



# Development of a pH Responsive Curcumin-alginate Biopolymer Indicator for Real-time Freshness Detection in Food

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10.18805/ajdfr.DR-2448

## ABSTRACT

**Background:** In this study, a natural pH-sensitive indicator film based on sodium alginate and curcumin is developed and rigorously tested for use in intelligent food packaging. The main goal was to develop a biodegradable colorimetric sensor that could detect pH fluctuations associated with freshness, namely those caused by volatile amines produced during food deterioration.

**Methods:** Curcumin was extracted and purified using HPLC for high pigment purity and colorimetric response incorporated into sodium alginate matrices. The pH sensitivity was assessed using UV-vis spectroscopy. Mechanical properties like tensile strength and elongation at break and physicochemical characteristics like film thickness, moisture content, water solubility and water vapor transmission rate were measured for durability and flexibility barrier stability. The films' responsiveness to food spoilage conditions was simulated.

**Result:** The pure curcumin's pH sensitivity was validated by the UV-vis spectral analysis, which showed a change in maximum absorption from 421 nm in acidic to 467 nm in alkaline conditions. Because of the homogeneous pigment dispersion and robust polymer-pigment interactions, the optimized sodium alginate-curcumin film demonstrated improved tensile strength and elongation at break. Favourable characteristics were shown by physicochemical examination, such as consistent thickness, a moderate moisture content, regulated water solubility and stable water vapor barrier function. Additionally, the films showed quick color changes when exposed to ammonia vapor, demonstrating their sensitivity and mechanical durability for application as freshness markers in food packaging systems.

**Key words:** Active packaging, Curcumin, Food deterioration detection, pH indicator film, Sodium alginate.

## INTRODUCTION

Intelligent packaging is designed to monitor food quality by tracking its freshness, safety and overall condition, contrasting with active packaging that primarily aims to extend shelf life. According to Dirk *et al.* (2018), evaluating food degradation is crucial for developing innovative packaging solutions to enhance food security. Various external factors such as humidity, storage temperature and microorganisms, along with intrinsic variables like moisture content, pH level, composition and microbial load, significantly affect food quality (Priyadarshini *et al.*, 2019). Intelligent packaging utilizes continuous monitoring to give timely alerts about these parameters (Andrea *et al.*, 2021).

A notable example of intelligent packaging is the pH indicator, which changes color based on the acidity or basicity of its environment, signaling any changes in food pH due to spoilage (Palanisamy *et al.*, 2025; Ardicli *et al.*, 2019). The color change occurs when food spoils and volatile amines increase the pH in the packaging headspace, leading to a visible shift in the pH-sensitive dye contained within the polymer film (Pacquit *et al.*, 2007 and Sheet *et al.*, 2026). Effective intelligent packaging requires a biopolymer matrix and a pigment that reacts to pH shifts. Incorporating bioactive substances into packaging systems, particularly natural pigments, is effective in boosting food safety and quality (Khaneghah *et al.*, 2018; Ojha *et al.*, 2015). Natural alternatives to synthetic pigments, such as curcumin, are favoured for

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**How to cite this article:** Kamble, S.M., Sontakke, M.D., Raut, V.P., Harke, S.N. and Ranveer, R.C. (2026). Development of a pH Responsive Curcumin-alginate Biopolymer Indicator for Real-time Freshness Detection in Food. *Asian Journal of Dairy and Food Research*. 45(5): 854-861. doi: 10.18805/ajdfr.DR-2448.

**Submitted:** 29-01-2026 **Accepted:** 02-04-2026 **Online:** 30-04-2026

their health safety (Choi *et al.*, 2019). Curcumin enhances the durability and bioavailability of the packaging system while allowing for food quality monitoring. As pH levels surpass 7, reactions involving curcumin's phenolic hydroxyl groups cause a color change (Aliabbasi *et al.*, 2021).

The interest in developing packaging solutions using natural polymers has increased, focusing on achieving high mechanical performance and desirable physical properties. Research highlights the use of strains such as *Pseudomonas* (Guo *et al.*, 2023) and *Azotobacter* (Hao

*et al.*, 2022) in creating durable support materials like sodium alginate infused with curcumin pigment. Alginate's excellent film-forming capabilities yield transparent, flexible films with strong mechanical strength and effective gas barrier properties (Mao *et al.*, 2023). Colorimetric intelligent films based on curcumin have been extensively studied for tracking changes in freshness in meat, fish and marine products, dairy products (Sharma *et al.*, 2021) by using visible pH-responsive color transitions linked to the production of volatile amines. (Thiyagarajan *et al.*, 2025; Bourtzi *et al.*, 2025; Sheet *et al.*, 2026).

This study specifically aimed to develop a natural pH indicator film using sodium alginate as its base and curcumin as the indicator dye, with enhanced stability, minimum curcumin leaching and improved assessment of the properties of this sodium alginate/curcumin indicator film. A previous study mainly focused on buffer-based pH simulations with comprehensive structural –functional properties. This work advances curcumin-based indicators towards practical, low-cost, biodegradable intelligent packaging applications.

## MATERIALS AND METHODS

All the analysis throughout the research was carried out at MGM University Chhatrapati Sambhajinagar in the year 2024-2025. Curcumin powder was sourced from Dayaz Orchidarium in India, specifically the Pratibha variety of turmeric. Sodium alginate, glycerol, polyvinyl alcohol, ethanol and a 25-28% ammonia solution were supplied by Sigma-Aldrich.co. India. The other chemicals used to prepare the buffer solutions were of analytical grade. The five treatments were selected with three replicates and each consisted of a variable concentration of curcumin from 0.1 to 0.5 mg of curcumin as S1 to S5.

### Extraction of curcumin

Using a Soxhlet apparatus, 500 mL of 95% ethanol was employed to extract 50 g of dried curcumin powder (Pratibha Internationals, India) until the dark solvent became colorless. The dark brown ethanolic extract was then filtered and concentrated using a rotary evaporator. To prepare a stock solution of curcumin, 10 mg (milligrams) of the dried ethanolic extract was dissolved in 10 mL (millilitres) of 50% ethanol, yielding a concentration of 1mg per mL (Singh *et al.*, 2022).

### Purification of curcumin

Curcumin isolation was achieved using a Shimadzu system with a UV-visible detector and High-performance liquid chromatography (HPLC). A reversed-phase Shim-Pack GWS C18 column was utilized for non-polar substances like curcumin and separation was performed using a mobile phase consisting of a 50:50 (v/v) mixture of acetonitrile and 2% acetic acid (Mollayi *et al.*, 2015). The mobile phase was degassed in an ultrasonic bath and filtered through a 0.45 µm membrane filter to ensure baseline stability. Subsequently, a clear solution was prepared by dissolving

the crude curcumin extract in the mobile phase, which was further filtered through a 0.22 µm syringe filter to prevent particle entry into the column. Spectral features and retention times confirming that the peaks corresponded to curcumin.

### Spectral characteristics of natural dye curcumin solutions across varying pH values

Colorimetric data and UV-vis spectra of Cur solutions were analyzed using a UV spectrophotometer (Model Jasco V750) with a wavelength range of 200-900 nm and Spectraman Ager software; the pH levels of the solutions were adjusted to the desired range of 3.0-10 using 0.1 mol/L HCl or NaOH solutions; the blank solution was free of Cur; each 4 cm by 1 cm sample was placed directly into the spectrophotometer cell for the film transmittance test, with measurements taken between 400 and 900 nm, with air as the standard for clarity throughout the measurement process (Gómez *et al.*, 2024).

### Preparation of sodium alginate/curcumin film

Initially, a 1:1000 wt/v ethanol solution was used to dissolve curcumin and sodium alginate (SA) was added as a binder at a concentration of 2% (wt/v) while heating to 70°C. The mixture was agitated using an overhead stirrer for 30 minutes at 700 revolutions per minute. The SA and dye solutions were combined and then subjected to magnetic stirring on a hot plate for 30 minutes at temperatures between 50 and 55°C. After this period, glycerol was introduced at a concentration of 10% v/w starch. Finally, the sample was dried in a hot air oven at 40°C for six hours, as cited in Zhang *et al.* (2024).

### Color response to volatile ammonia

The approach described by Zhai *et al.* (2017) was utilized, with minor adjustments, to evaluate the color responses of the colorimetric films when exposed to volatile ammonia. A 1 cm by 1 cm piece of film was meticulously cut and suspended in a 500 mL reagent container, positioned 1 cm above an 80 mL solution of ammonia at room temperature, with a concentration of 10 ppm. Exposure time for 5 to 45 seconds, colorimetric data and images from the films were systematically gathered for intervals of 10 sec, adhering to the methodology outlined (Chen *et al.*, 2019). All measurements were carried out in triplicate.

### Film morphology

The film's thickness was measured using a digital calliper at five randomly selected locations.

### Moisture content (MC)

The moisture content was assessed by thermally drying the sample to a constant weight in a hot air oven at 105°C (Gontard *et al.*, 1992).

$$(m-M)/m = 100 \text{ times MC}$$

Where

m = Weight of the film before drying.

M = Stable weight after the drying process.

### Water solubility (WS)

The assessment of WS was carried out following the methodology outlined by Gontard *et al.* (1992). A 2 cm × 2 cm piece of film was meticulously cut, weighed and submerged in 50 mL of water at a stable temperature of 25°C for a period of 24 hours. The leftover film was then dried to a uniform weight at 105°C after the water was removed. The dry weight of the original film was determined using a specific equation. The calculation for WS was executed using the equation:

$$WS = \frac{100 \times (M - W)}{M(2) | WS}$$

Where

W = Weight of the remaining film and

M = Weight of the original film.

### Rate of water vapor transmission (WVTR)

The standard methods were utilized to quantitatively assess the films' properties regarding water vapor transmission rate (g/m<sup>2</sup>) (ASTM, 1995; Zhang *et al.*, 2016). The measurements were carried out three times and the experiments took place at room temperature. Analyses were conducted in triplicate and the results are presented as mean ± standard deviation. Statistical analysis was performed using one-way analysis of variance (ANOVA) to determine significant differences among samples at a confidence level of 95% (p < 0.05).

### Mechanical properties

The tensile strength and elongation at break were evaluated using the TA-XT Plus Texture Analyzer (Stable Micro

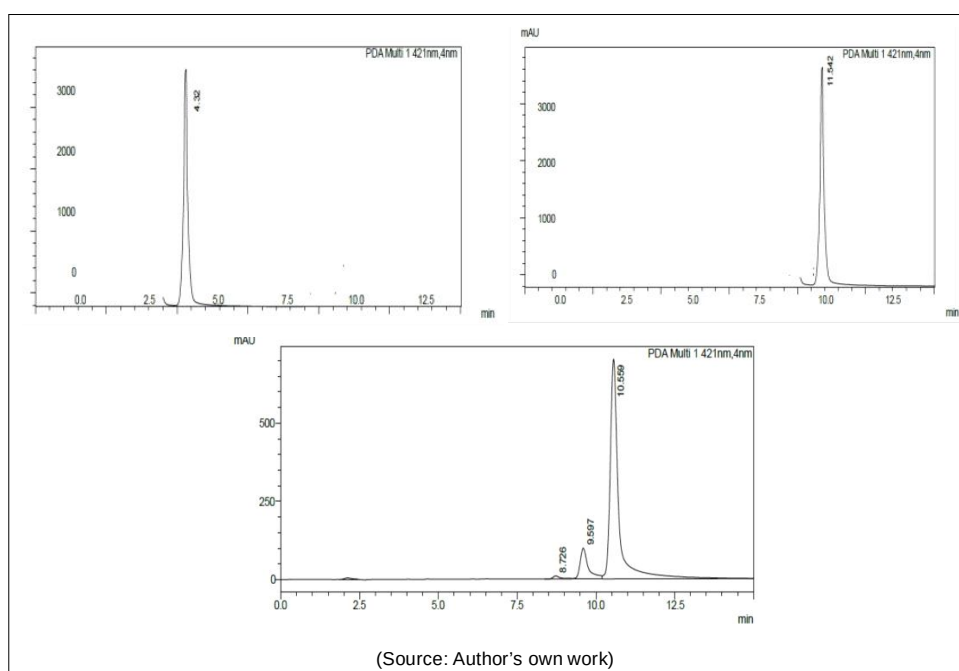
Systems, Co., UK), in accordance with the standards outlined in ASTM D 882-91. Each specimen was subjected to five measurements (1 cm by 10 cm) to determine the average value. The experiment was carried out with a crosshead speed established at 0.5 mm/s and an initial grip separation of 50 mm. The TS and EB values of the specimens were determined through the analysis of stress-strain curves (Liu *et al.*, 2018). All measurements were carried out in triplicate.

### Thermal transitions (T<sub>m</sub> and T<sub>g</sub>) : Differential scanning calorimetry (DSC)

The films were analyzed using differential scanning calorimetry (DSC) with a Shimadzu DSC 60 Plus thermal analyzer. Each sample was precisely weighed (5-10 mg) and placed in an aluminum pan, accompanied by an empty sealed pan as the reference. The heating process ranged from 30°C to 300°C at a rate of 10°C/min in a nitrogen atmosphere (flow rate: 20-50 mL/min) to prevent oxidative degradation. All measurements were carried out in triplicate and curves were analyzed using the same DSC instrument (Gao *et al.*, 2024).

## RESULTS AND DISCUSSION

Purification of curcumin was analyzed using High-performance liquid chromatography (HPLC). The standard curcumin exhibited a peak at a retention time (R<sub>t</sub>) of 4.39 minutes, aligning with established R<sub>t</sub> ranges of 4-5 minutes under similar chromatographic conditions. The turmeric extract chromatogram indicated three distinct peaks in Fig 1 at 8.72, 9.59 and 10.56 minutes, corresponding to bisdemethoxycurcumin (BDMC), demethoxycurcumin (DMC) and



**Fig 1:** The HPLC chromatogram of the (A) standard curcumin sample, (B) pure curcumin and (C) extracted curcumin sample.

curcumin (CUR), respectively aligning with similar results found (Gounder and Lingamallu, 2012; Kolevatov *et al.*, 2021). CUR, being the most hydrophobic, displayed the longest retention time (Paramasivam *et al.*, 2009). Following purification, an HPLC chromatogram revealed a clear peak at 11.54 minutes, signifying no detectable impurities, while the peak at 10.56 minutes confirmed curcumin as the primary compound. The results echoed findings from previous studies and confirmed that the extraction method yielded high-purity curcumin, which may have potential applications in smart packaging, antioxidant incorporation and pH-responsive films (Rafiee *et al.*, 2019; Shirsath *et al.*, 2017; Patil *et al.*, 2018).

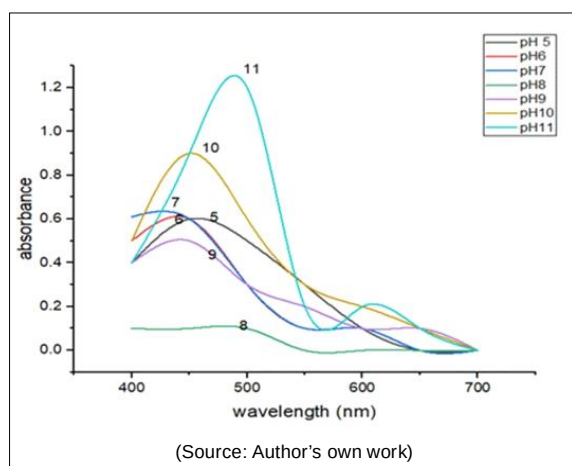
The UV-Vis spectra of curcumin solutions, analyzed over a pH range of 5-11, in Fig 2 reveal the compound's sensitivity to protonation-deprotonation, evidenced by significant changes in absorbance intensity and  $\lambda_{\text{max}}$ . The study observed a structural transformation of curcumin from its neutral keto-enol form into phenolate and enolate anionic forms, indicated by bathochromic (red) and hyperchromic effects under varying pH levels (Priyadarsini *et al.*, 2014). At lower pH values (5-7), curcumin showed a strong absorption band in the 420-450 nm range with absorbance values between 0.45 and 0.65, consistent with findings indicating pronounced absorption features in the

blue spectrum and a yellow hue in solution (Pourjavaher *et al.*, 2017). As pH increased, notably at pH 8, absorbance dropped below 0.2, while at pH 9, the peak near 430 nm faded and a shoulder peak appeared in the 480-500 nm region. The documented bathochromic shift in  $\lambda_{\text{max}}$  with increasing reaching optimal absorbance at pH 10 and 11, where pH 11 yielded the highest peak (absorbance > 1.2) in the ~500-520 nm region, showing a color shift from yellow to reddish-brown (Menon *et al.*, 2007; Nurfina *et al.*, 2017). These observations suggest that curcumin could be utilized as a pH-sensitive indicator in intelligent packaging, particularly for monitoring spoilage in protein-rich foods.

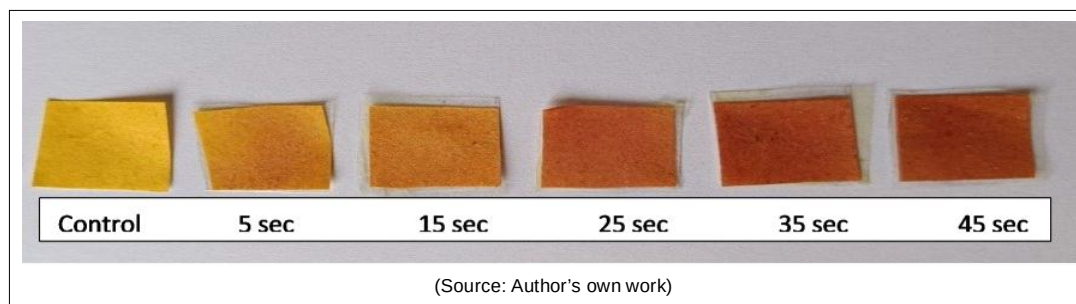
#### Color response to volatile ammonia

The study evaluated the colorimetric response of a curcumin-infused film to ammonia vapor was shown in Fig 3 and color analysis carried out using CIELAB parameters ( $L^*$ ,  $a^*$ ,  $b^*$ ) over seven exposure intervals ranging from 5 to 45 seconds in Table 1. A significant decrease in  $L^*$  values was noted, with a reduction from 65.47 (5 s) to 33.57 (45 s), indicating a darkening effect. Correspondingly,  $a^*$  values increased, reaching 32.77 at 45 seconds compared to 22.81 at 5 seconds, consistent with previous findings of curcumin-composite pH films reacting to volatile amines (Choi *et al.*, 2017; Pourjavaher *et al.*, 2017; Balbinot-Alfaro *et al.*, 2019). The  $b^*$  values generally declined over time, showing a shift from 61.54 at 5 seconds to 24.30 at 45 seconds, reflecting reduced yellowness and a transition toward orange-red hues, aligning with known bathochromic shifts of curcumin in alkaline environments (Akshay *et al.*, 2020). The study also observed substantial increases in  $\Delta E$  values, exceeding the detectable threshold ( $\Delta E > 3$ ) at five seconds (1.05), 17.67 at fifteen seconds and reaching 49.32 by 45 seconds, signaling significant color changes (Pereira *et al.*, 2022). These properties indicate the film's effectiveness for real-time applications in monitoring volatile amines, food spoilage and intelligent packaging systems.

Table 2 displays the physical characteristics of the films, including their thickness, moisture content (MS), water solubility (WS) and water vapour permeability (WVTR). The study investigates the morphology and properties of composite films containing curcumin, revealing thicknesses ranging from 0.059 to 0.071 mm, largely influenced by curcumin dosage through increased viscosity



**Fig 2:** UV spectra of the natural dye curcumin at various pH ranges (5-11).



**Fig 3:** Color- changing behavior of SA/Cu film after exposure to ammonia gas for different time durations.

and solids content. Notably, the  $S_2$  film, with a thickness of 0.062 mm, showcases a uniform structure, balancing handling strength and flexibility. Comparative data from Yang *et al.* (2022) underscore varying thicknesses in related films, indicating the potential for creating smooth surfaces for optical sensing applications while meeting biodegradable film standards.

Water solubility (WS) values of the films ranged from 20.02% to 21.32%, with  $S_2$  exhibiting balanced water sensitivity at 20.68%, suggesting enhanced hydrophilic interactions. Moisture content ranged between 14.32% and 15.42%, where controlled moisture levels are critical for flexibility and color consistency, aligning with Pereira *et al.* (2021) findings on moisture retention's impact on optical clarity and elasticity.

The water vapor transmission rate (WVTR) showed an initial increase up to  $S_3$ , followed by a decrease in  $S_4$  and  $S_5$ , confirming the films' effectiveness in minimizing water vapor transmission. Low WVTR in  $S_2$  indicates limited vapor diffusion, which enhances the film's overall

compactness. Additionally, research by Tian *et al.* (2023) suggests that optimal curcumin levels in films improve polymer chain density and barrier properties, further demonstrating the protective qualities against oxygen, water vapor and UV radiation as noted by Cazon *et al.* (2019).

#### The tensile strength (TS) and elongation at break (EB)

In the context of food transport and preservation, films used must possess specific mechanical properties such as stretchability and strength (Ren *et al.*, 2017; Lipatova *et al.*, 2020). The tensile strength and elongation-at-break characteristics of curcumin-sodium alginate composite films in graph (Fig 4) revealed elongation values ranging from 18.31% to 28.34% and tensile strength from 8.23 MPa to 17.23 MPa. Notably, the  $S_2$  film demonstrated the highest tensile strength at 17.23 MPa, attributed to improved intermolecular interactions and a uniform curcumin distribution within the polymer matrix. Previous studies have indicated that the inclusion of natural pigments like curcumin can decrease mechanical strength due to pigment-polymer

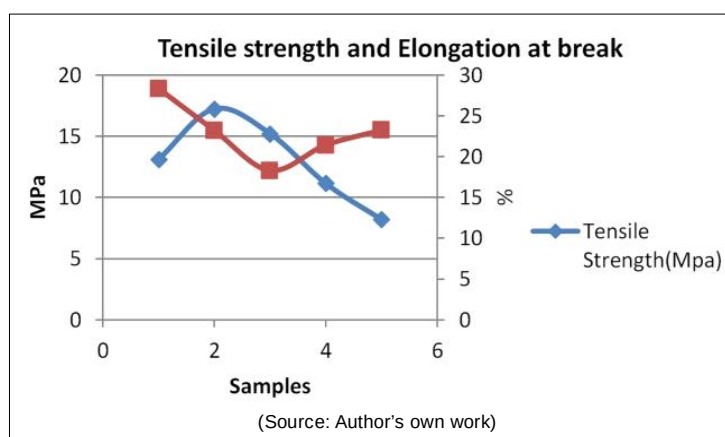
**Table 1:** Color analysis of SA/Cu film after exposure to ammonia gas for different time (sec) durations.

| Exposure time (sec) | Color value             |                         |                         |            |
|---------------------|-------------------------|-------------------------|-------------------------|------------|
|                     | L*                      | a*                      | b*                      | $\Delta E$ |
| Control             | 65.47±0.07 <sup>a</sup> | 22.61±0.03 <sup>f</sup> | 60.51±0.04 <sup>c</sup> | -          |
| 5                   | 65.47±0.03 <sup>a</sup> | 22.81±0.03 <sup>e</sup> | 61.54±0.05 <sup>b</sup> | 1.05       |
| 15                  | 53.78±0.04 <sup>b</sup> | 25.47±0.03 <sup>b</sup> | 73.45±0.02 <sup>a</sup> | 17.67      |
| 25                  | 37.35±0.02 <sup>c</sup> | 23.84±0.07 <sup>d</sup> | 36.12±0.06 <sup>d</sup> | 37.25      |
| 35                  | 35.34±0.03 <sup>d</sup> | 25.23±0.05 <sup>c</sup> | 32.22±0.07 <sup>e</sup> | 41.39      |
| 45                  | 33.57±0.02 <sup>e</sup> | 32.77±0.03 <sup>a</sup> | 24.30±0.04 <sup>f</sup> | 49.32      |

**Table 2:** Physical properties of SA/Cu films.

| Film  | Thickness (mm)           | Water solubility (%)    | Moisture content (%)    | WVTR (g/m <sup>2</sup> ) |
|-------|--------------------------|-------------------------|-------------------------|--------------------------|
| $S_1$ | 0.061±0.001 <sup>b</sup> | 20.02±0.04 <sup>a</sup> | 14.32±0.06 <sup>a</sup> | 14.16±0.05 <sup>a</sup>  |
| $S_2$ | 0.062±0.001 <sup>b</sup> | 20.68±0.07 <sup>b</sup> | 14.89±0.07 <sup>b</sup> | 14.27±0.07 <sup>a</sup>  |
| $S_3$ | 0.059±0.001 <sup>a</sup> | 21.3±0.072 <sup>e</sup> | 15.42±0.07 <sup>e</sup> | 15.21±0.06 <sup>c</sup>  |
| $S_4$ | 0.070±0.001 <sup>c</sup> | 21.22±0.07 <sup>d</sup> | 15.12±0.07 <sup>d</sup> | 15.10±0.07 <sup>b</sup>  |
| $S_5$ | 0.071±0.001 <sup>c</sup> | 21.11±0.06 <sup>c</sup> | 15.02±0.06 <sup>c</sup> | 14.87±0.06 <sup>b</sup>  |

( $S_1$ - 0.1%,  $S_2$ - 0.2%,  $S_3$ - 0.3%,  $S_4$ - 0.4%,  $S_5$ - 0.5% curcumin).



**Fig 4:** Tensile strength (MPa) and elongation at break of (%) of curcumin-sodium alginate composite films ( $S_1$ - $S_5$ ).

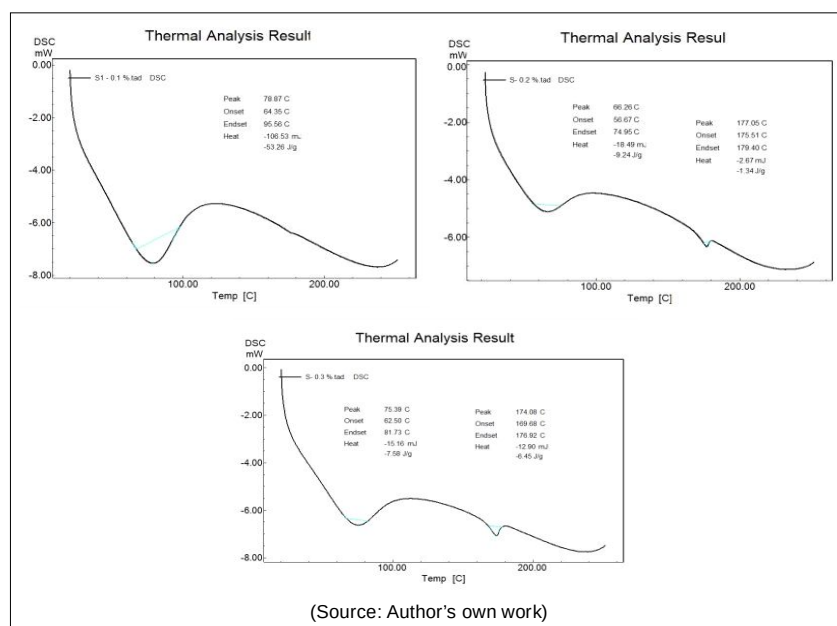


Fig 5: DSC thermo grams (S2-0.2%, S3-0.3%, S4-0.4% curcumin) of SA/Cu film.

incompatibility and inadequate interfacial adhesion (Bakhtiari *et al.*, 2020; Choi *et al.*, 2017). The stress-strain curves for these films displayed typical polymer behavior, with the  $S_2$  film showing heightened stiffness, while the  $S_5$  film exhibited diminished mechanical integrity. A similar study was found by Liu *et al.* (2018). Overall, incorporating a small amount of curcumin can enhance structural integrity. For intelligent packaging applications that require a balance between mechanical robustness and optical responsiveness, films with moderate curcumin concentrations can maintain acceptable strength despite reduced tensile strength. Despite promising performance, several practical limitations remain; curcumin is sensitive to light and prolonged storage which may reduce the color stability of curcumin over the time.

#### Thermal transitions ( $T_m$ and $T_g$ ): DSC (Differential Scanning Calorimetry)

Differential scanning calorimetry (DSC) analysis demonstrates distinct thermal characteristics of curcumin-loaded films, revealing that the film with 0.1% curcumin has a broad endothermic transition (78–80°C) associated with moisture evaporation and polymer relaxation, with no melting peak between 170 and 180°C was shown in Fig 5. This broad endothermic event is due to moisture loss and partial disruption of hydrogen bonds within the polymer matrix, resulting in higher molecular mobility and lower thermal resistance as curcumin is weakly associated with the biopolymer matrix. The appearance of high-temperature endothermic peaks suggests enhanced crosslinking density, improving thermal resistance essential for food packaging applications (Tan *et al.*, 2019; Li *et al.*, 2022). The sample with 0.2% curcumin exhibited optimal polymer-curcumin interaction, reduced moisture sensitivity and enhanced thermal stability, making it the most suitable for intelligent food packaging. This finding aligns with research

indicating that when curcumin loading exceeds certain thresholds, it can surpass its miscibility limit within biopolymer matrices (Valenti *et al.*, 2023; Rashid *et al.*, 2023). Additionally, recent studies highlight improvements in the sensing performance of curcumin-based intelligent packaging systems, particularly in amorphous dye states (Miao *et al.*, 2024; Zhang *et al.*, 2024; Qin *et al.*, 2023).

## CONCLUSION

A biodegradable film made from curcumin and sodium alginate has been developed as a natural colorimetric sensor for food packaging, responding to pH changes. It effectively detects spoilage-related volatile amines through rapid color changes in ammonia exposure. The film exhibits optimal tensile strength and elongation, demonstrating suitable mechanical and physical properties for flexible packaging. This development showcases the promise of natural pigment-based biopolymer films as scalable and eco-friendly smart food packaging solutions that enhance food safety, extend shelf life and reduce environmental impact. Thermal stability tests using differential scanning calorimetry (DSC) indicated distinct endothermic transitions linked to polymer-curcumin interactions and moisture loss. Comprehensive analyses confirm the film's durability, versatility and responsiveness, reinforcing its potential in innovative food safety applications.

## ACKNOWLEDGEMENT

Not applicable.

## Funding

No funding received to support this research.

## Data availability statement

The data supporting the findings of this study are not shared.

**Clinical studies**

Not applicable.

**Ethical guidelines**

Ethics approval was not required for this research.

**Conflict of interest**

The authors have no conflict of interest to declare.

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