

BIODEGRADABLE PACKAGING FILM WITH pH SENSITIVE INDICATORS FOR FISH FRESHNESS

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Abstract.

The growing demand for sustainable and smart food packaging has led to the development of eco-friendly alternatives to conventional plastics. In this study, a smart biodegradable packaging film based on agro-waste materials was developed and evaluated for real time monitoring of fish freshness. Guava leaf extract, onion peel extract and urease enzyme from watermelon seed were incorporated into biodegradable film matrix to impart antimicrobial activity, pH-responsive color indication and freshness sensing capability, respectively. Characterization of the developed film was done for tensile strength, pH, biodegradability and freshness indicating performance. Tensile strength was determined using the maximum force sustained by the film and its cross-sectional area, while biodegradability was evaluated through soil burial studies under natural conditions. The color changes of fish samples in packages were observed during seven days storage to evaluate the freshness monitoring ability of the film. The developed film showed a tensile strength of about 13 MPa, which indicated adequate mechanical stability for food packaging applications. The pH was stable at 6.5 in all trials, thus making the film suitable for fish packaging. Biodegradation studies showed degradation to 100% in 25 days under natural soil conditions, confirming its environmentally friendly nature. The developed indicator film showed a gradual color change during storage of fish samples. On Day 1 the film was pale yellow and became yellow and golden yellow in Days 2–4. With spoilage, the film changed to yellowish-orange on Day 5, light orange-brown on Day 6, and reddish-brown by Day 7. The gradual color change is attributed to the interaction between volatile basic compounds generated by the spoilage and the bioactive pigments in the film, which suggests the increasing fish deterioration during the storage period. The results showed that the developed smart bio-degradable film based on agro-waste has satisfactory mechanical properties, rapid bio-degradability and effective freshness-indicating capability. It therefore has a great potential as a sustainable and affordable replacement to conventional plastic packaging for fish and other perishable food products.

Keywords: Smart packaging, Biodegradable film, Agro-waste utilization, Fish freshness indicator, Onion peel extract, Guava leaf extract, Urease enzyme, Sustainable packaging.

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1. Introduction

Fish and fishery products are highly perishable foods due to their high moisture content, near-neutral pH, and abundance of nitrogenous compounds, which favour rapid microbial growth. During storage and transportation, microbial degradation of fish leads to the formation of volatile nitrogenous compounds such as ammonia, trimethylamine, and total volatile basic nitrogen, which significantly reduce quality and compromise food safety (Hussain et al., 2021; Gram and Dalgaard, 2020; Reza et al., 2022).

The traditional methods to assess the freshness of fish are sensory evaluation, microbial analysis, and chemical tests. These methods are invasive, time-consuming, and require trained personnel and laboratory settings (Olafsdottir et al., 2020; Kumari

et al., 2022). Such techniques are not suitable for continuous or real time monitoring of food quality during storage and transportation. Therefore, the evolution of intelligent or smart packaging systems for providing real-time information of food freshness through visual indicators is gaining interest (Kerry et al., 2021; Kuswandi et al., 2020; Priyadarshi et al., 2021).

Smart packaging films incorporating pH-sensitive indicators have gained considerable attention due to their simplicity, low cost, and ease of interpretation. Natural pigments derived from plant sources exhibit visible color changes in response to pH variation and can be safely incorporated into biodegradable polymer matrices (Priyadarshi et al., 2020). During fish spoilage, the accumulation of alkaline

compounds increases the internal pH of the packaging environment, triggering a color change in the indicator film that visually signals deterioration. Antimicrobial and enzymatic components incorporated in packaging materials can further enhance food safety, in addition to freshness indication. Plant-derived antimicrobial compounds can inhibit spoilage microorganisms, while enzymes such as urease can catalyse the formation of ammonia from nitrogenous substrates, thus amplifying pH changes to enhance the sensitivity of the indicator system (Yam et al., 2021; Zhang et al., 2023). The application of these multifunctional natural additives contributes to the development of active-intelligent packaging systems.

Simultaneously, the extensive use of synthetic plastic packaging materials has resulted in severe environmental pollution due to their non-biodegradable nature. The replacement of conventional plastics with biodegradable films derived from renewable resources is therefore essential to promote sustainable food packaging practices (Siracusa et al., 2020; European Biopolymer Review, 2022; Shah et al., 2024). Biopolymer-based films offer an environmentally friendly alternative while allowing the incorporation of functional compounds for smart packaging applications.

Temperature fluctuations and extended storage durations during fish handling often accelerate biochemical reactions that are not immediately detectable by visual inspection or odour. As a result, spoilage may begin internally even when the product appears acceptable, posing hidden risks to consumers. Packaging systems capable of responding to these subtle biochemical changes offer a practical solution for early-stage spoilage detection (Cheng et al., 2021; Li et al., 2023). By providing continuous monitoring throughout the supply chain, such systems can improve quality control during storage, transportation, and retail display of fish and fishery products.

From an industrial perspective, the implementation of intelligent packaging technologies can support compliance with food safety regulations and quality assurance standards. Real-time freshness indication reduces reliance on batch testing and minimizes the need for frequent laboratory analysis. This can lead to improved operational efficiency and reduced economic losses caused by spoilage-related recalls or product rejection (Kerry et al., 2021; Pathak et al., 2024). Therefore, the integration of smart indicator films into fish packaging has the potential to enhance traceability, strengthen safety management systems, and support innovation in the seafood packaging industry.

The present study aims to develop a biodegradable pH-sensitive packaging film for fish freshness monitoring using natural bioactive compounds. The physicochemical, mechanical, and functional

properties of the developed films were evaluated, and their effectiveness in indicating fish spoilage under refrigerated storage conditions was investigated (Priyadarshi et al., 2020; Zhang et al., 2023; Singh et al., 2025). This study contributes to the advancement of eco-friendly smart packaging solutions for improving food safety and reducing plastic waste.

2. Materials and Methods

2.1. Materials

Guava leaves (*Psidium guajava*), onion peels (*Allium cepa*), and watermelon seeds (*Citrullus lanatus*) were collected from local agricultural and household sources and used as the primary agro-waste materials. Agar-agar was used as the film-forming biopolymer, while glycerol served as the plasticizer. Ethanol and distilled water were used as extraction and film preparation solvents. Sodium chloride and ammonium sulphate of analytical grade were used as chemical reagents during the study. All chemicals used were of analytical grade and procured from standard laboratory suppliers.

2.2. Methods

2.2.1. Sample Preparation

Bioactive compounds were then extracted from the respective powders, wherein quercetin was extracted from onion peels, antimicrobial compounds from guava leaves, and urease enzyme from watermelon seeds. The enzymatic extraction of urease was carried out using a refrigerated centrifuge to maintain enzyme activity, while ethanolic extracts of onion peel and guava leaf powders were concentrated using a rotary evaporator to remove excess solvent. A biodegradable film-forming solution was prepared using agar-agar as the base polymer and glycerol as a plasticizer. The extracted bioactive compounds were incorporated into the film-forming solution, which was then cast onto clean surfaces and allowed to dry under controlled conditions to obtain uniform biodegradable films. The dried films containing the bioactive compounds were used to package fish samples, and the color change of the films was monitored during storage to assess fish freshness and spoilage based on pH variation.

2.2.2. Solvent Extraction

2.2.2.1. Raw Materials and Chemicals

Guava leaves (*Psidium guajava*), onion peels (*Allium cepa*), and watermelon seeds (*Citrullus lanatus*) were collected from local agricultural and household sources. Agar-agar was used as the film-forming biopolymer, while glycerol served as the plasticizer. Ethanol, sodium chloride, and ammonium sulphate of analytical grade were used for extraction and enzyme purification processes. Distilled water was used throughout the study.

2.2.2.2. Extraction of Quercetin and Bioactive Compounds

The collected onion peels and guava leaves were washed with distilled water, tray-dried at 60°C for

6–8 h until constant weight was achieved, and ground into fine powders. For extraction, the powders were mixed separately with ethanol in a 1:10 (w/v) ratio and heated in a water bath at 60°C for 15 min. The extracts were filtered and concentrated using a rotary evaporator at 45°C under reduced pressure for 20–30 min to remove the solvent and obtain concentrated crude extracts rich in quercetin and bioactive compounds. The extracts were stored under refrigerated conditions (4°C) until further use.

2.2.2.3. Extraction and Partial Purification of Urease Enzyme

Watermelon seeds were washed, tray-dried at 60°C for 6–8 h, ground into powder, and mixed with sodium chloride solution. The mixture was centrifuged at 4000 rpm for 15 min at 4°C using a refrigerated centrifuge. The resulting supernatant containing urease enzyme was collected and subjected to partial purification by the gradual addition of ammonium sulphate. The urease-rich extract obtained was stored at 4°C until film preparation.

2.2.3. Preparation of Biodegradable Indicator Film

Agar–agar was dissolved in distilled water and heated until complete solubilization. Glycerol was added as a plasticizer, followed by the incorporation of guava leaf extract, onion peel extract, and urease enzyme extract. The resulting film-forming solution was cast onto clean trays and dried under controlled conditions to obtain biodegradable indicator films.

2.2.4. Characterization of Films

The developed films were characterized for tensile strength, pH, biodegradability, and freshness-indicating performance. Tensile strength was determined using the maximum force sustained by the film before rupture. Film pH was measured using a calibrated pH meter. Biodegradability was evaluated through soil burial tests under natural conditions. The freshness-indicating ability of the films was assessed by monitoring color changes during the storage of packaged fish samples over seven days.

Figure 1: Solvent Extraction

PAR AME TER	FOR MUL ATIO N 1	FO RMUL ATION 2 (ml)	FO RMUL ATION 3 (ml)	FO RMUL ATION 4 (ml)
Q uercet in	8	6	8	4

Ur case	4	4	6	10
A ntimic robial extrac t	2	0.5	1	2
A gar agar	5	5	10	8
W ater	10 0	100	100	100
Gl ycerol	5	5	8	10

Table 1: Composition of film formation

(a)

(b)

(c)

(d)

Figure 2: Film formation (a) Formulation 1 (b) Formulation 2 (c) Formulation 3 (d) Formulation 4

2.2.5. Water Activity (a_w)

Water activity (a_w) indicates the amount of unbound water available in the packaging material and is an important factor influencing microbial growth, enzymatic activity, and chemical reactions. Lower water activity values contribute to enhanced stability and extended shelf life of packaged foods. Water activity of the developed film samples was determined using a water activity meter following the standard method described by AOAC (2023). The measurements were carried out at $25 \pm 1^\circ\text{C}$, and the results were expressed as a_w values.

2.2.6. Moisture Content

Moisture content refers to the total amount of water present in the biodegradable film and is generally expressed as a percentage of the sample weight. It influences the mechanical properties, flexibility, and storage stability of the film. The moisture content of the film samples was determined by drying a known weight of the sample in a hot air oven at 105°C for 24 h until a constant weight was obtained, following the standard method described by AOAC (2023). The moisture content was calculated using the weight difference before and after drying and expressed as a percentage.

$$\text{Moisture content}(\%) = \frac{(W1 - W2)}{W1} \times 100$$

Where:

W1 = Initial weight of the film sample (g)

W2 = Final weight of the dried film sample (g)

2.2.7. pH

pH represents the acidic or alkaline nature of the packaging material and affects microbial growth and chemical interactions between the film and the food product. An appropriate pH is essential for maintaining packaging safety and functional performance. The pH of the biodegradable film samples was measured using a digital pH meter (Model: pH 700, Eutech Instruments, Singapore) with a least count of 0.01 pH units. Briefly, 1 g of film sample was dispersed in 10 mL of distilled water and allowed to equilibrate for 30 min at room temperature ($25 \pm 2^\circ\text{C}$). The pH meter was calibrated using standard buffer solutions of pH 4.0, 7.0, and 9.2 prior to measurement. The pH value of the film suspension was then recorded.

2.2.8. Colour Analysis (Using Colorimeter)

Colour analysis was performed to evaluate the surface colour characteristics of the biodegradable film samples. The colour parameters were measured using a portable colorimeter (CR-400, Konica Minolta, Tokyo, Japan) with a measurement aperture of 8 mm and an illuminant D65 standard light source. The instrument was calibrated using a standard white calibration plate before analysis.

The colour of the film samples was expressed in terms of L^* , a^* , and b^* values, where L^* represents lightness (0 = black, 100 = white), a^* represents redness (+) to greenness (-), and b^* represents yellowness (+) to blueness (-). Measurements were taken at three different locations on each film sample, and the average value was reported.

2.2.9. Tensile Strength

Tensile strength is defined as the maximum stress that the film can withstand before rupture and reflects the mechanical strength and durability of the packaging material. The tensile strength of the biodegradable film samples was determined using a Universal Testing Machine (UTM) (Model: Instron 3345, Instron Corporation, Norwood, MA, USA) equipped with a 100 N load cell. Film specimens were cut into rectangular strips (100 mm $\times$ 15 mm) and conditioned at $25 \pm 2^\circ\text{C}$ and $50 \pm 5\%$ relative humidity for 48 h prior to testing. The initial grip separation was maintained at 50 mm, and the crosshead speed was set at 50 mm min^{-1} . Tensile strength was calculated as the maximum force at break divided by the initial cross-sectional area of the film and expressed in MPa.

$$\text{Tensile strength (MPa)} = \frac{\text{Maximum Load (N)}}{\text{Cross - Sectional Area (mm}^2\text{)}}$$

Where:

Maximum Load = Force at film break (N)

Cross-sectional Area = Film thickness $\times$ film width (mm^2)

2.2.10. Water Absorption (Hydrophilic Test)

Water absorption capacity was determined to evaluate the hydrophilic nature and water resistance of the biodegradable film samples. Film specimens

(2 cm $\times$ 2 cm) were initially dried in a hot air oven at 105°C for 24 h and weighed to obtain the initial dry weight (W_0). The dried samples were then immersed in distilled water at $25 \pm 2^\circ\text{C}$ for 24 h. After immersion, the surface water was gently removed using filter paper, and the samples were immediately weighed to obtain the final weight (W_1). Water absorption was calculated using the following equation and expressed as a percentage.

$$\text{Water Absorption(\%)} = \frac{(W_1 - W_0)}{W_0} \times 100$$

Where:

W_0 = Initial dry weight of the film (g)

W_1 = Weight of the film after water immersion (g)

Lower water absorption values indicate better moisture barrier properties and improved resistance to water penetration, which are desirable characteristics for food packaging applications. Recent studies have highlighted that reducing water uptake enhances the structural stability and barrier performance of biodegradable packaging films during storage and food contact applications (Gupta et al., 2022; Xie, 2023).

2.2.11. Chemical Stability

Chemical stability refers to the ability of the packaging film to retain its structural integrity and functional properties when exposed to different chemical environments. It ensures the durability of the film matrix and the stability of incorporated bioactive compounds under acidic and alkaline conditions. The chemical stability of the developed films was evaluated by immersing pre-weighed film samples (2 cm $\times$ 2 cm) in different media, including distilled water, acidic solution (pH 3, 0.1 N HCl), and alkaline solution (pH 10, 0.1 N NaOH), at $25 \pm 2^\circ\text{C}$ for 24 h. After immersion, the samples were removed, gently blotted with filter paper to remove surface moisture, and dried at room temperature. The samples were then reweighed to determine the percentage weight change.

Chemical stability was calculated using the equation:

$$\text{Chemical stability(\%)} = \frac{(W_1 - W_0)}{W_0} \times 100$$

Where:

W_0 = Initial weight of film (g)

W_1 = Final weight after immersion (g)

The chemical stability of the films was assessed based on the percentage weight change after exposure to acidic, alkaline, and neutral environments. Lower weight variation indicates greater stability of the film matrix and enhanced resistance to chemical degradation (Sharma et al., 2022).

2.2.12. Biodegradability Test

The biodegradability of the developed films was evaluated using a soil burial method adapted from Azevedo et al. (2022) and Kumar et al. (2021). Pre-weighed film samples (2 cm $\times$ 2 cm) were buried in moist garden soil at a depth of approximately 5 cm

and maintained at $25 \pm 2^\circ\text{C}$. The moisture content of the soil was maintained throughout the experimental period by periodic addition of distilled water. The samples were retrieved after 7, 14, 21, and 28 days, gently washed with distilled water to remove adhering soil particles, and dried in a hot air oven at 105°C for 24 h until constant weight was achieved. The dried samples were then weighed to determine the residual weight. All experiments were conducted in triplicate.

The percentage biodegradability was calculated using the following equation:

$$\text{Biodegradability}(\%) = \frac{(W1 - Wt)}{W1} \times 100$$

Where:

W1 = Initial weight of the film sample (g)

Wt = Weight of the film sample after degradation time (g)

The extent of biodegradation was assessed based on the percentage weight loss of the film during soil burial. Higher weight loss values indicate greater biodegradability and environmental compatibility of the developed packaging material.

2.2.13. Thickness

The thickness of the developed biodegradable films was measured according to the methods described by Spirk et al. (2021) and Yadav et al. (2022) with slight modifications. Film thickness was determined using a digital micrometer screw gauge (Mitutoyo, Model: 293-240-30, Mitutoyo Corporation, Japan) with a precision of 0.001 mm. Measurements were taken at five random locations on each film specimen (center and four corners) to account for thickness variations. The average thickness value was calculated and reported. All measurements were performed at room temperature ($25 \pm 2^\circ\text{C}$) in triplicate.

2.2.14. Uniformity

The uniformity assessment of the developed films was carried out following methodologies commonly employed for biopolymer-based biodegradable food packaging films as described by Abdollahzadeh et al. (2023) and Kumar et al., (2022). Film surfaces were examined for the presence of cracks, bubbles, pores, and phase separation. Thickness measurements were recorded at five random locations using a digital micrometer screw gauge (Mitutoyo, Model: 293-240-30, Mitutoyo Corporation, Japan). The mean thickness and standard deviation were calculated to assess film uniformity. Lower variation in thickness values indicated better homogeneity and uniform distribution of film components. All measurements were performed in triplicate.

3. Results and Discussions

3.1. Water activity of film

The water activity (a_w) of the developed biodegradable film was 0.583 at 30.9°C , which is within the safe limit (<0.6), indicating an unfavourable environment for microbial growth and

good shelf stability. The balanced a_w value reflects effective water binding by the natural components, enhancing the film's functional performance for food packaging applications.

Colour values of film samples have been presented through a graphical representation

Formulations	Water Activity (a_w)	Temperature
Formulation 1	0.612	30.9°C
Formulation 2	0.599	30.5°C
Formulation 3	0.586	31.2°C
Formulation 4	0.583	30.7°C

Table 2: Water Activity of Films

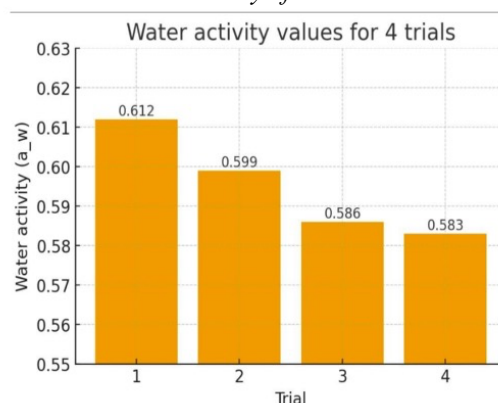


Figure 3: Water Activity values of film

The water activity measurements were performed on the final film samples available at the time of analysis. As additional samples were not available during revision, triplicate measurements could not be obtained.

3.2. Moisture Content :

The moisture content of the developed biodegradable film was 18.15%, indicating an optimum moisture balance that provides flexibility while preventing brittleness. This moderate moisture level enhances mechanical strength, dimensional stability, and film integrity due to hydrophilic compounds from the incorporated natural extracts.

Parameter	For mulatio n 1	For mulatio n 2	For mulatio n 3	For mulatio n 4
Temperature ($^\circ\text{C}$)	50	52	55	53
Time (mins)	10	12	14	13

Moi sture Percent age (%)	19. 0	18. 5	18. 2	18. 15
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Table 3: Moisture analyses of film

Figure 4: Graphical representation of moisture content of film

The moisture content measurements were performed on the final film samples available at the time of analysis. As additional samples were not available during revision, triplicate measurements could not be obtained.

3.3. pH

The pH of the developed biodegradable film ranged 6.5 across four trials, indicating a near-neutral environment suitable for fish packaging. This pH ensures minimal chemical interaction with fish proteins and maintains product quality. The consistency of pH across trials reflects the stability of the film's natural components

Formulation	pH
1	6.9
2	6.7
3	6.6
4	6.5

Table 4 : pH test for film

Figure 5: Graphical representation of pH of film

The pH measurements were performed on the final film samples available at the time of analysis. As additional samples were not available during revision, triplicate measurements could not be obtained.

3.4. Colour Analysis (Colorimeter)

The colour characteristics of the developed biodegradable film were measured using a colorimeter (CIE L*, a*, b* values). The film exhibited a moderately light appearance with slight reddish-yellow tones, indicated by positive a* and b* values, due to natural pigments from guava leaves, onion peels, and watermelon seeds. The moderate L* value reflects uniform colour and partial opacity, enhancing both aesthetic appeal and protection of packaged foods from light-induced degradation.

Sample	L* (Lightn ess)	B *(Red/ Green)	A *(Yello w/ Blue)	Re mark
Formul ation 1	61. 20	15 .20	2. 80	Lig ht yellowi sh green

Formul ation 2	57. 50	17 .0	3. 50	Lig ht Browni sh Green
Formul ation 3	55. 00	18 .20	4. 10	Pale olive green
Formul ation 4	53. 01	18 .84	4. 40	Stab le Light green

Table 5: Colour Analysis for Film

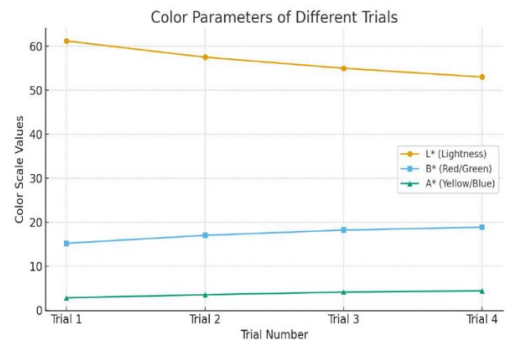


Figure 6: Graphical Representation for Colour Analysis for Film

The color analysis were performed on the final film samples available at the time of analysis. As additional samples were not available during revision, triplicate measurements could not be obtained.

3.5. Tensile Strength :

The film exhibited a maximum tensile force of 26 N, which corresponds to an approximate tensile strength of ~13 MPa.

- Applied force, $F = 26 \text{ N}$
- Width of film, $w = 2 \text{ cm} = 0.02 \text{ m}$
- Thickness of film, $t = 0.1 \text{ mm} = 0.0001$
- Area, $A = 2 \times 10^{-6} \text{ m}^2$

$$\sigma = \frac{F}{A} = \frac{26}{2 \times 10^{-6}} = 13,000,000 \text{ Pa} = 13 \text{ MPa}$$

3.6. Water Absorption (Hydrophilic Test)

The film samples were cut into small pieces and weighed accurately. Each film piece was immersed in distilled water at room temperature. Observations were made every 4 hours for 24 hours to monitor swelling, dimensional changes, and structural integrity. The swelling (%) and water uptake were calculated to evaluate moisture absorption.

i me (hou r)	Weigh t Before Immersio n(g)	Weigh t After Immersio n(g)	Water Absorption (%)
0	3.000	3.000	0
4	3.000	3.030	1.0
8	3.030	3.048	1.6

1 2	3.048	3.060	2.0
1 6	3.060	3.072	2.4
2 0	3.072	3.090	3.0
2 4	3.090	3.120	4.0

Table 6: Hydrophilic test for Film Water absorption(%)

$$= \frac{(W_{after} - W_{before})}{W_{before}} \times 100$$

$$= \frac{3.120 - 3.000}{3.000} \times 100 = 4\%$$

3.7. Chemical Stability

The film was evaluated by immersing samples in solutions of varying pH (acidic, neutral, and basic) for 24 hours.

pH Condition	Visual Observation	Degradation	Swelling	Discoloration
Acidic	Slight changes observed	Minimal	Minimal	Slight
Neutral	No change	None	None	None
Basic	Completely dissolved	Complete	Complete	Complete

Table 7: Chemical stability test for Film

3.8. Biodegradability Test

The film completely degraded within 25 days under natural soil conditions. The result confirms that the materials used-onion peel extract, guava leaf extract, and urease enzyme-contribute to the film's eco-friendly nature and make it suitable as a sustainable alternative to conventional plastic packaging.

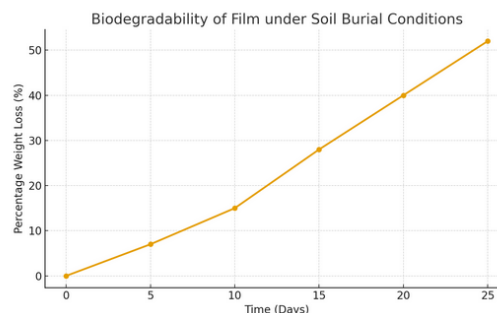


Figure 7: Graphical Representation for Biodegradability of Film

3.9. Thickness and Uniformity

The thickness of the developed biodegradable film was measured before and after spoilage analysis. The film showed a thickness of 0.253 mm before spoilage and 0.271 mm after spoilage. A slight increase in thickness after spoilage was observed, which may be due to moisture absorption and swelling of the polymer matrix. The presence of hydrophilic components in the film contributes to this behaviour. Despite the variation, the thickness values remained within a narrow range. This indicates good thickness uniformity of the film. Uniform thickness is essential for consistent mechanical and barrier properties in packaging applications.

3.10. Colour Change Response of Indicator Film during Fish Spoilage

Figure 8 illustrates the visual colour changes of fish samples packed with the developed biodegradable indicator film over a period of seven days under controlled storage conditions. A gradual and distinct colour variation was observed from Day 1 to Day 7, corresponding to the progression of fish spoilage. The colour change is attributed to the interaction between volatile basic compounds released during spoilage and the bioactive pigments present in the film. These changes indicate the film's sensitivity to spoilage-related chemical changes. The controlled environment ensured reliable and reproducible observations. This demonstrates the potential application of the film as a visual freshness indicator for fish products.

- (a)
- (b)
- (c)
- (d)
- (e)
- (f)
- (g)

Figure 8 : Visual Representation Colour Change Response of Indicator Film during Fish Spoilage at (a) Day 1 (b) Day 2 (c) Day 3 (d) Day 4 (e) Day 5 (f) Day 6 (g) Day 7

4. Conclusion

In the present study, a smart biodegradable packaging film was successfully developed using agar-agar incorporated with bioactive extracts from

onion peel, guava leaves, and watermelon seeds. The film exhibited acceptable mechanical strength, thickness uniformity, and structural stability suitable for food packaging applications. The indicator film showed a distinct and progressive colour change during fish spoilage under controlled storage conditions, effectively correlating with freshness deterioration. The observed colour response is attributed to the interaction between spoilage-related volatile compounds and naturally derived pigments present in the film. The film's biodegradable nature and use of Agro-waste-based bioactive compounds enhance its sustainability and environmental relevance. Overall, the developed film demonstrates strong potential as an eco-friendly, visual freshness indicator for intelligent food packaging applications.

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