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Evaluation of quality parameters of biodegradable films from arrowroot starch and glycerol concentrations

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Abstract
The present study aimed to develop biodegradable films from arrowroot starch plasticized with glycerol and to characterize five formulations containing 5, 10, 15, 20 and 25% (w/v) arrowroot starch by evaluating their film thickness, tensile strength, percentage elongation, film solubility, transparency, water vapour permeability (WVP), printability and sealing ability. The film thickness increased from 0.277 ± 0.015 to 0.673 ± 0.021 mm, film solubility decreased from 64.223 ± 1.326 to 37.860 ± 0.243 %, water vapour permeability decreased from 4.572×10^{-11} ±0.279 to 1.800×10^{-11} ±0.140 $g.m^{-1}s^{-1}Pa^{-1}$, transparency decreased from 4.913 ± 0.040 to 0.639 ± 0.014, tensile strength increased from 1.904 ± 0.034 to 4.501 ± 0.045 MPa, and percentage elongation decreased from 55.700 ± 1.572 to 25.367 ± 1.305 % with increasing arrowroot starch concentration from 5 to 25% (w/v). Qualitative evaluation showed that printability improved with increasing starch concentration, whereas sealing ability was satisfactory up to 15% (w/v) starch and declined at higher starch concentrations due to increased film rigidity.

Keywords: Arrowroot starch, Biodegradable film, Glycerol, Properties of film, Water vapour permeability, Sustainable food packaging

1. Introduction

Food packaging plays a vital role in protecting food products from physical damage, microbial contamination, moisture loss, oxygen exposure, and other environmental factors, thereby extending shelf life and maintaining quality during storage, transportation, and distribution. Conventional packaging materials, particularly petroleum-based plastics, have been extensively used due to their excellent mechanical strength, barrier properties, lightweight nature, and low production cost. However, their widespread use has created serious environmental concerns because these materials are non-renewable, resistant to degradation, and accumulate in landfills and natural ecosystems for prolonged periods, contributing to plastic pollution and greenhouse gas emissions Ncube *et al.* (2020) [1]. Biodegradable films are thin polymeric materials produced from renewable biological resources that can be decomposed by microorganisms into harmless products such as carbon dioxide, water, methane (under anaerobic conditions), and biomass under suitable environmental conditions. These films offer an environmentally friendly alternative to conventional plastic packaging by reducing dependence on fossil fuel-based materials and minimizing environmental pollution. Siracusa *et al.* (2008) [2]; Abdillah *et al.* (2021) [3].

Biodegradable films can be prepared from a wide range of natural biopolymers including polysaccharides (starch, cellulose, chitosan, alginate, pectin), proteins (gelatin, whey protein, soy protein, zein, casein), and lipids (waxes and fatty acids). Among these materials, polysaccharides have received considerable attention because of their excellent film-forming ability, biodegradability, renewability, and wide availability. Mayachiew *et al.* (2010) [4]; Vieira *et al.* (2011) [5]. The global demand for biodegradable packaging materials has increased rapidly owing to growing environmental awareness, regulations on single use plastics, and increasing consumer preference for sustainable packaging solutions. According to recent market reports, the global biodegradable packaging market was valued at approximately USD 105-115 billion in 2024 and is projected to grow at a compound annual growth rate (CAGR) of about 5-7% during the next decade, driven mainly by the food and beverage sector, which represents the largest application segment. This growing demand has accelerated research on biodegradable films derived from renewable agricultural resources.

Among various biodegradable materials, starch is considered one of the most promising natural polymers for biodegradable film production because it is readily available, renewable, biodegradable, non-toxic, inexpensive, and capable of forming transparent and odourless films with good oxygen barrier properties Soares *et al.* (2021) [6]. Starch is mainly composed of amylose and amylopectin, whose molecular arrangement plays an important role in determining the structural and functional characteristics of the films. The linear nature

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of amylose contributes significantly to film formation, while amylopectin influences the mechanical and barrier properties of the polymer matrix Vieira *et al.* (2011) [5].

Arrowroot (*Maranta arundinacea L.*) is a tropical rhizomatous crop cultivated primarily for its starch-rich underground rhizomes. Arrowroot starch contains relatively low levels of proteins and lipids and is characterized by appreciable amylose content, high paste clarity, good water-holding capacity, and excellent film-forming properties Moorthy, (2002) [7]; Kaur *et al.*, (2010) [8]. Recent studies have highlighted the potential of arrowroot starch as a sustainable biomaterial for biodegradable packaging applications due to its renewability, biodegradability, transparency, and relatively low oxygen permeability Soares *et al.*, (2021) [6]; Vekhande *et al.*, (2025) [9]. These characteristics make arrowroot starch a promising alternative starch source for developing environment friendly packaging materials.

Despite its favourable film-forming characteristics, native starch films are generally brittle and rigid because of strong intermolecular hydrogen bonding between starch chains, resulting in limited flexibility and poor handling properties Sothornvit *et al.*, (2005) [10]; Vieira *et al.*, (2011) [5]. To overcome the limitations as mentioned above, the incorporation of plasticizers is essential to improve the mechanical and functional properties of starch-based films. Plasticizers are low molecular weight compounds that reduce intermolecular forces, increase free volume, and enhance polymer chain mobility, thereby imparting flexibility to the film matrix Sejidov *et al.*, (2005) [11]; Vieira *et al.*, (2011) [5].

Among the various plasticizers, glycerol is one of the most widely used in starch-based films because of its non-toxic nature, low molecular weight, high water solubility, and excellent compatibility with starch polymers Talja *et al.*, (2007) [12]. Glycerol molecules interact with the hydroxyl groups of amylose and amylopectin and reduce starch–starch interactions by forming new hydrogen bonds within the polymer matrix. This interaction increases molecular mobility and transforms the rigid starch network into a more flexible and ductile structure Mali *et al.*, (2005) [13]; Vieira *et al.*, (2011) [5].

The concentration of glycerol substantially influences the physical, mechanical, and barrier properties of starch-based films. Increasing glycerol content generally increases film thickness because of enhanced separation of polymer chains and increased free volume within the matrix Sarmah *et al.*, (2015) [14]; Hundekari *et al.*, (2024) [15]. Films containing lower glycerol concentrations usually exhibit higher tensile strength and lower percentage elongation owing to their compact and rigid structure. Conversely, increasing glycerol concentration decreases tensile strength and enhances elongation at break by increasing the flexibility and mobility of polymer chains Talja *et al.*, (2007) [12]; Vieira *et al.*, (2011) [5]. Due to its hygroscopic nature, glycerol also affects the interaction of films with moisture. Higher glycerol concentrations generally increase film solubility and water vapour permeability by increasing water affinity and facilitating moisture diffusion through the polymer network Bourtoom, (2008) [16]; Mali *et al.*, (2005) [13]. Furthermore, variations in glycerol concentration can modify transparency, printability, and sealing ability by altering the structural arrangement and homogeneity of the film matrix Abdillah *et al.*, (2021) [3].

Therefore, the present study was undertaken to develop biodegradable films from arrowroot starch plasticized with different concentrations of glycerol and to evaluate the influence of glycerol on film thickness, tensile strength, percentage elongation, film solubility, transparency, water vapour permeability, printability, and sealing ability. Understanding the relationship between glycerol concentration and film properties is essential for optimizing arrowroot starch films for potential applications in sustainable food packaging systems.

2. Materials and methods

2.1 Raw material

Fresh arrowroot (*Maranta arundinacea L.*) rhizomes of the Trivandrum variety were obtained from the University Farm, Central Research Station, Wakawali, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Maharashtra, India. The harvested rhizomes were sorted and washed thoroughly to remove adhering soil and other impurities. Glycerol and acetic acid used for film preparation were Purchased from Loba Chemie Pvt. Ltd., Mumbai, India.

2.2 Extraction of arrowroot starch

Arrowroot starch was extracted according to the method described by Cruz *et al.* (2004) [17]. Freshly harvested rhizomes were cleaned, washed, and manually peeled. The peeled rhizomes were cut into slices of approximately 3 mm thickness and crushed using a mixer grinder. The crushed material was mixed with deionised water in a 1:2 ratio to form a slurry. The slurry was allowed to stand for 15 min and subsequently filtered through muslin cloth to remove fibrous matter. The filtrate was left undisturbed for 12 h to facilitate starch sedimentation, after which the supernatant was carefully decanted. The settled starch was dried in a hot air oven at 50 °C for 6 h. The dried starch was grounded into a fine powder and stored in polyethylene bags until further use for film preparation.

2.3 Preparation of arrowroot starch films

Fig. 1 shows the flow chart for preparation of arrowroot film with glycerol. The arrowroot starch 5, 10, 15, 20, and 25% w/w was dispersed in 100 mL of distilled water containing 10 mL of 0.1 N acetic acid to obtain a uniform suspension. Glycerol was incorporated at different concentrations 8, 9, 10, 11 and 12 ml, and the mixture was stirred for 5 min to ensure proper mixing. The suspension was heated in a water bath maintained at 90 ± 2 °C for 20 min with continuous stirring. Since the gelatinization temperature of arrowroot starch is above 70 °C, stirring was continued for 3-5 min after the temperature of the film-forming solution reached approximately 70 °C to achieve complete gelatinization and obtain a homogeneous gel. In table 1. shows the treatment combination for arrowroot starch with glycerol concentration.

The gelatinized solution was cooled to approximately 50 °C and subsequently placed in a vacuum desiccator for 30 min to eliminate entrapped air bubbles. The degassed solution was manually poured into silicone moulds to obtain films of approximately 1-3 mm thickness and dried in a hot air oven at 50 °C for 24 h. The dried films were carefully removed from the moulds and conditioned in desiccators containing a saturated magnesium nitrate [$Mg(NO_3)_2$] solution at 53 ± 1% relative humidity and 25 ± 1 °C for its storage. All experiments were conducted in triplicate. Fig. 2, Fig. 3, Fig. 4, Fig. 5 and Fig. 6 show the images of film sample having a concentration of starch: glycerol is 5:8; 10:9; 15:10; 20:11 and 25:12 respectively.

Arrowroot starch (5, 10, 15, 20 and 25% w/w) + Acetic acid (0.1 N, 10 mL) + Distilled water (100 mL)

↓

Stirring (5 min)

↓

Formation of a uniform suspension

↓

Addition of glycerol according to the respective treatments (8, 9, 10, 11 and 12% w/w of starch)

↓

Heating in a water bath maintained at 90 ± 2 °C for 20 min with continuous stirring

↓

Gelatinization of the suspension by stirring for 3–5 min after the solution temperature reached approximately 70 °C

↓

Formation of a homogeneous milky gel

↓

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Cooling of the film-forming solution to 50 °C
↓
Degassing in a vacuum desiccator for 30 min
↓
Manual casting into silicone moulds (1–3 mm thickness)
↓
Drying at 50 °C for 24 h
↓
Peeling of the dried films
↓
Conditioning and storage at 53 ± 1% RH and 25 ± 1 °C in desiccators containing saturated magnesium nitrate [$Mg(NO_3)_2$] solution

Figure 1. Flow Chart of Preparation of Arrowroot film

Table 1. Arrowroot starch films with Glycerol

Treatments	Ingredients			
	Arrowroot starch (%)	Distilled water (ml)	Glycerol (%)	Acetic acid 0.1N (%)
T1	5	100	8	10
T2	10	100	9	10
T3	15	100	10	10
T4	20	100	11	10
T5	25	100	12	10

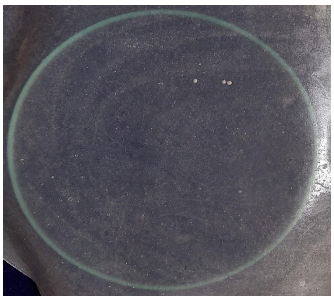


Fig. 2: Arrowroot starch (5%) film

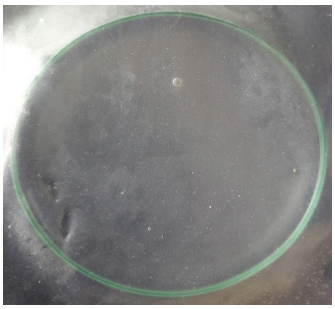


Fig. 3: Arrowroot starch (10%) film

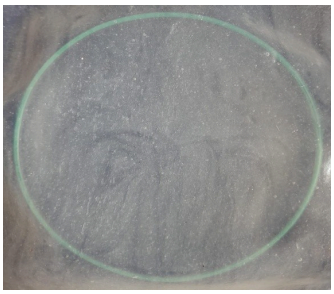


Fig. 4: Arrowroot starch (15%) film

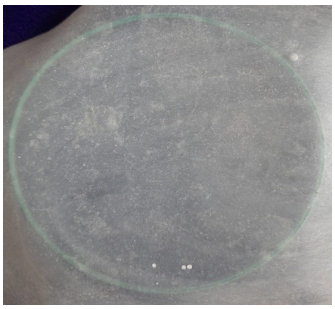


Fig. 5: Arrowroot starch (20%) film

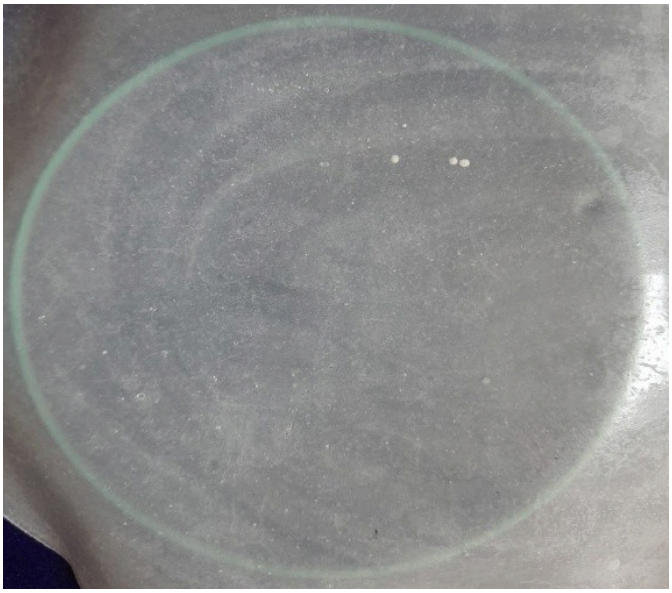


Fig. 6: Arrowroot starch (25%) film

2.4 Quality parameters of developed film

2.4.1 Film thickness

The thickness of arrowroot starch films prepared with different Arrowroot starch to glycerol concentrations (5:8; 10:9; 15:10; 20:11 and 25:12) was determined according to the method described by Sarmah *et al.* (2015) [14]. Film thickness was measured using a digital Vernier caliper (least count: 0.01 mm). the thickness of each film was measured at five different locations, one at the centre and four at points around the periphery of the film. The average of the five readings was recorded and expressed in millimetres (mm). All measurements were performed in triplicate, and the mean values were reported.

2.4.2 Tensile strength and percentage elongation

The tensile strength and percentage elongation at break of arrowroot starch films prepared with different Arrowroot starch to glycerol concentrations (5:8; 10:9; 15:10; 20:11 and 25:12) were determined according to the method described by Sarmah *et al.* (2015) [14] using a Tinius Olsen Universal Testing Machine Model - 50 ST having load cell capacity 50kN. Film specimens measuring 100 mm × 15 mm were used for the analysis. The specimens were mounted between the upper and lower jaws of the testing machine, and the tests were performed at an initial gauge length of 100 mm and a crosshead speed of 50 mm min^{-1}. A tensile load was continuously applied until the film samples ruptured, and the corresponding stress and extension were recorded throughout the test. The tensile strength and percentage elongation at break (EAB) were obtained directly from the instrument and expressed in megapascals (kgf) and percentage (%), respectively. All measurements were carried out in triplicate, and the mean values were reported.

Tensile Strength = $\frac{F}{A}$ … (1)

Where,

F = Force (1 kgf = 9.80665 N)

A = Area (mm^2)

2.4.3 Film solubility

The solubility of arrowroot starch films prepared with different Arrowroot starch to glycerol concentrations (5:8; 10:9; 15:10; 20:11 and 25:12) was determined by the gravimetric method described by Colla *et al.* (2006) [18]. Film samples measuring 25 mm × 25 mm were initially weighed using an analytical balance and immersed in 20 mL of distilled water contained in 50 mL screw-capped test tubes. The tubes were tightly sealed and maintained at room temperature (23 ± 1 °C) for 24 h. After the immersion period, the contents were filtered through Whatman No. 1 filter paper to recover the undissolved film residue. The retained residue was subsequently dried in a hot air oven at 70 °C for 4 h and weighed again. The film solubility was calculated as the percentage of dry matter dissolved in water using the

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following equation (2): All the measurements were performed in triplicate and the mean value were reported.

Film Solubility (%) = $\frac{FB - FA}{FB} \times 100$ … (2)

Where:

F_B = initial mass of film

F_A = mass of dried residue

2.4.4 Film transparency

The transparency of arrowroot starch to glycerol films prepared by incorporating 5, 10, 15, 20 and 25 % (w/v) arrowroot starch with corresponding 8, 9, 10, 11 and 12 mL of glycerol concentration was determined according to the method described by Han *et al.* (1997) [19]. Rectangular film specimens measuring 4 cm × 1 cm were placed vertically in the cuvette of a UV Visible spectrophotometer. The percentage transmittance of the films was recorded at a wavelength of 600 nm. The thickness of each film was measured prior to the analysis and used for the calculation of transparency. Film transparency was calculated using the following equation (3): All the measurements were performed in triplicate and the mean value were reported.

Transparency = $\frac{\log(T\%)}{b}$ … (3)

Where:

($T^{\%}$) = The light transmittance %

b = The thickness of film (mm)

2.4.5 Water vapour permeability (WVP)

The water vapour permeability (WVP) of arrowroot starch films Arrowroot starch to glycerol concentrations (5:8; 10:9; 15:10; 20:11 and 25:12) was determined by the dry cup method following ASTM E96/E96M (2016) [20] and the procedure reported by Sothornvit *et al.* (2000) [21]. Circular film samples were sealed over the mouth of Petri plates containing silica gel as the desiccant (0% RH). The Petri plates were then placed in desiccators maintained at 53 ± 1% relative humidity using a saturated magnesium nitrate [$Mg(NO_3)_2$] solution at 25 ± 1 °C, thereby creating a water vapour pressure gradient across the film.

The Petri plates were weighed at 12 hour intervals, and the increase in weight due to moisture permeation through the film was recorded until a linear relationship between cumulative weight gain and time was obtained. The water vapour transmission rate (WVTR) was calculated from the slope of the linear regression plot of cumulative weight gain versus time divided by the exposed film area. The water vapour permeability (WVP) was subsequently calculated by multiplying the WVTR by the average film thickness and dividing by the water vapour pressure difference across the film.

The calculations were performed using the following equations:

Using linear regression for these points: $W = mt + c$

Where, W = Weight; m = Slope of the line; t = Time; C = Intercept

Rate of weight gain with respect to time is: $\frac{\Delta W}{\Delta t}\ g/day\ = slope\ g/day$ … (4)

Calculate WVTR from slope: $WVTR = \frac{slope}{Area}\ g/m^2day$ … (5)

Area = $\pi r^2\ m^2$

Where,

A = Surface area exposed to water, m^2

r = Radius of petri dish, m

Water vapour permeability (WVP) $WVP = \frac{WVTR \times X}{\Delta P}\ g.\ m^{-1}day^{-1}Pa^{-1}$

Where,

WVTR = Water Vapour Transmission Rate

Δw = Change in Weight

Δt = Change in Time

x = Average film thickness

ΔP = Water vapour pressure difference across the film

2.4.6 Printability

Printability of the bioplastic film was evaluated by using a standard manual printing machine. The prepared film sample was placed in the machine, and a simple text or pattern was printed using water-based ink. The clarity, sharpness, and uniformity of the printed image was visually inspected after drying to determine the films suitability for printing.

2.4.7 Sealing ability

Sealing ability was tested using an impulse heat-sealing machine. Two film strips 15 × 10 cm was overlapped and sealed at a fixed temperature, pressure, and time. The quality of the seal was checked by gently pulling the films apart manually; a strong, continuous seal without tearing or separation indicated good sealing performance.

3. Results and discussion

Table 2. ANOVA for Physico mechanical properties of Arrowroot starch films containing glycerol as a plasticizer

Treatments	Properties of Arrowroot starch film					
	(a) Film Thickness (mm)	(b) tensile strength (MPa)	(c)elongation at break (%)	(d) Film Solubility (%)	(e) Film transparency	(f) WVP (g m^{-1} s^{-1} Pa^{-1})
T1	0.277 ± 0.015	1.904 ± 0.034	55.700 ± 1.572	64.223 ± 1.326	4.913 ± 0.040	4.572×10^{-11} ±0.279
T2	0.327 ± 0.015	2.913 ± 0.075	45.147 ± 2.405	53.817 ± 1.459	2.793 ± 0.035	3.507×10^{-11} ±0.225
T3	0.430 ± 0.020	3.304 ± 0.009	38.327 ± 2.225	48.070 ± 1.120	1.503 ± 0.015	3.283×10^{-11} ±0.214
T4	0.593 ± 0.015	3.714 ± 0.277	29.787 ± 1.941	43.413 ± 1.875	0.903 ± 0.025	2.845×10^{-11} ±0.192
T5	0.673 ± 0.021	4.501 ± 0.045	25.367 ± 1.305	37.860 ± 0.243	0.639 ± 0.014	1.800×10^{-11} ±0.140
SE	0.0112	0.0728	1.1761	0.8399	0.0179	0.0291
CD	0.0364	0.2362	3.8156	2.7249	0.0581	0.0945

Significant ($p \leq 0.05$) (T1 = 5% w/v; T2 = 10% w/v; T3 = 15% w/v; T4 = 20% w/v; T5 = 25% w/v.

3.1 Film thickness

Fig. 7 shows the effect of arrowroot starch concentration on the thickness of the developed films. The thickness of arrowroot starch films prepared with 5, 10, 15, 20 and 25% w/v starch concentrations was found to be 0.277 ± 0.015, 0.327 ± 0.015, 0.430 ± 0.020, 0.593 ± 0.015 and 0.673 ± 0.021 mm, respectively. Film thickness ranged from 0.372 ± 0.03 to 0.762 ± 0.05 mm. The lowest thickness was observed at 5% w/v starch, while the highest was recorded at 25% w/v starch. Table 2. (a) shows ANOVA results and indicated that the effect of starch concentration on film thickness was significant at $p \leq 0.05$. A polynomial relationship was observed between arrowroot starch concentration and film thickness with $R^2 = 0.9811$, Equation 6. shows the relationship between the incorporation of Arrowroot starch on the film thickness.

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$$FT = 0.0003x^2 + 0.0109x + 0.2026, R^2 = 0.9811 \quad (6)$$

Where,
F_{TCS} = film thickness in mm,
x = arrowroot starch concentration % w/v.

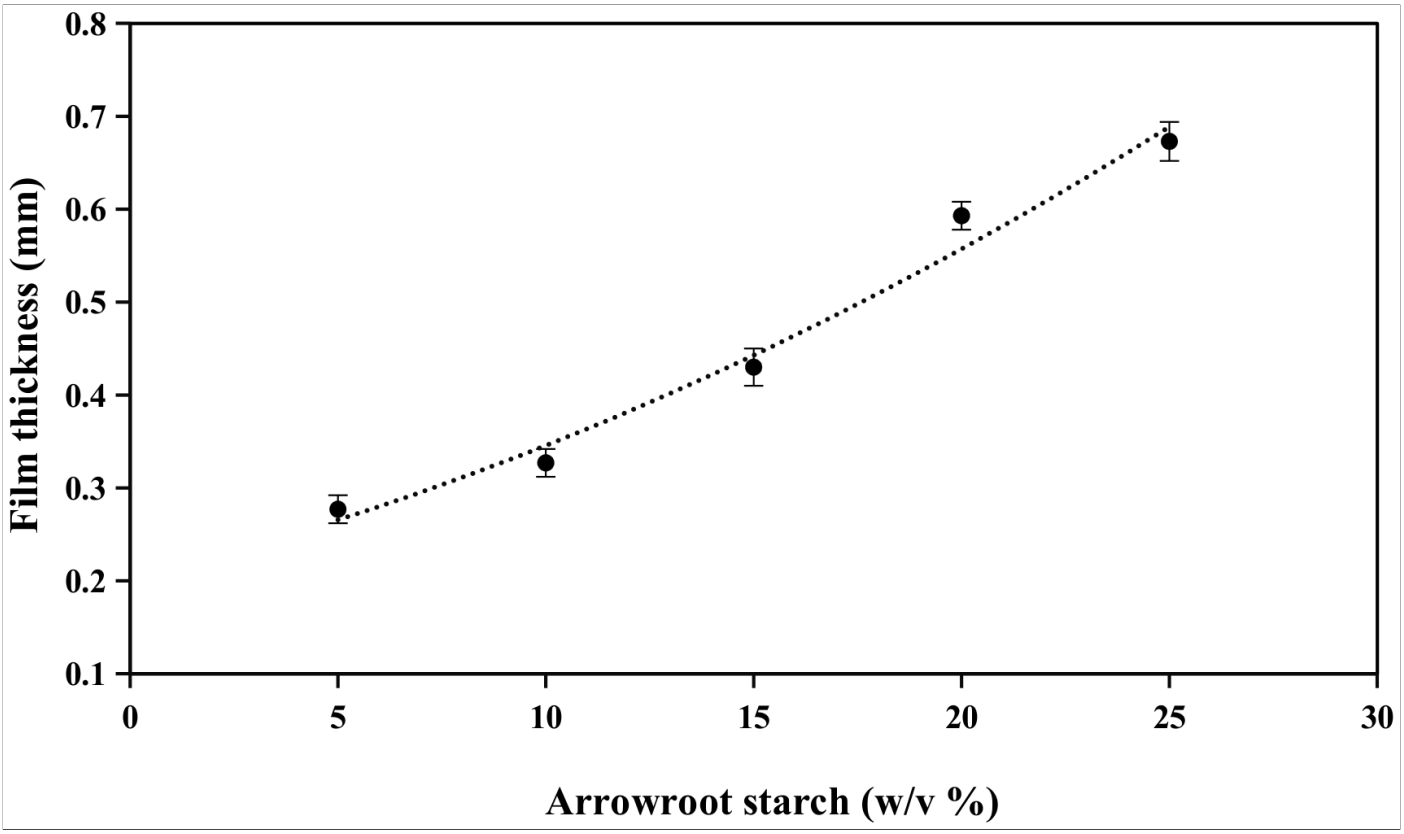


Figure 7. Effect of incorporation of Arrowroot starch on the thickness of film

The increase in film thickness with increasing starch concentration can be attributed to higher total solids in the film-forming solution. At higher starch levels, more polymeric material was deposited per unit area during casting and drying, resulting in thicker films. A denser and more compact matrix formed due to increased starch interactions. Oliveira *et al.* (2021) [22] observed that arrowroot starch film thickness increased from 0.029 ± 0.010 mm to 0.101 ± 0.014 mm when starch concentration was increased from 1% to 5% (w/v). Nogueira *et al.* (2021) [23] reported arrowroot starch film thicknesses ranging from 0.026 ± 0.008 mm to 0.082 ± 0.011 mm, depending on starch and glycerol concentrations. Hundekari *et al.* (2024) [15] also reported that the thickness of cassava starch films increased (0.372 ± 0.03 mm, 0.584 ± 0.08, 0.646 ± 0.05, 0.718 ± 0.03 and 0.762 ± 0.05 mm) significantly with increasing starch concentration from 5%, 10%, 15%, 20% and 25% (w/v).

Fig. 8 shows the effect of arrowroot starch concentration on tensile strength of the developed films. The tensile strength of arrowroot starch films prepared with 5, 10, 15, 20 and 25% w/v starch concentrations was found to be 1.904 ± 0.034, 2.913 ± 0.075, 3.304 ± 0.009, 3.714 ± 0.277 and 4.501 ± 0.045 MPa, respectively. Tensile strength ranged from 1.904 ± 0.034 to 4.501 ± 0.045 MPa. The lowest tensile strength was observed at 5% w/v starch, while the highest was recorded at 25% w/v starch. Table 2. (b) shows ANOVA results and indicated that starch concentration had a significant effect on tensile strength $p \leq 0.05$. A polynomial relationship was observed between arrowroot starch concentration and tensile strength with R^2 = 0.973, Equation 7. shows the relationship between the incorporation of Arrowroot starch and tensile strength

$$TS = -0.0012x^2 + 0.156x + 1.2562, R^2 = 0.973 \quad (7)$$

Where,
TS = tensile strength in MPa
x = arrowroot starch concentration % w/v
The increase in tensile strength with starch concentration is attributed to formation of a denser polymer network with increased intermolecular hydrogen bonding between amylose and amylopectin chains. At higher starch levels, more polymer chains per unit volume increased cohesive strength and resistance to tensile stress.
Tarique *et al.* (2021) [24] reported tensile strength values ranging from 1.95 to 9.34 MPa for arrowroot starch films plasticized with different glycerol concentrations. Tarique *et al.* (2022) [25] reported a tensile strength of 2.42 MPa for the control arrowroot starch film, which increased after reinforcement with arrowroot fibres due to improved stress transfer within the film matrix. Hundekari *et al.* (2024) [15] reported that the tensile force of cassava starch films prepared with 5, 10, 15, 20 and 25% w/v starch, glycerol, sorbitol and acetic acid decreased from 63.40 ± 5.08 N, 40.84 ± 3.37 N, 31.85 ± 1.01 N, 26.10 ± 0.75 N and 14.62 ± 2.03 N respectively.

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3.2 Tensile strength

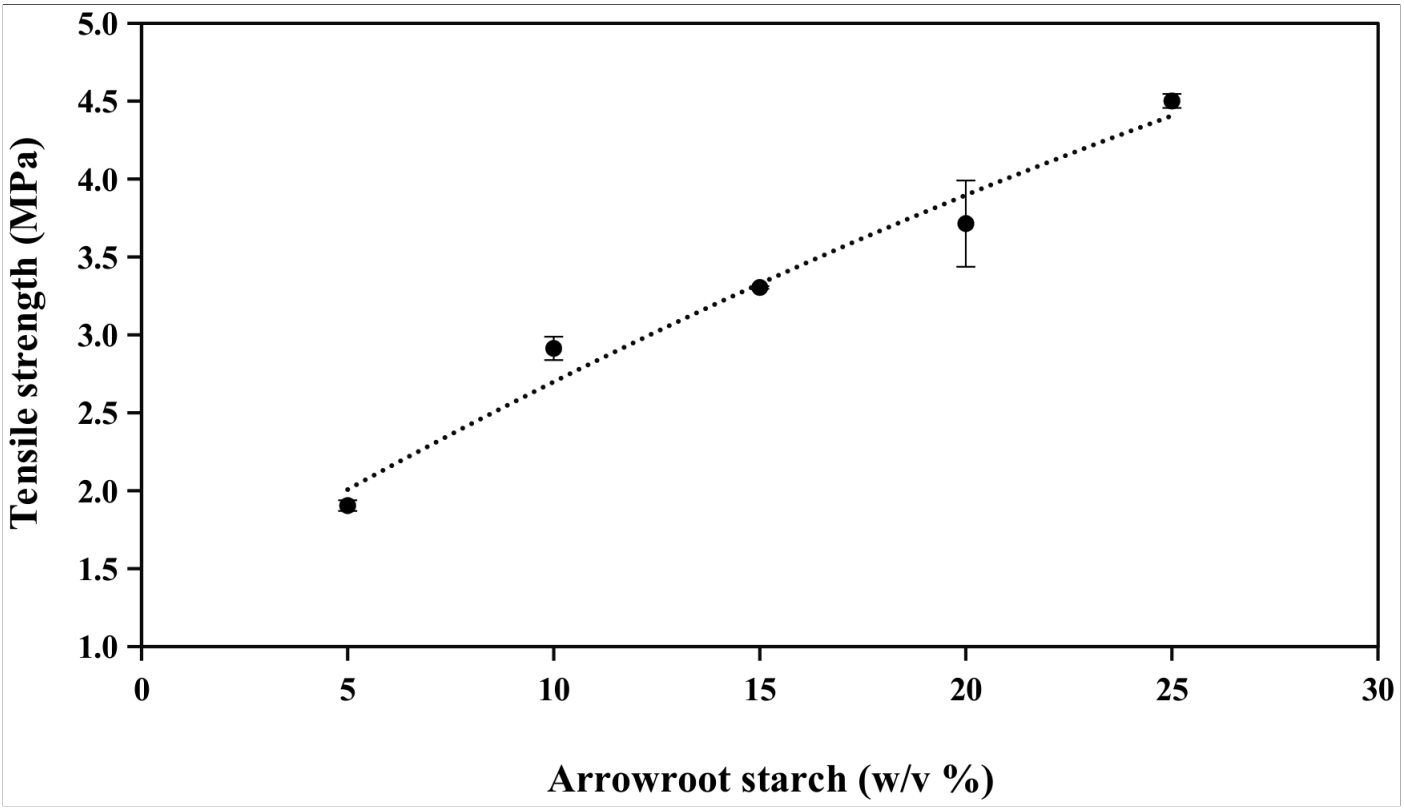


Figure 8. Effect of incorporation of Arrowroot starch on the Tensile strength of film

3.3 Elongation at break

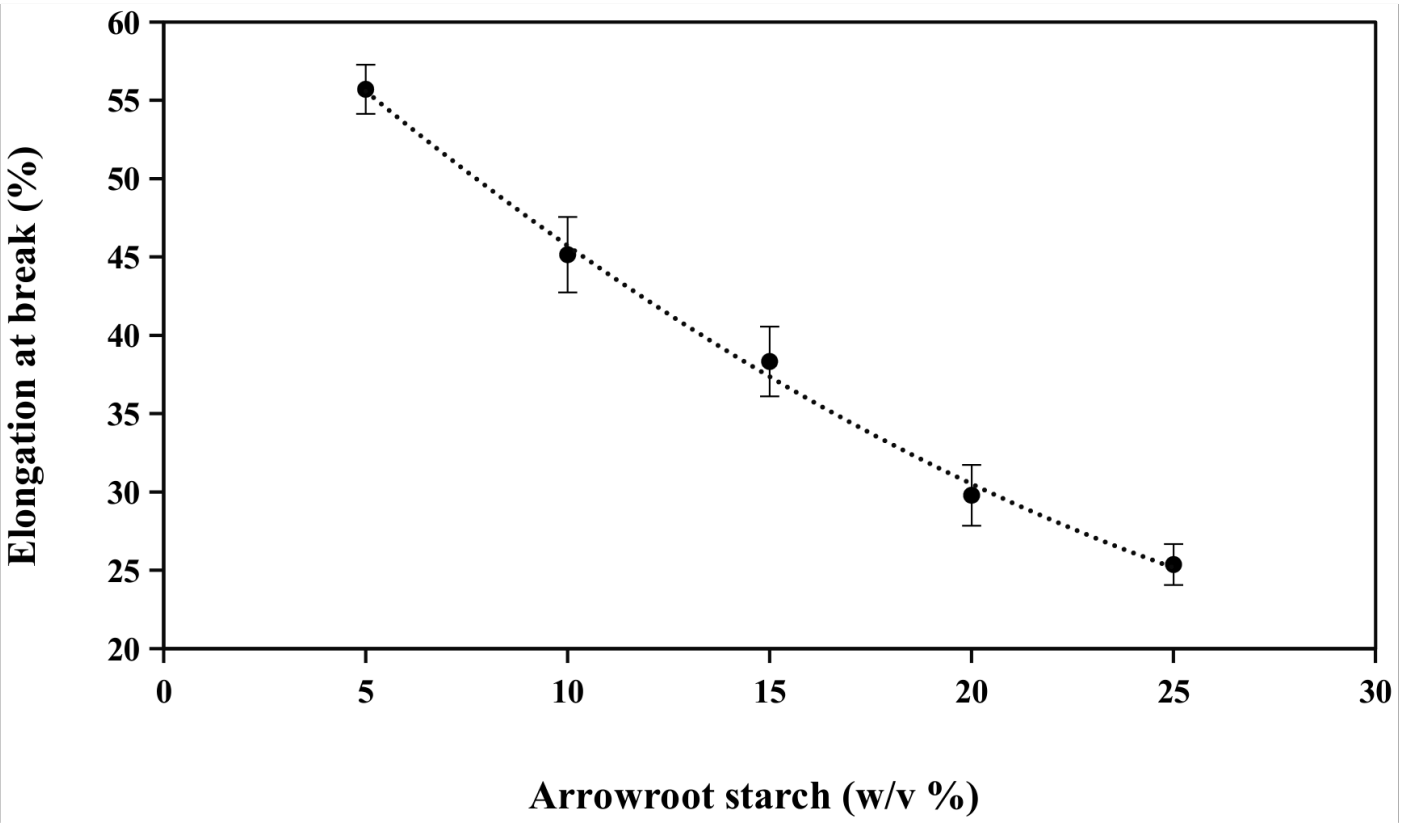


Figure 9. Effect of incorporation of Arrowroot starch on the elongation at break of film

Fig. 9 shows the effect of arrowroot starch concentration on elongation at break of the developed films. The elongation at break of arrowroot starch films prepared with 5, 10, 15, 20 and 25% w/v starch concentrations was found to be 55.700 ± 1.572, 45.147 ± 2.405, 38.327 ± 2.225, 29.787 ± 1.941 and 25.367 ± 1.305%, respectively. Elongation at break ranged from 55.700 ± 1.572 to 25.367 ± 1.305%. The highest elongation was observed at 5% w/v starch, while the lowest was recorded at 25% w/v starch. Table 2. (c) shows ANOVA re

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sults and indicated that starch concentration had a significant effect on elongation at break $p \leq 0.05$. A polynomial relationship was observed between arrowroot starch concentration and elongation at break with $R^2 = 0.9969$, Equation 8. shows the relationship between the incorporation of Arrowroot starch and elongation at break.

$$EB = 0.0301x^2 - 2.4245x + 66.946, R^2 = 0.9969 \quad (8)$$

Where,
EB = elongation at break in %
x = arrowroot starch concentration % w/v
The decrease in elongation at break with increasing starch concentration is attributed to reduced mobility and increased rigidity of polymer chains. Higher starch content increased starch interactions and reduced free volume, making films less extensible. With variable glycerol concentration, the plasticizing effect per unit starch decreased, causing brittle behaviour.

Tarique *et al.* (2021) [24] reported that elongation at break of arrowroot starch films increased from 2.41% to 57.33% as plasticizer increased and matrix became flexible. Tarique *et al.* (2022) [25] observed that control arrowroot starch films showed 46.62% elongation which decreased to 6.21% with fiber reinforcement due to reduced chain mobility. Hundekari *et al.* (2024) [15] reported that 113.76 ± 40.50%, 108.02 ± 11.46, 86.55 ± 17.54, 72.52 ± 16.15 and 58.86 ± 11.13 significantly with increasing starch concentration from 5%, 10%, 15%, 20% and 25% (w/v).

3.4 Film solubility

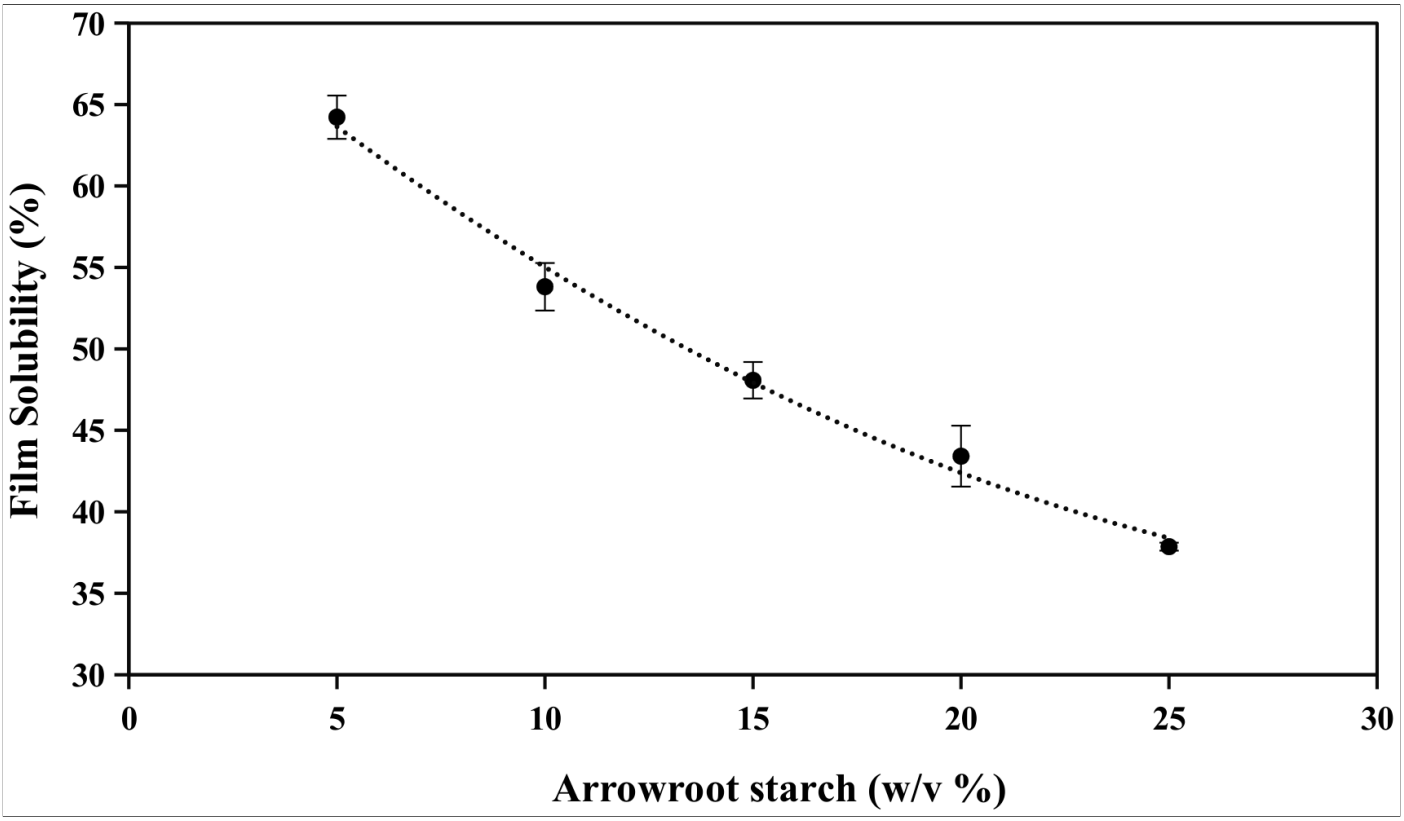


Figure 10. Effect of incorporation of Arrowroot starch on the solubility of film

Fig. 10 shows the effect of arrowroot starch concentration on film solubility of the developed films. The film solubility of arrowroot starch films prepared with 5, 10, 15, 20 and 25% w/v starch concentrations was found to be 64.223 ± 1.326, 53.817 ± 1.459, 48.070 ± 1.120, 43.413 ± 1.875 and 37.860 ± 0.243 % respectively. Film solubility ranged from 64.223 ± 1.326 to 37.860 ± 0.243 %. The highest film solubility was observed at 5% w/v starch, while the lowest was recorded at 25% w/v starch. Table 2 (d) shows ANOVA results and indicated that the effect of starch concentration on film solubility was significant at $p \leq 0.05$. A polynomial relationship was observed between arrowroot starch concentration and film solubility with $R^2 = 0.9924$, Equation 9. shows the relationship between the incorporation of Arrowroot starch and the film solubility.

$$FS = 0.0308x^2 - 2.188x + 73.814, R^2 = 0.9924 \quad (9)$$

Where,
FS = film solubility %
x = arrowroot starch concentration % w/v
The decrease in film solubility with increasing starch concentration is attributed to formation of a compact polymer network with enhanced amylose interactions. High amylose promotes linear chain alignment and stronger intermolecular hydrogen bonding, resulting in a denser matrix with reduced free hydroxyl groups available for water interaction. With glycerol concentration held variation in this study, its hydrophilic contribution was diluted by higher starch content, leading to reduced solubility.
The solubility range obtained in this study reported for glycerol plasticized arrowroot starch films. Tarique *et al.* (2021) [24] reported that arrowroot starch films plasticized with 15, 30 and 45% glycerol exhibited water solubility values of 14.86%, 22.43% and 29.50%, respectively, indicating that film solubility increased with increasing glycerol concentration due to the hydrophilic nature of glycerol. Basiak *et al.* (2017) [26] reported water solubility values of 14.52%, 30.16% and 44.76% for potato, wheat and corn starch films, respec

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tively. Hundekari *et al.* (2024) [15] also reported that the water solubility of cassava starch films 5, 10, 15, 20 and 25% w/v starch increased from 37.99 ± 4.24%, 40.81 ± 4.64%, 42.30 ± 5.59%, 47.74 ± 4.39% and 54.27 ± 1.26 % respectively.

3.5 Film transparency

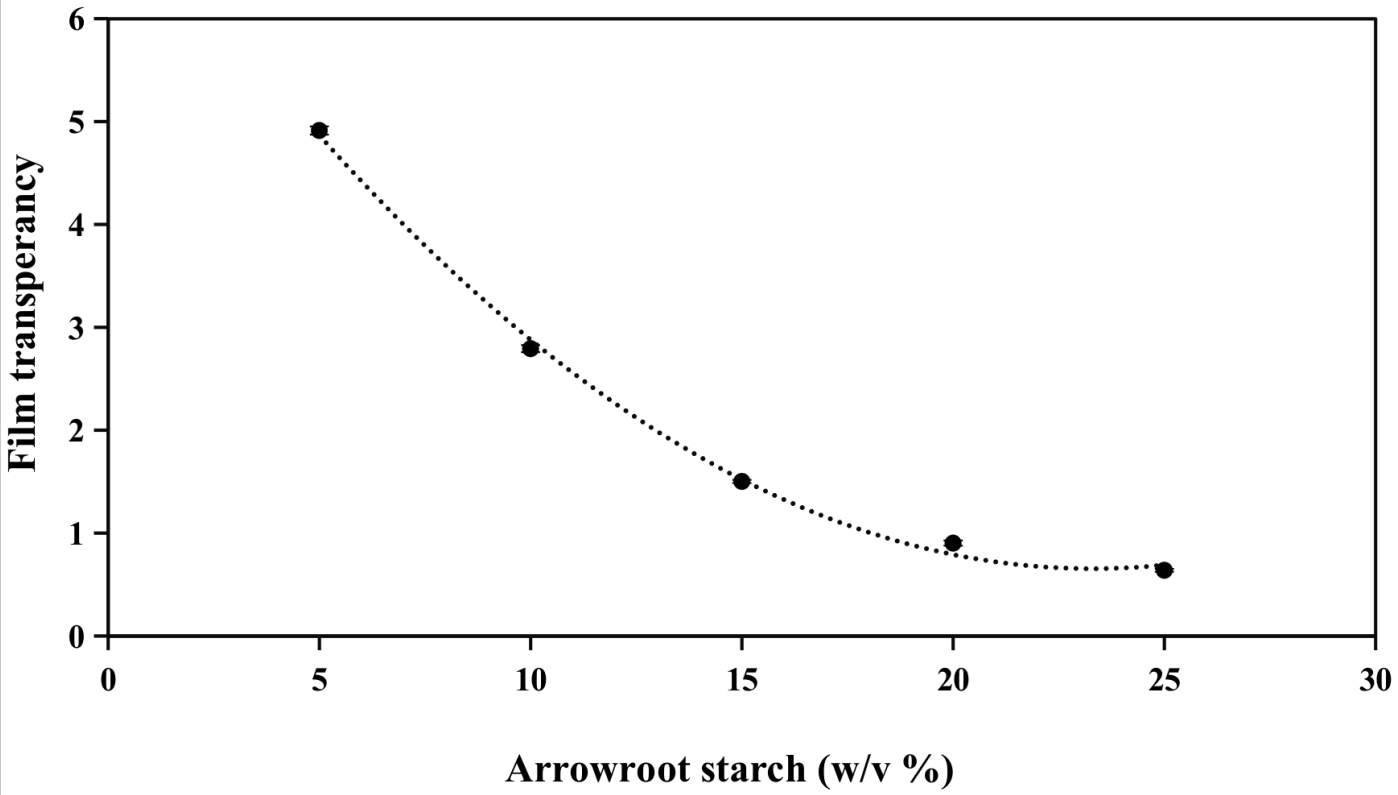


Figure 11. Effect of incorporation of Arrowroot starch on the Transparency of film

Fig. 11 shows the effect of arrowroot starch concentration on transparency of the developed films. Transparency of arrowroot starch films was determined as the ratio of transmittance at 600 nm to film thickness, where higher values indicate greater transparency. Films prepared with 5, 10, 15, 20 and 25% w/v starch concentrations exhibited transparency values of 4.913 ± 0.040, 2.793 ± 0.035, 1.503 ± 0.015, 0.903 ± 0.025 and 0.639 ± 0.014 respectively. Film transparency ranged from 4.913 ± 0.040 to 0.639 ± 0.014. The highest transparency was observed at 5% w/v starch, while the lowest was recorded at 25% w/v starch. Table 2 (e) shows ANOVA results and indicated that the effect of starch concentration on film transparency was significant at $p \leq 0.05$. A logarithmic relationship was observed between arrowroot starch concentration and film transparency with $R^2 = 0.998$, Equation 10. shows the relationship between the incorporation of Arrowroot starch and the film transparency.

$$\text{FTA} = 0.0126x^2 - 0.5861x + 7.4826, R^2 = 0.998 \quad (10)$$

Where,
FTA = film transparency and
x = arrowroot starch concentration % w/v
The transparency of biodegradable films decreased with increasing starch concentration due to the formation of a thicker and denser polymer matrix, which reduced light transmission through the film. Higher starch content increases the amount of solid material and promotes stronger intermolecular hydrogen bonding, resulting in greater light scattering and lower transparency. Similar findings have been reported in previous studies. Hundekari *et al.* (2024) [15] reported that cassava starch films containing 5%, 10%, 15%, 20% and 25% (w/v) starch with glycerol, sorbitol and acetic acid showed a decrease in transparency from 4.80 ± 0.51, 2.89 ± 0.56, 2.44 ± 0.30, 1.95 ± 0.10 and 1.05 ± 0.16 as starch concentration increased from 5% to 25% (w/v). Formulation and Characterization of Starch Based Novel Biodegradable Edible Films for Food Packaging (2023) reported transparency values ranging from 0.816 ± 0.007 to 2.685 ± 0.026 (A_{550}/mm) for starch-based edible films prepared from arrowroot powder, corn starch and wheat flour plasticized with glycerol, demonstrating that film transparency was significantly influenced by formulation composition and film thickness.

3.6 Water vapour permeability

Fig. 12 shows the effect of incorporation of arrowroot starch (5%, 10%, 15%, 20% and 25% w/v) on the water vapour permeability of developed film. Water vapour permeability of arrowroot starch films ranged from 4.572×10^{-11} ±0.279 to 1.800×10^{-11} ±0.140 g/m·s·Pa. The water vapour permeability of arrowroot starch films of 5%, 10%, 15%, 20% and 25% concentrations were 4.572×10^{-11}±0.279, 3.507×10^{-11} ±0.225, 3.283×10^{-11} ±0.214, 3.283×10^{-11} ±0.214 and 1.800×10^{-11} ±0.140 g/m·s·Pa respectively. Table 1 (f) shows the ANOVA for the water vapour permeability of the arrowroot starch edible film. Decrease in water vapour permeability with respect to increase in incorporation of starch (5% to 25% w/v) was significant at $p \leq 0.05$. Effect of incorporation of arrowroot starch with respect to the water vapour permeability indicated that there is logarithmic relationship with $R^2 = 0.9469$. Equation 11 shows the relationship between the incorporation of arrowroot starch and the water vapour permeability. Films at 5, 10, 15, 20 and 25 % were significant at $p \leq 0.05$.

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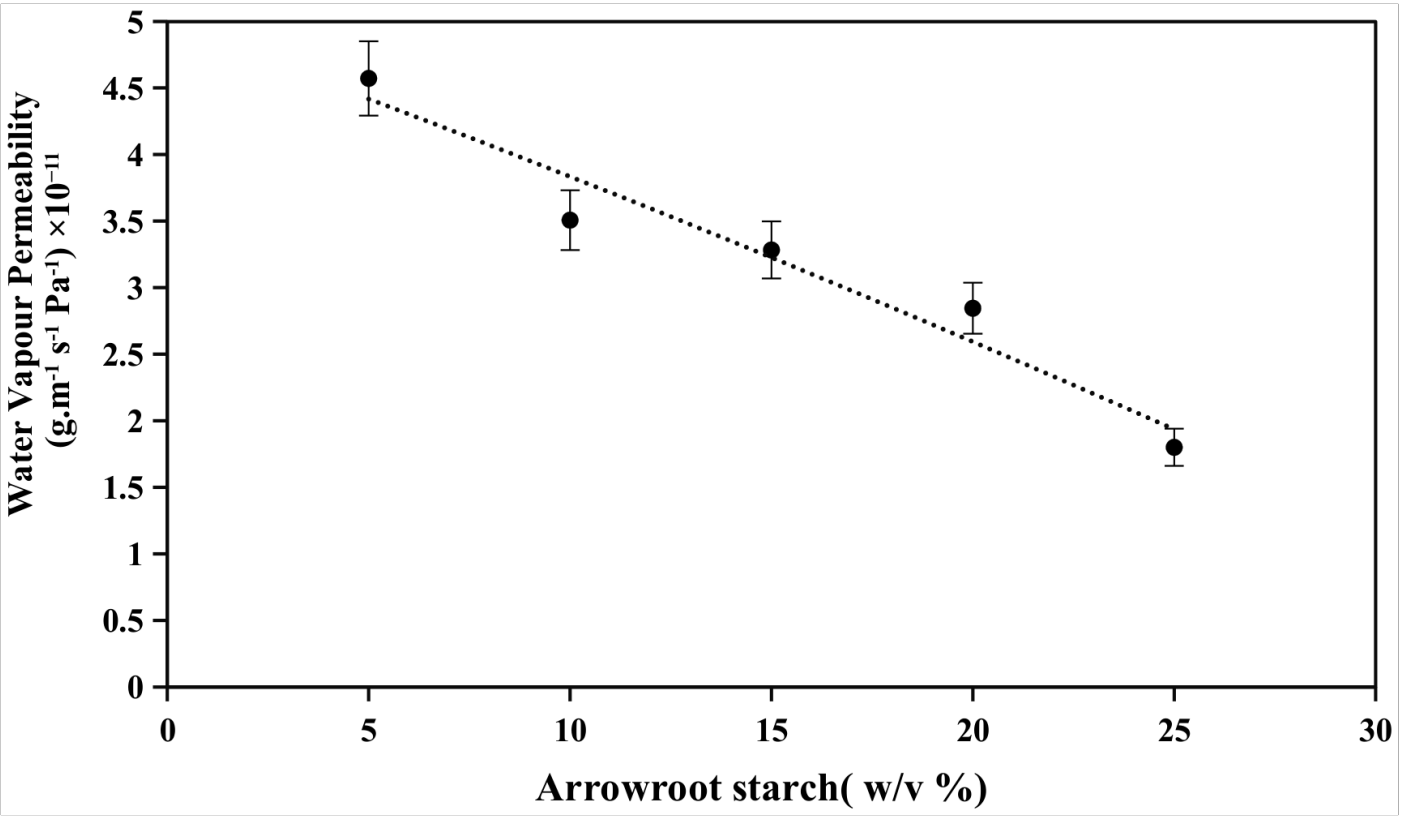


Figure 12. Effect of incorporation of Arrowroot starch on the WVP of film

$$\text{WVPA} = -0.0005x^2 - 0.1092x + 4.9762, R^2 = 0.9469 \quad (11)$$

Where,
WVPA = water vapour permeability g/m·s·Pa
x = arrowroot starch concentrations (w/v)
The significant decrease in WVP observed with increasing starch content is attributed to formation of a more compact and dense polymer matrix with reduced free volume. Arrowroot starch contains high amylose content of 23.5% as reported by Nuwamanya *et al.* (2010) [27]. High amylose promotes linear chain alignment and strong intermolecular hydrogen bonding, resulting in a tortuous path for water vapour diffusion.
Tarique *et al.* (2021) [24] reported WVP values ranging from 5.94 × 10^{-9}, 9.45 × 10^{-9}, 10.83 × 10^{-9} g m^{-1} s^{-1} Pa^{-1} for arrowroot starch films plasticized with 15, 30 and 45% (w/w) glycerol, where WVP increased with increasing glycerol concentration due to the hydrophilic nature of glycerol. Nogueira *et al.* (2021) [23] investigated arrowroot starch edible films prepared with different starch and glycerol concentrations and reported WVP values in the order of 10^{-10} to 10^{-9} g m^{-1} s^{-1} Pa^{-1}, indicating that film formulation significantly affected moisture barrier properties. Hundekari *et al.* (2024) [15] reported that cassava starch films containing 5%, 10%, 15%, 20% and 25% (w/v) starch with glycerol, sorbitol and acetic acid exhibited WVP values (0.144 ± 0.015, 0.116 ± 0.006, 0.108 ± 0.007, 0.097 ± 0.005 and 0.081 ± 0.005 g/m^2.hr) with WVP decreasing as starch concentration increased because of the formation of a more compact and less permeable polymer matrix.

3.7 Printability and sealing ability

Table 3. Effect of arrowroot starch concentration and glycerol on printability and sealing ability of arrowroot starch films.

Starch % w/v	Printability	Sealing ability
5	Moderate	Yes
10	Good	Yes
15	Good	Moderate
20	Moderate	No
25	Moderate	No

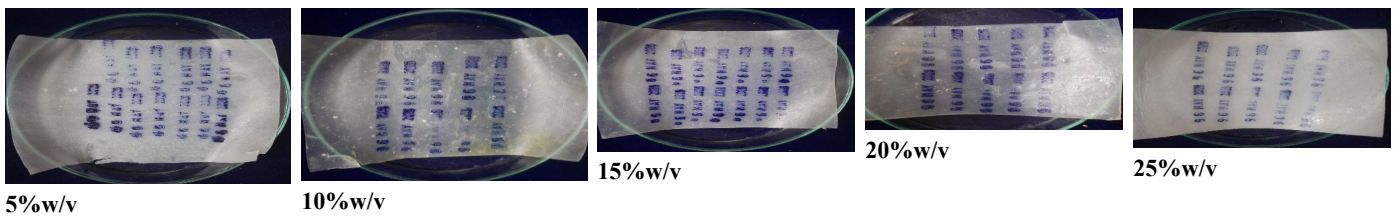


Figure 13. Effect of printing on various concentration of films

The printability of arrowroot starch films was influenced by starch concentration and glycerol concentration. Films prepared with 5% w/v starch exhibited moderate printability due to low solid content, resulting in a thin and porous matrix. This porous structure promoted ink spreading and reduced print sharpness. At 10-15% w/v starch, the films formed a smoother and more compact matrix with optimal solid-plasticizer balance. This improved surface morphology enhanced ink adhesion and produced clearer printed characters. At 20-25% w/v starch, the films became denser due to higher starch content and relatively lower plasticizing effect of glycerol. The increased matrix density and surface rigidity reduced ink spreading, resulting in moderate printability.
Sealing ability of arrowroot starch films was also affected by starch concentration. Films prepared with 5-10% w/v starch showed satisfactory sealing performance due to adequate chain mobility provided

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by higher plasticizer content relative to starch. The flexible matrix allowed effective molecular diffusion at the heat seal interface. At 15% w/v starch, sealing ability became moderate as increasing starch content raised matrix density and reduced chain mobility. At 20-25% w/v starch, the films became denser and more rigid because of increased starch content and the relatively lower plasticizing effect of glycerol. The reduced chain mobility during heat sealing limited molecular interaction at the seal interface, leading to poor sealing performance.

4. Optimum product quality based on desirable properties

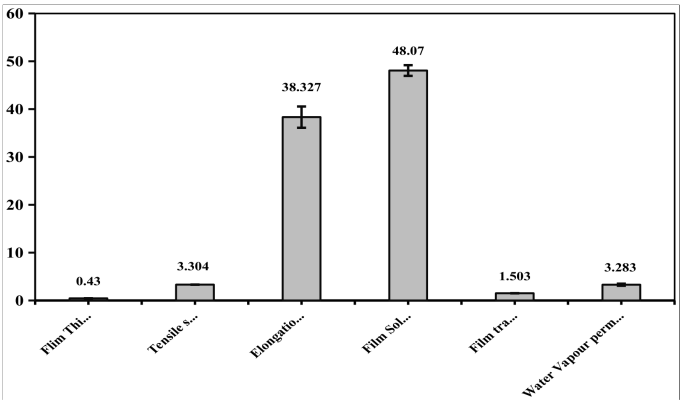


Figure 4.26. Effect of arrowroot starch: glycerol (15: 10) film formulation on desirable film quality properties

Based on these desirable characteristics, the arrowroot starch film prepared with 15% (w/v) starch concentration exhibited the most favourable overall performance among the treatments evaluated. The film thickness of this treatment was 0.430 ± 0.020 mm, indicating the formation of a thin and reasonably uniform film matrix. The tensile strength and percentage elongation at break were 3.304 ± 0.009 MPa and 38.327 ± 2.225 %, respectively, demonstrating a suitable combination of strength and flexibility required for packaging applications. The film exhibited a solubility of 48.070 ± 1.120 %, suggesting acceptable resistance to water-induced dissolution while maintaining its biodegradable nature. The transparency value of 1.503 ± 0.015 indicated satisfactory optical clarity and product visibility. Furthermore, the water vapour permeability of 3.283×10^{-11} ±0.214 g/m^{-1} s^{-1} Pa^{-1} reflected adequate barrier properties against moisture transfer. Considering the overall balance of physical, mechanical, optical, and barrier properties, the film prepared with 15% (w/v) arrowroot starch was identified as the optimum formulation for the development of biodegradable films.

5. Cost economics of the optimum arrowroot starch film

The economics of the developed biodegradable arrowroot starch film were estimated considering the market price of raw materials and the operational expenses involved in film production. The cost analysis included arrowroot starch, glycerol, acetic acid, electricity, labour and other miscellaneous expenses, whereas the silicone mould was considered a reusable laboratory accessory and only its depreciation cost was included. The optimum film formulation consisted of 15% (w/v) arrowroot starch plasticized with glycerol. Each film was cast in a silicone mould of 15 × 10 cm dimensions and had an average dry weight of approximately 7.5-8.0 g. Based on the formulation and theoretical material balance, about 133 films of the above dimensions could be prepared from 1 kg of arrowroot starch. The detailed cost economics of the developed film are presented in Table 4. The estimated production cost was ₹17.52 per film, indicating that the developed arrowroot starch film can be produced economically and has good potential for application as an eco-friendly alternative to conventional plastic packaging materials.

Table 4. Cost analysis of optimum arrowroot starch film (per 1 kg starch)

Sr. No.	Particulars	Quantity	Cost (₹)
1.	Arrowroot starch	1 kg	450
2.	Glycerol	667 ml	638
3.	Acetic acid (0.1 N)	330 ml	277
4.	Silicone mould	1 Nos.	50
5.	Labour charges	2 days	600
6.	Electricity charges	30 units @10.34/unit	315
	Total cost of production		2330

Conclusion

The present study demonstrated the potential of arrowroot starch with glycerol as a promising biodegradable material for the development of sustainable food packaging films. Increasing the arrowroot starch concentration from 5%, 10%, 15%, 20% and 25% (w/v) at 8, 9, 10, 11 and 12 ml glycerol concentration significantly influenced film thickness, water vapour permeability, tensile strength, elongation, transparency, solubility, printability, and sealing ability. Film thickness increased from 0.277 ± 0.015 to 0.673 ± 0.021 mm, while water vapour permeability decreased from 4.572×10^{-11}±0.279 to 1.800×10^{-11}±0.140 g.$m^{-1}s^{-1}Pa^{-1}$, transparency from 4.913 ± 0.040 to 0.639 ± 0.014, tensile strength increased from 1.904 ± 0.034 to 4.501 ± 0.045 MPa of the resultant Arrowroot starch films. Printability was best at 10-15% starch due to a smoother matrix, while sealing ability was satisfactory at 5-10% starch but reduced at higher starch due to increased matrix rigidity and reduced chain mobility. Glycerol acted as an effective plasticizer by reducing brittleness and improving flexibility. The 15% w/v arrowroot starch film showed the best balance of mechanical, barrier, optical, printability, and sealing properties, making it most suitable for biodegradable materials.

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