distilled water were used for bioplastic preparation. Equipment utilized included a tray drier, steel trays, mixer grinder, sieving mesh, heating mantle, hot plate, glassware, muslin cloth, screw gauge, and weighing balance.

3.2 Collection and Preparation of Samples

Fully ripened custard apple fruits and corn flour were collected and transported to the laboratory for further processing. Fruits were thoroughly washed with potable water to remove surface contaminants prior to peel separation.

3.3 Separation of Custard Apple Peel

Peel separation was carried out manually due to the soft nature of the pulp and the leathery texture of the peel. The washed fruits were gently split open, and the pulp along with seeds was scooped out. The peel, which was loosely attached to the pulp, was carefully separated and collected for starch extraction.

Figure (a): Custard Apple fruit &

Figure (b): Custard Apple Peel

3.4 Extraction of Starch

3.4.1 Starch Extraction from Custard Apple Peel

The separated peels were spread uniformly on steel trays and dried in a tray drier at 40 °C until moisture removal was complete. The dried peels were ground using a mixer grinder to obtain a fine powder, thereby increasing surface area for efficient starch extraction.

The powdered peel was mixed with distilled water and allowed to stand for several hours. The slurry was filtered through a muslin cloth, and the filtrate was collected and allowed to settle for 1–2 h. The supernatant was decanted, and the sediment was washed repeatedly (2–3 times) with distilled water until a clear liquid was obtained. The settled starch was dried under sunlight for 24 h, ground, and sieved to obtain fine, brownish-white custard apple peel starch powder.

Figure (c): Dried Custard Apple Peel Powder.

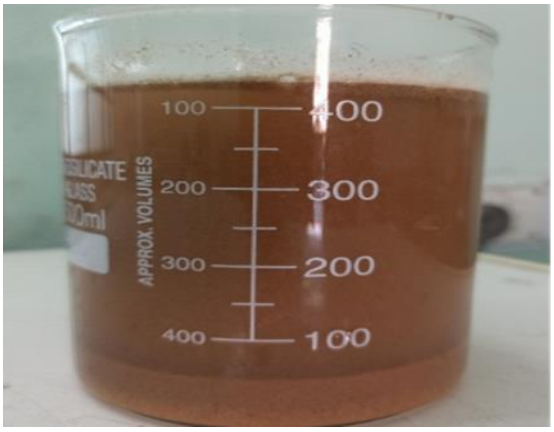

Figure (d): Extraction of Starch using distilled water.

Figure (e) : Extracted Custard Apple Peel Starch Powder

3.4.2 Starch Extraction from Corn Flour

Corn flour was mixed with distilled water and allowed to stand for several hours. The slurry was filtered through a muslin cloth, and the filtrate was allowed to settle for 1–2 h. The sediment was washed repeatedly with distilled water until clarity was achieved. The extracted starch was dried under sunlight for 24 h, ground, sieved, and stored in airtight containers for further use.

Figure (f): Extracted Corn flour Starch Powder

3.5 Formulation of Bioplastic Films

Bioplastic films were prepared using varying concentrations of custard apple peel starch (1, 2, 3, and 4 g), while corn starch concentration was maintained constant at 9 g. Distilled water (80 mL), glycerol (4 mL), and vinegar (8 mL; 4.5% acidity) were added to each formulation. The compositions of the different formulations are presented in Table 3.

Table 3: Formulation of bioplastic films prepared using custard apple peel starch

Components	Sample 1	Sample 2	Sample 3	Sample 4
Custard apple peel starch (g)	1	2	3	4
Corn starch (g)	9	9	9	9
Distilled water (mL)	80	80	80	80
Glycerol (mL)	4	4	4	4
Vinegar (mL)	8	8	8	8

Note. Vinegar used had 4.5% acidity; glycerol served as a plasticizer.

3.6 Preparation of Bioplastic Films

Custard apple peel starch and corn starch were dispersed in 80 mL of distilled water under continuous stirring. Vinegar (4.5% acidity) was added to the suspension, followed by the addition of propan-1,2,3-triol (glycerol) as a plasticizer. The mixture was heated on a hot plate at 75 ± 1 °C until a homogeneous gel was obtained. The gel was cast onto a non-stick surface and dried under sunlight for 48 h. The resulting bioplastic film was cooled to room temperature **(**27 ± 1 °C**),** peeled off, and stored for further characterization.

Figure (g): Bioplastic film of sample-1

Figure (h): Bioplastic film of sample-2

Figure (i): Bioplastic film of sample-3

Figure (j): Bioplastic film of sample-4

3.7 Characterization of Bioplastic Films

The developed bioplastic films were characterized for biodegradability, physical, mechanical, and solubility properties using standard laboratory methods.

3.7.1 Biodegradability Test

Biodegradability was evaluated using a soil burial method. Bioplastic samples (2 cm × 2 cm) were weighed (W_0) and buried at a depth of 8 cm in compost soil. Samples were incubated at room temperature for 10 days, with retrieval every 2 days. Retrieved samples were gently cleaned, dried, and weighed (W).

Biodegradation percentage was calculated using the equation:

$$\text{Biodegradation (\%)} = \frac{(W_0 - W)}{W_0} \times 100$$

where W_0 is the initial weight and W is the final weight.

3.7.2 Thickness

Film thickness was measured using a screw gauge at multiple locations on each film. The average thickness was calculated using:

$$\text{Thickness} = \text{MSR} + \text{CSR} \pm \text{Zero error}$$

where MSR is the main scale reading and CSR is the circular scale reading.

3.7.3 Density

Density was determined by cutting films into 10 cm × 10 cm squares. The mass was recorded, and film thickness was measured to calculate volume. Density was calculated using:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \ (\text{g/cm}^3)$$

$$\text{Volume} = \text{Length} \times \text{Breadth} \times \text{Thickness}$$

3.7.4 Grammage

Grammage was determined by weighing 10 cm × 10 cm film samples and calculating surface area. Grammage was expressed as:

$$\text{Grammage} = \frac{\text{Weight}}{\text{Area}} \ (\text{g/cm}^2)$$

3.7.5 Solubility Test

Bioplastic films were cut into 2 cm × 2 cm pieces and weighed (Wi). Samples were immersed separately in acetone, toluene, petroleum ether, hot water (60 °C), and cold water for 8 h, with periodic stirring. After exposure, samples were dried in an oven at 60 °C, and final weight (W_f) was recorded.

Solubility was calculated using:

$$\text{Solubility (\%)} = \frac{(W_i - W_f)}{W_i} \times 100$$

where Wi is the initial mass and W_f is the final mass of the film.

3.7.6 Tensile Strength

The tensile strength of the bioplastic films was determined using a Universal Testing Machine **(UTM)** in accordance with ASTM D882. Prior to testing, the film samples were conditioned at 23 ± 2 °C and 50 ± 5% relative humidity for 48 h. The conditioned films were cut into rectangular strips measuring 100 mm × 15 mm. Film thickness was measured at multiple locations using a digital micrometer, and the average thickness was recorded.

Tensile testing was performed with a gauge length of 50 mm and a crosshead speed of 50 mm/min until specimen rupture. Tensile strength was calculated by dividing the maximum load at break by the initial

cross-sectional area of the film and expressed in megapascals (MPa), using the following equation:

$$\text{Tensile strength (MPa)} = \frac{F_{max}}{W \times T}$$

where F_{max} is the maximum force at break (N),
W is the specimen width (mm), and
T is the film thickness (mm).

3.7.7 Water Absorption Capacity

The water absorption capacity of the bioplastic films was determined following a gravimetric method. Film samples were cut into 2 cm × 2 cm pieces, dried at 60 °C to constant weight, and weighed to obtain the initial mass (W_i). The samples were then immersed in distilled water at room temperature (27 ± 1 °C) for a predetermined period.

After immersion, the samples were removed, gently blotted with filter paper to remove surface water, and weighed to obtain the final mass (W_f). Water absorption capacity was calculated using the following equation:

$$\text{Water absorption (\%)} = \frac{(W_f - W_i)}{W_i} \times 100$$

where W_i is the initial dry weight and W_f is the final wet weight of the film.

All measurements were performed in triplicate, and the results were expressed as mean ± standard deviation

3.8 Mechanical and Moisture Properties

The prepared bioplastic films were further evaluated for tensile breaking load (tensile strength) and moisture absorption using standard laboratory procedures.

4. Results and Discussion

4.1 Biodegradability by Soil Burial Method

The biodegradability of the developed bioplastic films was evaluated using the soil burial method, and the results are presented in Table 4. All samples exhibited a noticeable reduction in weight after the burial period, confirming their biodegradable nature.

Table 4: Percentage degradation of bioplastic films determined by soil burial method

Sample	Initial weight (g)	Final weight (g)	Degradation (%)
Sample 1	0.2449 ± 0.01	0.1642 ± 0.01	32.95
Sample 2	0.3569 ± 0.05	0.1554 ± 0.02	56.45
Sample 3	0.4079 ± 0.05	0.1225 ± 0.01	59.58
Sample 4	0.7313 ± 0.01	0.4395 ± 0.04	39.90

Among the samples, Sample 3 exhibited the highest degradation rate (59.58%), followed closely by Sample 2 (56.45%), indicating enhanced biodegradability of these formulations. The increased degradation may be attributed to the optimal proportion of custard apple peel starch, which contains biodegradable polysaccharides such as starch, cellulose, and pectin that are readily attacked by soil microorganisms.

Sample 1 showed the lowest degradation (32.95%), possibly due to lower peel starch content resulting in a more compact polymer matrix. Although Sample 4 had the highest initial weight, it exhibited only moderate degradation (39.90%), which may be attributed to increased thickness and reduced microbial penetration. These results clearly indicate that biodegradability is strongly influenced by formulation composition.

Based on the superior biodegradability performance, Sample 3 was selected for further characterization.

4.2 Thickness

The thickness of Sample 3 was measured at different locations to assess film uniformity, and the results are shown in Table 5.

Table 5: Thickness of Sample 3 bioplastic film

Measurement point	Thickness (mm)	Thickness (µm)
1	0.64	640
2	0.73	730
3	0.77	770
4	0.75	750
Average	0.7225	722.5

The thickness values ranged from 640 to 770 µm, with an average thickness of 722.5 µm. Minor variations in thickness may be due to non-uniform spreading of the casting solution or uneven drying conditions. Overall, the film exhibited good thickness uniformity, which is essential for consistent mechanical performance and predictable biodegradation behaviour.

4.3 Density

The density of Sample 3 was calculated using its measured weight, area, and thickness, and the results are presented in Table 6.

Table 6: Density of Sample 3 bioplastic film

Sample	Weight (g)	Area (cm^2)	Thickness (cm)	Density (g/cm^3)
Sample 3	11.5123	447.72	0.0798	0.3223

The calculated density of 0.3223 g/cm^3 indicates a lightweight and relatively porous film structure. Lower density is advantageous for biodegradable packaging applications, as it enhances flexibility and facilitates microbial degradation.

4.4 Grammage

The grammage of Sample 3 was determined based on its weight and surface area, as shown in Table 7.

Table 7: Grammage of Sample 3 bioplastic film

Sample	Weight (g)	Length (cm)	Breadth (cm)	Grammage (g/cm^2)
Sample 3	11.5123	24.6	18.2	0.0257

The grammage value of 0.0257 g/cm^2 reflects a lightweight film with uniform material distribution, which is desirable for flexible and disposable packaging materials.

4.5 Solubility

The solubility behaviour of Sample 3 in different solvents is presented in Table 8.

Table 8: Solubility of Sample 3 bioplastic film in different solvents

Solvent	Initial weight (g)	Final weight (g)	Solubility (%)
Acetone	0.613	0.626	1.97
Toluene	0.418	0.432	3.29
Petroleum ether	0.331	0.352	6.34
Hot water	0.442	0.485	9.52
Cold water	0.455	0.488	9.67

The bioplastic film showed low solubility in organic solvents, indicating good solvent resistance and structural stability. Higher solubility was observed in water, which can be attributed to the hydrophilic nature of starch and glycerol. This water sensitivity supports biodegradability while remaining within acceptable limits for biodegradable applications.

4.6 Water Absorption Capacity

The water absorption capacity of Sample 3 is presented in Table 9.

Table 9: Water absorption capacity of Sample 3 bioplastic film

Sample	Initial weight (g)	Final weight (g)	Water absorption (%)
Sample 3	0.4079	0.4086	0.1716

The film exhibited very low water absorption (0.1716%), indicating good resistance to moisture uptake. This property enhances dimensional stability and broadens potential application areas.

4.7 Overall Performance of Sample 3

A summary of the key properties of Sample 3 is presented in Table 10.

Table 10: Summary of physicochemical properties of Sample 3 bioplastic film

Property	Value
Biodegradation (%)	59.58
Thickness (µm)	722.5
Density (g/cm³)	0.3223
Grammage (g/cm²)	0.025
Solubility (%)	Acetone (1.97), Toluene (3.29), Petroleum ether (6.34), Hot water (9.52), Cold water (9.67)
Water absorption (%)	0.1716

Overall, Sample 3 demonstrated the best balance of biodegradability, physical stability, and moisture resistance among all formulations. The combination of high biodegradation rate, low density, controlled solubility, and minimal water absorption suggests that this formulation is a promising candidate for eco-friendly bioplastic applications.

5. Conclusion

The present study successfully demonstrated the development of biodegradable plastic films using custard apple peel starch blended with corn starch and plasticized with glycerol. The prepared bioplastic films

exhibited satisfactory physicochemical properties, confirming the feasibility of utilizing agro-waste as a sustainable raw material for biodegradable plastics.

Among the formulations studied, Sample 3 showed superior performance, recording the highest biodegradation rate (59.58%) under soil burial conditions. The film exhibited uniform thickness (722.5 µm), low density (0.3223 g/cm³), and low grammage (0.025 g/cm²), indicating a lightweight and homogeneous structure. Solubility studies revealed good resistance to organic solvents and moderate sensitivity to water, attributed to the hydrophilic nature of starch and glycerol. Furthermore, the film demonstrated minimal water absorption capacity (0.1716%), suggesting enhanced dimensional stability and resistance to moisture uptake.

Overall, the results indicate that custard apple peel starch-based bioplastics possess promising biodegradability, structural integrity, and functional properties, making them suitable candidates for eco-friendly and disposable applications. The study highlights the potential of converting agricultural waste into value-added biodegradable materials, thereby contributing to waste management and environmental sustainability.

6. Future Scope

Although the developed bioplastic films showed encouraging results, further research is required to enhance their performance and expand their applications. The following future research directions are proposed:

1. **Mechanical and Thermal Optimization**
   - Incorporation of natural fibers or nano-fillers such as cellulose nanofibers, chitosan, or clay nanoparticles to improve tensile strength, flexibility, and thermal stability.
2. **Barrier Property Evaluation**
   - Detailed investigation of water vapor permeability, oxygen transmission rate, and oil resistance to assess suitability for food packaging applications.
3. **Chemical and Structural Characterization**
   - Advanced characterization techniques such as FTIR, SEM, XRD, and DSC can be employed to understand molecular interactions, crystallinity, and surface morphology.
4. **Shelf-Life and Application Studies**
   - Real-time storage studies under different environmental conditions to evaluate durability and functional stability during practical usage.
5. **Biodegradation Kinetics and Environmental Impact**
   - Long-term biodegradation studies under composting, marine, and landfill conditions to assess environmental fate and degradation mechanisms.
6. **Scale-Up and Economic Feasibility**
   - Pilot-scale production and cost analysis to evaluate commercial viability and industrial scalability of custard apple peel starch-based bioplastics.
7. **Functional Modification**
   - Development of antimicrobial or antioxidant bioplastic films by incorporating plant extracts or essential oils for active packaging applications.

In conclusion, custard apple peel starch-based bioplastics represent a promising and sustainable alternative to conventional petroleum-based plastics, with significant potential for further improvement and real-world applications.

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