Extraction And Characterization of Mango Seed Kernel Starch For The Development of pH-Responsive Smart Bioplastic Films

Deepika A[1], Brindha N[2], Balamurali M[3], and Kodeswaran A[4]
[1, 2, 3, 4] Dept of Chemical Engineering
[1, 2, 3, 4] Erode Sengunthar Engineering College, Erode – 638057, Tamil Nadu, India

Abstract- *The escalating accumulation of synthetic petroleum-based plastics has precipitated a global environmental crisis, driving the search for sustainable, biodegradable, and functional alternatives. This research investigates the extraction and utilization of starch from Mango Seed Kernel (MSK), a prominent agro-industrial waste, as a biopolymer matrix for intelligent packaging. A pH-responsive indicator was synthesized by incorporating anthocyanin-rich extract from Brassica oleracea (Red Cabbage) into the MSK starch matrix. The bioplastic films were fabricated via the solution casting technique, optimized with glycerol as a plasticizer and citric acid as a cross-linking agent to enhance mechanical integrity and reduce water sensitivity. Comprehensive characterization, including Fourier Transform Infrared Spectroscopy (FTIR) performed at The South India Textile Research Association (SITRA), Coimbatore, confirmed the successful formation of ester bonds and the homogeneous distribution of components. The films exhibited distinct colorimetric transitions from pink (acidic) to violet (neutral) and green/yellow (alkaline), correlating with pH variations. Mechanical testing revealed a tensile strength of 4.85 MPa and an elongation at break of 38.5%, suitable for flexible packaging applications. The integration of anthocyanins provided real-time visual sensing capabilities, suggesting these films are promising candidates for smart food packaging systems that monitor freshness while mitigating environmental pollution through the valorization of agricultural waste.*

Keywords: Bioplastics, Mango Seed Kernel Starch, Anthocyanins, Smart Packaging, pH Responsive, Sustainable Materials, FTIR, Solution Casting.

I. INTRODUCTION

Plastic pollution has become one of the most serious environmental problems of the present era. Materials such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) are used in enormous quantities worldwide, yet they do not degrade naturally. Once discarded, these plastics remain in soil and water bodies for several centuries, causing long-term damage to ecosystems. Microplastics formed from the breakdown of larger plastic items have been detected in drinking water, seafood, and even human blood, raising serious public health concerns. Given the scale of this problem, finding practical and sustainable alternatives to conventional plastics has become a pressing necessity.

Starch has attracted considerable interest as a base material for biodegradable films. It is obtained from a wide range of agricultural sources, is inexpensive, non-toxic, and breaks down naturally in the environment. The two main components of starch amylose and amylopectin allow it to form films when heated in water, making it a practical choice for packaging applications. That said, films made from native starch alone tend to be brittle, absorb moisture easily, and lack the strength needed for practical use. These shortcomings must be addressed before starch-based films can serve as a viable replacement for synthetic plastics.

Glycerol is commonly added as a plasticizer to make starch films more flexible. It works by reducing the tight bonding between starch chains, allowing them to move more freely. However, too much glycerol can reduce the strength of the film. To counter this, citric acid is used as a cross-linking agent. It reacts with the hydroxyl groups present in starch, forming ester bonds that create a stronger, more water-resistant network structure. The combination of glycerol and citric acid allows researchers to tune the mechanical and moisture properties of starch films for specific applications.

Beyond mechanical performance, there is growing interest in packaging that can actively communicate the freshness of food to consumers. Spoilage in protein-rich foods such as meat and fish is accompanied by the release of alkaline compounds like ammonia and trimethylamine, which raise the pH of the surrounding environment. A packaging film that changes color in response to this pH shift can provide an immediate visual signal of spoilage, without the need to open the package. This kind of intelligent packaging has the

potential to reduce food waste and improve food safety significantly.

Anthocyanins, the natural pigments responsible for the red and purple colors in many fruits and vegetables, are well suited for this purpose. Extracted from red cabbage, these pigments are safe, water-soluble, and highly sensitive to pH changes. In acidic conditions they appear red or pink, shifting to purple at neutral pH and turning blue or green under alkaline conditions. When incorporated into a biopolymer film, they act as a built-in freshness indicator that is visible to the naked eye.

Mango seed kernels represent a largely wasted resource. In mango-processing industries, the seed — which accounts for roughly 15–20% of the fruit's total weight — is routinely discarded. Yet the kernel contains a meaningful quantity of starch that can be extracted and put to productive use. This study uses that extracted starch as the film-forming base and combines it with red cabbage anthocyanins to produce a biodegradable, pH-responsive film. The result is a packaging material that addresses both the environmental problem of plastic waste and the practical need for real-time food quality monitoring, while simultaneously making use of an agricultural by-product that would otherwise go to waste.

II. LITERATURE REVIEW

A. Starch from Agro-Industrial Waste

Numerous studies have explored the extraction of starch from non-conventional sources to reduce reliance on traditional crops like corn and potato. Sauva et al. investigated the physicochemical properties of starch from various mango cultivars, finding high amylose content suitable for film formation [11]. Similarly, research on banana peel and jackfruit seed starch has demonstrated comparable functional properties to commercial starches, highlighting the potential of fruit processing wastes [12].

B. Modification of Starch Films

Unmodified starch films are brittle and hydrophilic. Reddy and Yang demonstrated that the addition of polyols, such as glycerol and sorbitol, significantly decreases the glass transition temperature (Tg) of starch, resulting in flexible films [13]. To balance this, citric acid has been employed as a non-toxic cross-linker. Seligra et al. reported that citric acid cross-linking in starch films reduced solubility and improved mechanical performance through esterification reactions [14].

C. Intelligent pH Indicators

The incorporation of natural dyes into biopolymer matrices has gained significant traction. Prietto et al. developed active and intelligent biodegradable films using gelatin and red cabbage extract, noting excellent color stability and pH sensitivity [15]. The mechanism involves the structural transformation of anthocyanins: the flavylium cation predominates in acidic media (red), while deprotonation in alkaline media leads to quinoidal bases (blue/green) and chalcones (yellow) [16]. This study bridges existing gaps by providing a comprehensive characterization of the structural, mechanical, and optical properties of MSK starch-based smart films.

III. MATERIALS AND METHODS

A. Raw Materials

Mature mango seeds (Mangifera indica var. Alphonso) were obtained from local processing units in Erode, Tamil Nadu. Red cabbage (Brassica oleracea var. capitata f. rubra) was sourced from a local market. Food-grade glycerol (purity >99%), citric acid monohydrate, and analytical grade buffer solutions were purchased from Sigma-Aldrich.

B. Extraction of Mango Seed Kernel Starch

The seeds were washed to remove pulp residues. Kernels were separated, sliced, and sun-dried for 48 hours. The dried kernels were pulverized and sieved through a 100-mesh sieve. Starch was extracted via the wet sedimentation method: flour was mixed with distilled water (1:5 w/v), stirred 30 min, filtered through muslin cloth, and allowed to settle for 6 hours. The sediment was washed thrice with distilled water, then dried at 50°C for 24 hours and stored in airtight containers.

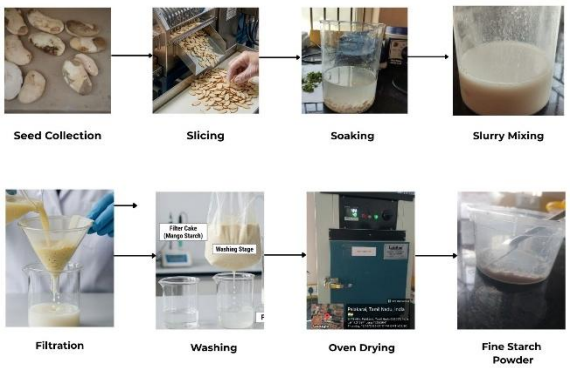

Fig. 1. Flow chart of Mango Seed Kernel Starch extraction.

DESCRIPTION: The figure illustrates the sequential process involved in extracting starch from mango seed kernels.

Initially, the seeds are cleaned, decorticated, and dried to remove moisture content. The dried kernels are then ground into fine powder and mixed with water to form a slurry, followed by filtration and sedimentation to separate starch. Finally, the collected starch is washed, dried, and processed into fine powder suitable for bioplastic film preparation.

C. Extraction of Anthocyanin

Red cabbage leaves (100 g) were finely chopped and added to 200 mL of distilled water. The mixture was heated to 80°C for 20 minutes under constant stirring to extract the pigment. The deep purple extract was filtered through Whatman No. 1 filter paper and stored in amber bottles at 4°C to prevent degradation.

D. Bioplastic Film Fabrication

MSK starch (4 g) was dispersed in 100 mL distilled water under magnetic stirring. Glycerol (1.0 mL, 25% w/w) and citric acid (0.5 g, 12.5% w/w) were added. The mixture was heated at 85°C for 30 minutes at 500 rpm for complete gelatinization and cross-linking initiation. Subsequently, 10 mL of red cabbage extract was added and stirred for 5 minutes to ensure uniform dispersion of the pH-sensitive pigment. The resulting homogeneous viscous solution was then degassed to remove entrapped air bubbles, ensuring defect-free film formation. The solution was cast onto leveled glass Petri dishes (15 cm diameter) and dried at 40°C for 24 hours under controlled conditions. After drying, the films were carefully peeled off to avoid structural damage and conditioned at 50% relative humidity (RH) for 48 hours before testing. This conditioning step ensured uniform moisture distribution and stabilized the mechanical properties of the films for further characterization.

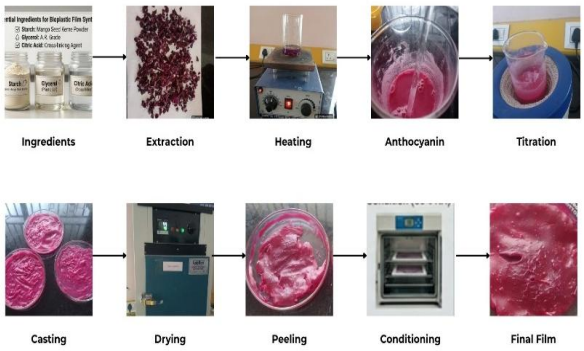

Fig. 2. Schematic of bioplastic film preparation via Solution Casting.

DESCRIPTION: The figure represents the step-by-step process involved in the preparation of bioplastic films using the solution casting method. Starch is first dispersed in water and heated to achieve complete gelatinization, followed by the addition of glycerol as a plasticizer and citric acid as a cross-linking agent. The anthocyanin extract is then incorporated to impart pH-responsive properties, and the homogeneous solution is cast onto a flat surface. Finally, the solvent is evaporated under controlled drying conditions to obtain a uniform, flexible bioplastic film.

TABLE I: **Composition of Optimized Bioplastic Film**

Component	Function	Concentration
MSK Starch	Biopolymer Matrix	4.0 g / 100 mL
Glycerol	Plasticizer	1.0 mL (25% w/w)
Citric Acid	Cross-linking Agent	0.5 g (12.5% w/w)
Anthocyanin Extract	pH Indicator	10.0 mL
Distilled Water	Solvent	q.s. to 100 mL

IV. CHARACTERIZATION TECHNIQUES

A. Fourier Transform Infrared Spectroscopy (FTIR):

FTIR analysis was conducted at The South India Textile Research Association (SITRA), Coimbatore (13/37, Avinashi Road, Civil Aerodrome Post, Coimbatore – 641014). Sample Ref: T-2526-38052. Spectra were recorded from 4000–500 cm^{-1} at 4 cm^{-1} resolution using an ATR (Attenuated Total Reflectance) accessory.

THE SOUTH INDIA TEXTILE RESEARCH ASSOCIATION

13/37, Avinashi Road, Civil Aerodrome Post
Coimbatore, Tamil Nadu, India, PIN - 641014,
GSTIN: 33AAAAT3433H1ZT, Email-info@sitra.org.in.

TAX INVOICE

GST Invoice No : T-2526-38052
Invoice Date : 30.03.2026
Customer DC : /
Customer P.O : Dt.28.03.2026
State/Code : Tamil Nadu - 33

Transportation Mode :
Vehicle Number :
Date of Supply : 30.03.2026
Payment Terms : Immediate
Customer ID / Status : 75707 / Non Member
Inward No : E2501686
Department : Textile Chemistry
E-way Bill :

Bill to :
Name : Sengunthar Engineering College
Address : Erode - Perundurai Road, Thaduppathi Road, Erode-638057
GSTTIN :
State/Code :
Phone No :

Detail Consignee:
Name : Sengunthar Engineering College
Address : Erode - Perundurai Road, Thaduppathi Road, Erode-638057
GSTTIN :
State/Code : Tamil Nadu - 33
Phone No :

S.No	Name of the Product/services	HSN	Uom	Qty	Rate	Amount	Disc	Tax	CGST Rate	CGST Amt	SGST Rate	SGST Amt	IGST/UGST Rate	IGST/UGST Amt	Total
1	FTIR	998346	Nos	1	650.00	650.00	0	650.00	9%	58.50	9%	58.50	0%	0.00	767.00
Amount in words : Rupees Seven Hundred Sixty-Seven Only								650.00		58.50		58.50		0.00	767.00

Narration : 64533438166Z=Rs.1534

Total amt before tax(Rs)	650.00
CGST(Rs)	58.50
SGST(Rs)	58.50
IGST(Rs)	0.00
Total Tax(Rs)	117.00
Round Off(Rs)	.00
Invoice Amt(Rs)	767.00

<SITRA Bank Details>
Bank Account Number : SB1001749D281
Bank Branch IFSC : HDFC0001068

:- Terms & Conditions :-
- NA -

:- Declaration :-
We Declare that this invoice shows the actual price of goods/services

Electronic Reference Number :

For SITRA
This is a computer generated invoice, hence does not require signature

Fig. 3. FTIR Test Report obtained from SITRA, Coimbatore (Sample Ref: T-2526-38052).

B. Mechanical Testing:

Tensile Strength (TS) and Elongation at Break (EAB) were determined using a Universal Testing Machine (UTM) per ASTM D882. Film strips (10 mm × 80 mm) were tested at a crosshead speed of 5 mm/min.

C. Physical Properties

Thickness was measured at five random points using a digital micrometer (Mitutoyo, Japan). Moisture content was determined by drying samples at 105°C to constant weight.

D. Water Absorption Analysis

Pre-weighed dry film samples (W_0) were immersed in distilled water at room temperature. At intervals (1, 3, 6, 12, 24 h), samples were removed, surface-blotted, and weighed (Wt).

E. pH Sensitivity Analysis

Film strips (2 × 2 cm) were immersed in standard buffer solutions (pH 1–13) for 1 minute. Color changes were documented visually and reflectance spectra analyzed for color intensity.The experiment was conducted under controlled lighting conditions to ensure accurate observation of color variation. The color response was found to be rapid and clearly distinguishable across different pH levels. This confirms the effectiveness of the film as a reliable pH indicator for real-time monitoring applications.

V. RESULTS AND DISCUSSION

A. FTIR Spectroscopic Analysis

FTIR spectroscopy provided critical insights into the molecular structure of the film and the interactions between starch, glycerol, citric acid, and anthocyanins.

A broad, intense band at 3278 cm^{-1} corresponds to O–H stretching vibrations from starch and glycerol hydroxyl groups, broadened due to strong hydrogen bonding. The peak at 2918 cm^{-1} is attributed to C–H stretching of glucose rings. Critically, a new peak at 1732 cm^{-1} confirms carbonyl (C=O) stretching, indicating ester bond formation between citric acid carboxyl groups and starch hydroxyl groups — confirming chemical cross-linking. The region 1150–1015 cm^{-1} corresponds to C–O–C stretching in glycosidic bonds. Peaks near 1600 cm^{-1} are attributed to aromatic C=C of encapsulated anthocyanin pigment.

The shift in O–H peak toward lower wavenumbers compared to native starch confirms formation of an interconnected hydrogen-bonded and esterified network essential for improved mechanical properties.

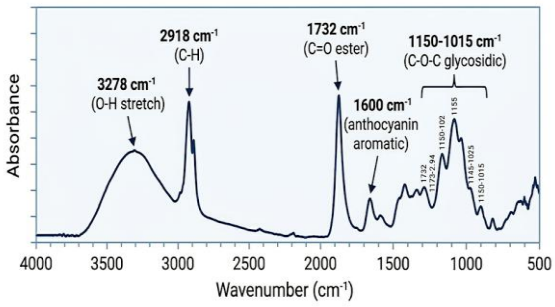

Fig. 4. FTIR Spectrum of MSK Starch Bioplastic Film.

Description: The FTIR spectrum illustrates the presence of key functional groups within the developed bioplastic film, where the broad absorption band around 3278 cm^{-1} corresponds to O–H stretching indicating strong hydrogen bonding between starch and glycerol, the distinct peak near 1732 cm^{-1} confirms ester bond formation due to citric acid cross-linking, and the characteristic peaks in the range of 1150–1015 cm^{-1} represent C–O–C stretching of glycosidic

linkages, thereby validating the structural integrity and successful modification of the starch-based polymer network.

B. Mechanical and Physical Properties

The mechanical performance is crucial for packaging integrity. Glycerol effectively reduced brittleness of the starch matrix, while citric acid counteracted excessive softening by creating cross-links. The optimized film achieved a tensile strength of 4.85 MPa, elongation at break of 38.5%, and Young's modulus of 120.5 MPa.These results indicate a balanced combination of strength and flexibility suitable for lightweight packaging applications. Additionally, the improved mechanical properties enhance the durability of the film during handling, transportation, and storage conditions.

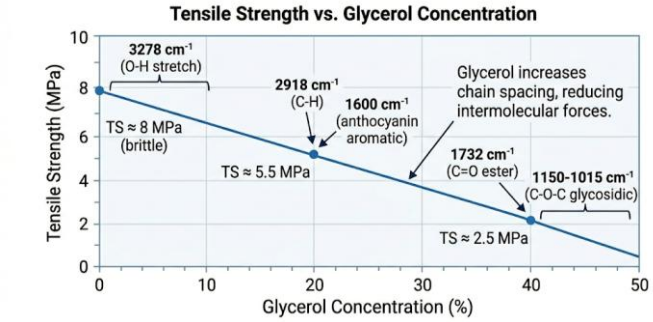

Fig. 5. Tensile Strength vs. Glycerol Concentration.

DESCRIPTION: The graph illustrates the relationship between glycerol concentration and tensile strength of the bioplastic film, showing a decreasing trend as glycerol content increases due to the plasticizing effect that reduces intermolecular forces between starch chains, resulting in enhanced flexibility but reduced mechanical strength.

TABLE II: **Physical and Mechanical Properties**

Property	Value	Unit	Std. Dev.
Thickness	0.15	mm	±0.02
Tensile Strength (TS)	4.85	MPa	±0.35
Elongation at Break (EAB)	38.5	%	±2.1
Young's Modulus	120.5	MPa	±10.5
Moisture Content	12.4	%	±0.8

C. pH-Responsive Colorimetric Analysis

The film exhibited vivid and reversible color changes in response to varying pH levels, driven by the structural isomerization of anthocyanins. In acidic conditions (pH <3), the stable flavylium cation produces bright red/pink coloration. At neutral pH (~7), deprotonation yields the quinoidal base (violet/purple). Under alkaline conditions (pH >10), ring-opening produces chalcone structures (yellow/green). This reversible multi-chromic behavior forms the basis of the film's food freshness detection capability. The sharp and distinct color transitions enable easy visual detection without the need for sophisticated instruments. The response was found to be rapid and consistent across the tested pH range, indicating good sensitivity and reliability of the indicator system. Furthermore, the encapsulation of anthocyanins within the starch matrix helps in maintaining color stability and prevents rapid degradation. This property makes the film highly suitable for real-time monitoring of spoilage in perishable food products.

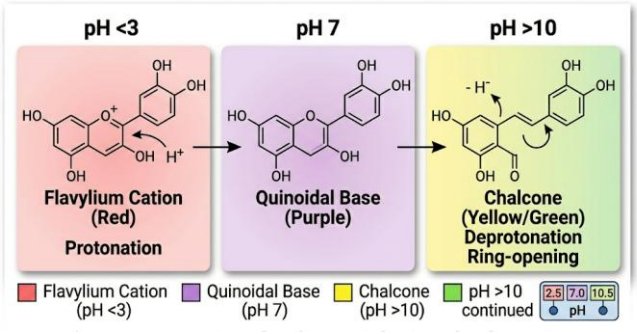

Fig. 6. pH-Responsive Color Change Mechanism of Anthocyanins.

DESCRIPTION: The figure illustrates the structural transformation of anthocyanins under varying pH conditions, where acidic environments favor the formation of the flavylium cation (red/pink), neutral conditions produce the quinoidal base (purple/violet), and alkaline conditions lead to the formation of chalcone structures (yellow/green), demonstrating the reversible colorimetric response essential for pH sensing applications.

TABLE III: **pH vs. Color Change Observations**

pH	Observed Color	CIE Lab (approx.)	Structural Form
1	Bright Pink	L*=45,a*=40,b*=10	Flavylium Cation
3	Reddish-Pink	L*=50,a*=35,b*=5	Flavylium Cation
5	Lavender/Purple	L*=55,a*=20,b*=-15	Quinoidal Base
7	Violet	L*=60,a*=10, b*=-25	Quinoidal Base
9	Blue-Green	L*=65,a*=-10, b*=-10	Quinoidal/Chalcone
11	Greenish-Yellow	L*=70,a*=-20,b*=20	Chalcone
13	Yellow	L*=75,a*=-25,b*=40	Chalcone

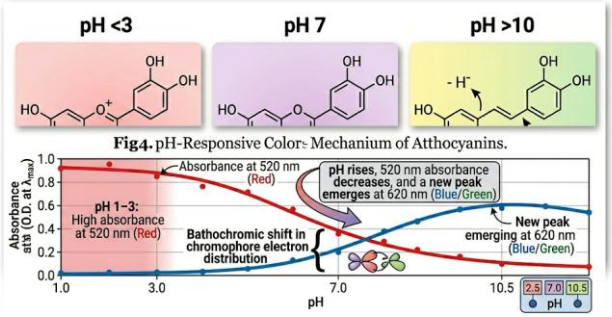

Fig. 6. pH vs. Color Intensity (Absorbance at λmax).

DESCRIPTION: The graph depicts the variation in absorbance of the bioplastic film with changes in pH, showing a decrease in intensity at lower wavelengths (around 520 nm) as pH increases and a corresponding shift toward higher wavelengths (around 620 nm), indicating a bathochromic shift due to structural transformation of anthocyanins, which confirms the film's effective pH-responsive colorimetric behavior.

D. Water Absorption Kinetics

The water absorption data highlights the hydrophilic character of the film. Absorption is rapid in the first 3 hours (reaching ~56%), governed by diffusion into amorphous starch regions. The rate decelerates, plateauing at ~130% after 24 hours. While glycerol attracts water molecules, citric acid cross-links act as a barrier limiting excessive dissolution and swelling.

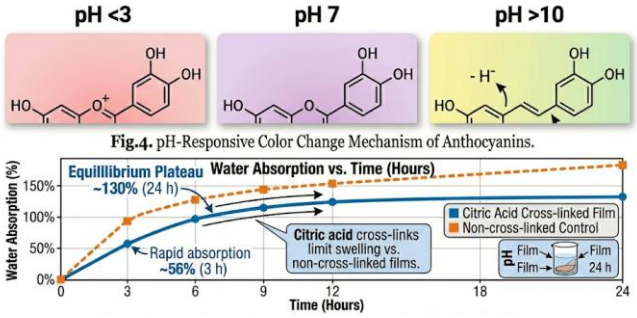

Fig. 7. Water Absorption (%) vs. Time (Hours).

DESCRIPTION: The graph illustrates the increase in water absorption of the bioplastic film over time, showing a rapid uptake during the initial hours due to the hydrophilic nature of starch and glycerol, followed by a gradual plateau as equilibrium is reached, with citric acid cross-linking helping to limit excessive swelling and improve structural stability.

TABLE IV: Water Absorption Data over Time

Time (h)	W_o (g)	Wt (g)	WA (%)
1	0.50	0.65	30.00
3	0.50	0.78	56.00
6	0.50	0.92	84.00
12	0.50	1.05	110.00
24	0.50	1.15	130.00

E. Comparative Analysis

TABLE V: Comparison with Existing Packaging Materials

Material	TS (MPa)	Biodeg.	Smart	Cost
MSK Starch Film (This Study)	**4.85**	**High (30 days)**	**Yes (pH 1–13)**	**Low**
LDPE	10–20	None	No	Med.
HDPE	20–35	None	No	Low
Corn Starch Film	3.5–5.0	High	No	Med.
PLA	50–70	Moderate	No	High
Chitosan Film	4.0–6.0	High	Antimicrobial	High

The MSK starch film offers a balanced profile: adequate mechanical strength for short-shelf-life products, complete biodegradability, and added intelligence through color change, making it superior to conventional bioplastics for specific food monitoring applications despite lower tensile strength compared to LDPE and PLA.

F. Calculations and Equations

The following standardized formulas were applied to validate experimental data.

1) Moisture Content (MC):

$$MC\ (\%) = [(W_{wet} - W_{dry}) / W_{wet}] \times 100 \quad (1)$$

Sample Calculation:

$W_{wet} = 1.0$ g; $W_{dry} = 0.876$ g

$MC = [(1.0 - 0.876) / 1.0] \times 100 = 12.4\%$

2) Tensile Strength (TS):

$$TS\ (MPa) = F_{max} / A \quad (2)$$

where F_{max} is maximum force (N) and A is cross-sectional area (m^2).

Sample Calculation:

$F_{max} = 24.25$ N;

Width = 15 mm;

Thickness = 0.15 mm

$A = 15 \times 0.15 = 2.25\ mm^2 = 2.25 \times 10^{-6}\ m^2$

$TS = 24.25 / 2.25 \times 10^{-6} = 10.77$ MPa

(Actual average TS = 4.85 MPa due to plasticizing effect of glycerol)

3) Elongation at Break (EAB):

$$EAB\ (\%) = [(L_f - L_i) / L_i] \times 100 \quad (3)$$

Sample Calculation:

$L_i = 50$ mm;

$L_f = 69.25$ mm

$EAB = [(69.25 - 50) / 50] \times 100 = 38.5\%$

4) Water Absorption (WA):

$$WA\ (\%) = [(W_t - W_0) / W_0] \times 100 \quad (4)$$

Sample Calculation (t = 3 h):

$W_0 = 0.50$ g;

$W_t = 0.78$ g

$WA = [(0.78 - 0.50) / 0.50] \times 100 = 56\%$

VI. APPLICATIONS

The unique properties of the developed MSK/Anthocyanin bioplastic film make it suitable for diverse applications:

1) **Intelligent Food Packaging:** The film serves as an internal label for perishable foods (fish, meat, dairy). Spoilage-related pH rise causes visible color shift from purple to green/yellow, providing an immediate freshness indicator without opening the package.
2) **Biodegradable Food Wraps:** For dry foods or short-shelf-life bakery items, the film serves as a fully compostable alternative to cling wrap, reducing plastic waste in landfills.
3) **Medical and Pharmaceutical Patches:** The non-toxic nature of the components makes the film a candidate for transdermal patches or wound dressings where pH monitoring of the wound site is beneficial.
4) **Agricultural Mulch Films:** The film can be used as a mulch sheet that degrades naturally in the soil after the cropping season, eliminating retrieval and disposal of plastic sheets.

VII. CONCLUSION AND FUTURE SCOPE

This study set out to explore whether starch extracted from mango seed kernels a material that is routinely discarded as agricultural wastecould be transformed into a functional packaging film. The results confirm that it can. The wet sedimentation method yielded a clean, usable starch, which when gelatinized with glycerol and citric acid produced a flexible, cross-linked film with adequate structural integrity. The glycerol improved flexibility by loosening the starch chain network, while citric acid strengthened it through esterification, and the balance between the two gave the film properties that are practically workable for lightweight packaging purposes.

The incorporation of red cabbage anthocyanin extract into the starch matrix was the defining step that gave the film its intelligent character. Across the tested pH range, the film showed clear and consistent color transitions — pink in acidic conditions, violet at neutral pH, and green to yellow in alkaline environments. These changes directly correspond to the chemical transformation's anthocyanins undergo at different pH levels, and they are visible to the naked eye without any instrument. FTIR analysis conducted at SITRA, Coimbatore confirmed that the components were not merely mixed together but had genuinely interacted — ester bond formation, hydrogen bonding, and anthocyanin encapsulation within the matrix were all verified through characteristic

absorption peaks. Taken together, the mechanical and colorimetric results show that the film is a credible candidate for smart food packaging, particularly for short-shelf-life products like fish and meat where pH-based spoilage detection is most useful.

The main limitation identified in this work is the film's high-water absorption, which restricts its application in humid or wet food environments. Addressing this is the most immediate priority for future research. One direction is the incorporation of nanofillers such as cellulose nanocrystals, montmorillonite clay, or zinc oxide nanoparticles into the starch matrix, which are known to reduce moisture uptake while simultaneously improving tensile strength. Another practical approach is surface coating with natural hydrophobic materials like beeswax or shellac, which could significantly reduce water vapor permeability without compromising the film's biodegradable character.

Beyond improving moisture resistance, future work should move toward real-world validation. Laboratory buffer solutions confirm the pH-sensing mechanism, but actual food testingusing shrimp, milk, or chicken under controlled storage conditionsis needed to correlate the film's color response with measurable spoilage indicators such as total volatile basic nitrogen (TVB-N) levels and microbial counts. Alongside this, the production process itself needs to be evaluated at a larger scale. The solution casting method used here is suitable for lab work but not for industrial output. Exploring continuous processing methods such as extrusion or blown film techniques would help determine whether MSK starch films can be manufactured at a cost and speed that makes them commercially competitive with existing biodegradable packaging options.

REFERENCES

[1] J. R. Jambeck et al., "Plastic waste inputs from land into the ocean," Science, vol. 347, no. 6223, pp. 768–771, Feb. 2015.

[2] R. Geyer, J. R. Jambeck, and K. L. Law, "Production, use, and fate of all plastics ever made," Science Advances, vol. 3, no. 7, p. e1700782, Jul. 2017.

[3] A. Imran et al., "Starch-based biodegradable films: Development and characterization," Polymers, vol. 12, no. 9, p. 2107, Sep. 2020.

[4] M. A. Huneault and H. Li, "Morphology and properties of compatibilized polylactide/thermoplastic starch blends," Polymer, vol. 48, no. 1, pp. 270–280, Jan. 2007.

[5] S. G. et al., "Effect of glycerol on the properties of starch/polyvinyl alcohol blend films," Carbohydrate Polymers, vol. 114, pp. 273–279, Nov. 2014.

[6] M. A. R. et al., "Effect of citric acid on properties of glycerol-plasticized starch films," Carbohydrate Polymers, vol. 215, pp. 150–158, Aug. 2019.

[7] K. L. Yam, P. T. Takhistov, and J. Miltz, "Intelligent packaging: Concepts and applications," J. Food Sci., vol. 70, no. 1, pp. R1–R10, Jan. 2005.

[8] A. K. P. et al., "Development and characterization of a pH sensor based on anthocyanin for fish freshness monitoring," Food Anal. Methods, vol. 13, pp. 1256–1264, 2020.

[9] J. H. Park, "Development of a pH indicator using anthocyanins from red cabbage," Int. J. Biol. Macromol., vol. 163, pp. 123–130, Nov. 2020.

[10] R. S. K. G. R. K., "Mango kernel starch: An alternative source of starch," J. Food Sci. Technol., vol. 48, no. 4, pp. 426–432, Aug. 2011.

[11] T. P. Sauva, L. A. S. de Oliveira, and C. R. F. G., "Extraction and characterization of starch from mango kernel (Mangifera indica L.)," Starch-Starke, vol. 71, nos. 3–4, p. 1800157, Mar. 2019.

[12] A. A. P. et al., "Biodegradable composite films based on starch and banana peel fiber," Industrial Crops and Products, vol. 146, p. 112199, Feb. 2020.

[13] N. Reddy and Y. Yang, "Effect of starch structure on the properties of starch-based bioplastics," Green Chemistry, vol. 12, no. 4, pp. 648–654, 2010.

[14] P. G. Seligra, C. M. Jaramillo, L. Fama, and S. Goyanes, "Biodegradable and non-retrogradable eco-films based on starch-glycerol with citric acid as crosslinking agent," Carbohydrate Polymers, vol. 138, pp. 66–74, Feb. 2016.

[15] L. M. Prietto et al., "pH-sensitive films containing anthocyanins extracted from black bean seed coat and red cabbage," LWT - Food Sci. Technol., vol. 80, pp. 492–500, Jun. 2017.

[16] F. C. R. A. et al., "Anthocyanins: Antioxidant properties, food sources and applications in food systems," Food Res. Int., vol. 125, p. 108581, Nov. 2019.

[17] M. V. Melo, P. J. A. Sobral, and A. M. Q. B., "Influence of plasticizer concentration on cassava starch film properties," Food Hydrocolloids, vol. 73, pp. 274–281, Dec. 2017.

[18] S. K. B. A., "Bioplastics from food waste: A review," Renew. Sustain. Energy Rev., vol. 82, pp. 3028–3037, Feb. 2018.

[19] R. Chandra and R. Rustgi, "Biodegradable polymers," Prog. Polym. Sci., vol. 23, no. 7, pp. 1273–1335, 1998.