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Eco Sense Gel: A Biodegradable pH-Responsive Hydrogel Indicator for Real-Time Food Freshness Monitoring

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ABSTRACT: Food spoilage remains a major challenge in the food industry, leading to significant economic losses and potential health risks. The development of intelligent packaging systems capable of real-time freshness monitoring has emerged as an effective solution to enhance food safety and reduce waste. In the present study, a biodegradable pH-sensitive hydrogel indicator was developed for the rapid detection of food spoilage through visible color changes. The hydrogel matrix was formulated using biodegradable and environmentally friendly polymeric materials, incorporating natural pH-responsive pigments that exhibit distinct color transitions in response to changes in acidity and alkalinity. During food deterioration, the production of volatile basic compounds such as ammonia and amines alters the surrounding pH, triggering a measurable color change in the hydrogel indicator. The developed system demonstrated high sensitivity, rapid response, excellent visual detectability, and good stability under storage conditions. Furthermore, the biodegradable nature of the hydrogel contributes to sustainable packaging practices by minimizing environmental impact compared to conventional synthetic indicators. The proposed hydrogel indicator offers a cost-effective, non-toxic, and user-friendly approach for real-time monitoring of food freshness and spoilage. Therefore, this smart biodegradable sensing platform has significant potential for application in intelligent food packaging systems, improving consumer safety, product quality assurance, and sustainability in the food supply chain.

KEYWORDS: Biodegradable Hydrogel, Food Spoilage Detection, Intelligent Packaging, Ph-Sensitive Indicator, Natural Pigments, Smart Food Packaging, Food Safety

OBJECTIVES:

1. **To prepare a biodegradable pH-sensitive hydrogel** using sodium alginate and natural pigments extracted from beetroot (betalain) and turmeric (curcumin).
2. **To develop an eco-friendly colorimetric indicator system** capable of exhibiting visible color changes in response to pH variations associated with food spoilage.
3. **To characterize the synthesized hydrogel using FTIR analysis** and confirm the successful incorporation of natural pigments and hydrogel network formation.
4. **To evaluate the pH responsiveness and microbial spoilage detection capability** of the hydrogel against food spoilage microorganisms such as *Bacillus subtilis* and *Proteus mirabilis*.
5. **To assess the practical applicability of the hydrogel in intelligent food packaging** by monitoring freshness changes in perishable food products such as milk and paneer.

I. INTRODUCTION

Food spoilage is a significant global concern that affects food quality, consumer safety, and economic sustainability. According to the Food and Agriculture Organization (FAO), approximately one-third of all food produced worldwide is lost or wasted annually due to microbial contamination, improper storage, and deterioration during transportation and distribution. Traditional food packaging systems primarily serve as passive barriers against environmental factors; however, they do not provide information regarding the real-time freshness status of food products. Consequently, there is an increasing demand for intelligent packaging technologies capable of monitoring food quality and spoilage throughout the supply chain [1,2].

Smart packaging systems have emerged as innovative solutions that combine conventional packaging functions with sensing and monitoring capabilities. Among these systems, freshness indicators have gained substantial attention because they can provide visual information regarding food quality through color changes or other measurable responses. Freshness indicators typically respond to chemical compounds generated during food degradation, including volatile amines, ammonia, hydrogen sulfide, and organic acids [3,4].

The spoilage of protein-rich foods such as meat, fish, poultry, and seafood is commonly associated with microbial metabolism that produces volatile basic nitrogen compounds. These compounds increase the pH of the food environment and can be effectively monitored using pH-sensitive materials. Therefore, pH-responsive indicators have become one of the most widely investigated approaches for food freshness monitoring due to their simplicity, reliability, and cost-effectiveness [5,6].

Hydrogels are three-dimensional polymeric networks capable of absorbing and retaining large amounts of water while maintaining structural integrity. Their porous structure, biocompatibility, flexibility, and responsiveness to environmental stimuli make them excellent candidates for sensing applications. In recent years, hydrogel-based indicators have attracted considerable interest in intelligent food packaging because they can incorporate pH-sensitive dyes or natural pigments that undergo visible color transitions in response to changes in acidity or alkalinity [7,8].

Biodegradable hydrogels are particularly advantageous because they address environmental concerns associated with synthetic plastic-based packaging materials. Natural polymers such as chitosan, gelatin, starch, cellulose, alginate, pectin, and carrageenan have been extensively explored for the fabrication of biodegradable hydrogel matrices. These materials are renewable, non-toxic, biocompatible, and environmentally friendly, making them suitable for food-contact applications [9–12].

Natural pigments including anthocyanins, curcumin, betalains, and shikonin have been widely incorporated into hydrogel systems as pH-sensitive indicators. Anthocyanins, extracted from red cabbage, purple sweet potato, black rice, berries, and other plant sources, exhibit remarkable color variations over a wide pH range. These pigments can change from red under acidic conditions to purple, blue, green, or yellow under alkaline conditions, providing a simple visual method for detecting food spoilage [13–16].

Several studies have demonstrated the successful application of pH-sensitive hydrogel indicators in monitoring the freshness of fish, shrimp, chicken, pork, beef, and dairy products. The indicators exhibit rapid response times and clear color changes corresponding to microbial growth and the accumulation of spoilage metabolites. Furthermore, biodegradable hydrogel indicators contribute to sustainable packaging practices by reducing plastic waste and promoting environmentally responsible food preservation technologies [17–20].

Recent advances in nanotechnology and polymer science have further improved the performance of hydrogel-based indicators. The incorporation of nanomaterials, bioactive compounds, and multifunctional polymers has enhanced mechanical strength, sensitivity, stability, and antimicrobial properties. These developments have expanded the potential applications of hydrogel indicators in intelligent packaging systems and food quality monitoring [21–24].

Despite significant progress, challenges remain regarding long-term stability, large-scale manufacturing, regulatory approval, and commercialization. Future research should focus on improving indicator durability, color stability, consumer acceptance, and integration with digital monitoring technologies. The development of biodegradable pH-sensitive hydrogel indicators represents a promising approach toward achieving safer food products, reducing food waste, and supporting sustainable packaging solutions. Therefore, continued investigation into environmentally friendly hydrogel-based freshness indicators is essential for advancing next-generation intelligent food packaging systems [25–30]. Curcumin is a natural bioactive compound derived from *Curcuma longa* (turmeric) and has attracted considerable attention due to its antioxidant, antimicrobial, anti-inflammatory, and pH-responsive properties. Its ability to undergo visible color changes under different pH conditions makes it an effective natural indicator for intelligent food packaging and freshness monitoring applications. Curcumin has been successfully incorporated into biodegradable polymers such as chitosan, sodium alginate, gelatin, and starch to fabricate eco-friendly films and hydrogels capable of detecting food spoilage through pH variations caused by microbial activity. Furthermore, curcumin-based materials exhibit significant antioxidant and antimicrobial activities, which contribute to enhanced food preservation and extended shelf life. Owing to its biodegradability, non-toxicity, and sustainability, curcumin is considered a promising alternative to synthetic colorimetric indicators in smart packaging systems. However, limitations such as poor water solubility and sensitivity to light remain challenges, which are being addressed through advanced approaches including polymer modification, nanoencapsulation, and nanocomposite-based delivery systems [31].



Fig-1. Curcumin antioxidant

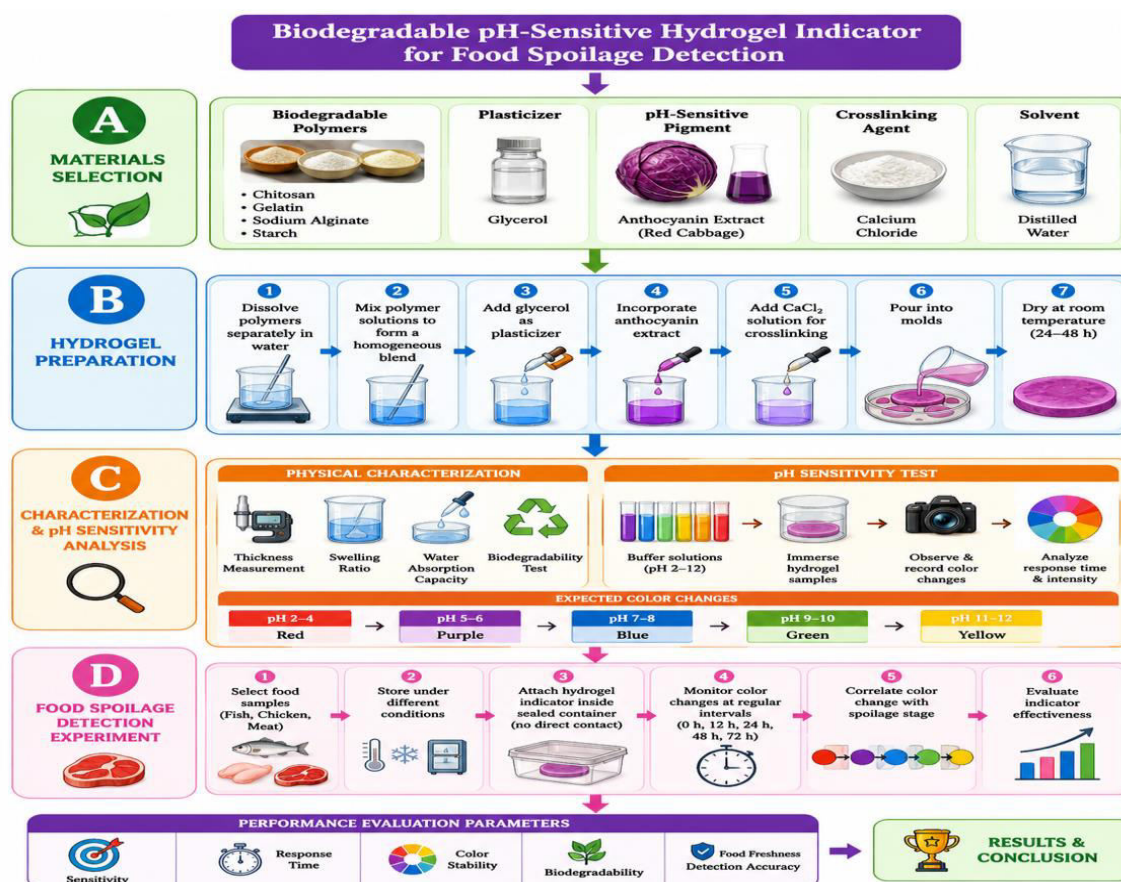
Betalains are natural water-soluble pigments primarily obtained from *Beta vulgaris* (beetroot) and are recognized for their vibrant red, violet, and yellow colors, along with their antioxidant and pH-sensitive properties. Due to their ability to exhibit distinct color changes in response to pH variations, betalains have emerged as promising natural indicators for intelligent food packaging and freshness monitoring applications. These pigments have been successfully incorporated into biodegradable polymers such as chitosan, sodium alginate, starch, and gelatin to develop eco-friendly films and hydrogels capable of detecting food spoilage through color changes caused by microbial-induced pH alterations. In addition to their sensing capability, betalains possess antioxidant activity that can help maintain food quality and enhance storage stability. Their natural origin, non-toxic nature, and biodegradability make them attractive alternatives to synthetic colorants in smart packaging systems.



Fig -2 Betalains (water-soluble pigments)

Nevertheless, challenges related to their sensitivity to heat, light, and oxygen can affect their stability and performance, prompting ongoing research into advanced stabilization techniques to improve their long-term applicability in sustainable packaging materials [32].

II. METHODOLOGY



A. Materials Selection

Biodegradable polymers such as chitosan, gelatin, sodium alginate, and starch were selected as the hydrogel matrix due to their biocompatibility, biodegradability, and food-safe properties. Natural pH-sensitive pigments (anthocyanins extracted from red cabbage) were used as indicator dyes because of their ability to change color in response to pH variations associated with food spoilage.

1) Materials Used

- Chitosan
- Gelatin
- Sodium Alginate
- Distilled Water
- Glycerol (Plasticizer)
- Anthocyanin Extract (Red Cabbage)
- Calcium Chloride (Crosslinking Agent)

2) B. Preparation of pH-Sensitive Hydrogel

The hydrogel was prepared using a solution-casting technique.

3) Procedure

1. Chitosan and gelatin were dissolved separately in distilled water under continuous stirring.
2. The polymer solutions were mixed to obtain a homogeneous blend.
3. Glycerol was added as a plasticizer to improve flexibility.
4. Anthocyanin extract was incorporated into the polymer mixture.
5. Calcium chloride solution was added to initiate crosslinking.
6. The mixture was poured into molds and allowed to dry at room temperature for 24–48 hours.
7. The formed hydrogel films were removed and stored for further analysis.

4) C. Characterization and pH Sensitivity Analysis

The prepared hydrogel indicators were evaluated for their physical and sensing properties.

5) Physical Characterization

- Thickness Measurement
- Swelling Ratio
- Water Absorption Capacity
- Biodegradability Test

6) pH Sensitivity Test

1. Buffer solutions with pH values ranging from 2 to 12 were prepared.
2. Hydrogel samples were immersed in each solution.
3. Color changes were observed and recorded.
4. Images were captured for comparison.
5. Response time and color intensity were analyzed.

7) Expected Color Changes

pH Range	Color
2–4	Red
5–6	Purple
7–8	Blue
9–10	Green
11–12	Yellow

8) D. Food Spoilage Detection Experiment

The developed hydrogel indicator was tested using real food samples.

9) Experimental Setup

1. Fresh fish, chicken, and meat samples were stored at room temperature and refrigerated conditions.
2. Hydrogel indicators were attached inside sealed food containers without direct contact with the food.
3. Color changes were monitored at regular intervals (0 h, 12 h, 24 h, 48 h, and 72 h).
4. Changes in indicator color were correlated with food spoilage stages.

5. The effectiveness of the indicator was evaluated based on visual detection and response time.

10) Performance Evaluation Parameters

- Sensitivity
- Response Time
- Color Stability
- Biodegradability
- Food Freshness Detection Accuracy

The overall workflow involved material selection, hydrogel fabrication, pH-response characterization, and real-time food spoilage monitoring. The developed biodegradable hydrogel indicator demonstrated potential as an eco-friendly intelligent packaging solution for rapid and visual detection of food spoilage.

Instruments and solutions:



FTIR



Magnetic stirrer

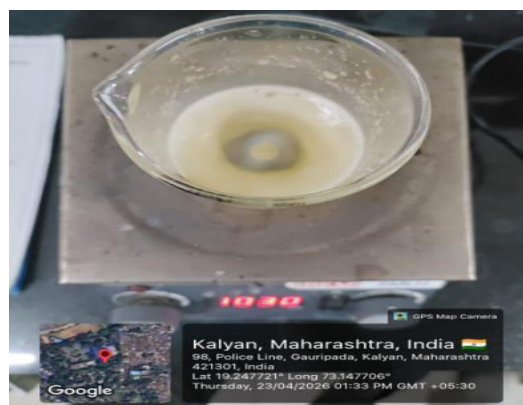


Fig-3 Sodium Alginate Solution

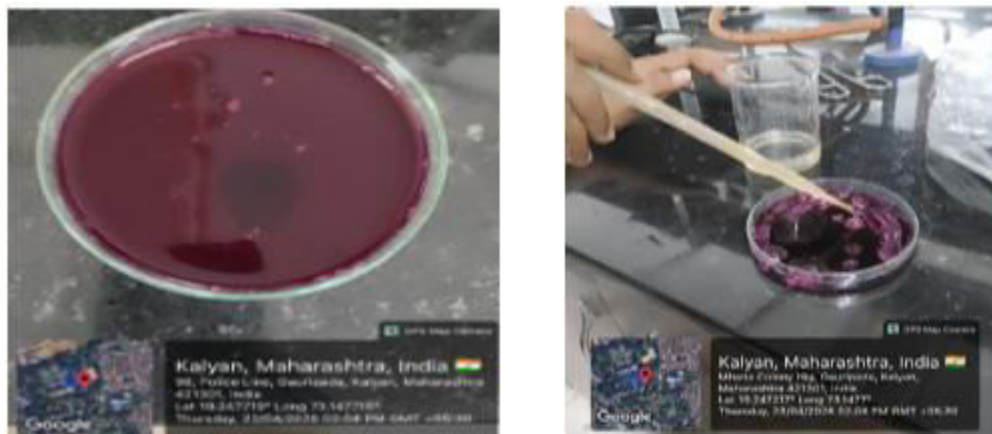
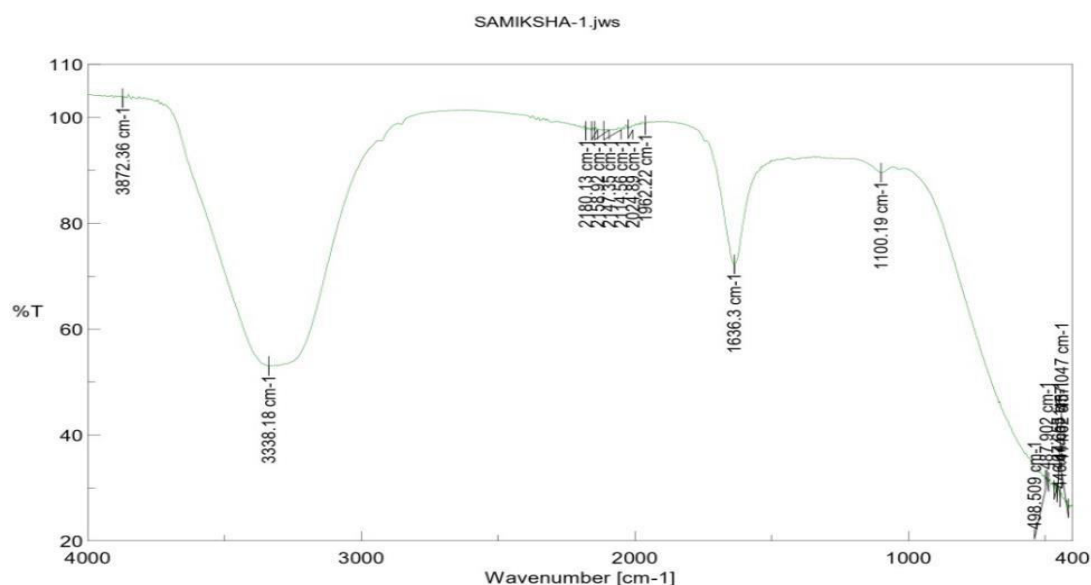


Fig-4 Betalain extract and curcumin extract in to the alginate solution



Fig -5 Hydrogel Formation (Crosslinking Process)



III.CHARACTERIZATION

Peak Position (cm ⁻¹)	Functional Assignment	Group	Interpretation
~3381.8	O–H stretching vibration		Broad absorption peak attributed to hydroxyl (–OH) groups present in sodium alginate, betalain, curcumin, and absorbed water molecules within the hydrogel matrix.
~1653.3	COO [–] asymmetric stretching / H–O–H bending		Indicates the presence of carboxylate groups of sodium alginate and confirms interactions with calcium ions during ionic crosslinking of the hydrogel network.
~1101.1	C–O–C and C–O stretching		Characteristic peak of the polysaccharide backbone of sodium alginate and phenolic compounds present in betalain and curcumin extracts.
1000–400	Fingerprint region		Represents complex vibrational modes of alginate, betalain, and curcumin molecules, confirming the successful incorporation of natural constituents within the hydrogel network.

IV. EXPERIMENTAL RESULTS

1. Successful Hydrogel Formation

Sodium alginate was successfully crosslinked with Ca²⁺ ions, producing a stable and flexible hydrogel network suitable for food-packaging applications.

2. Efficient Incorporation of Natural Pigments

Betalain (beetroot extract) and curcumin (turmeric extract) were uniformly incorporated into the hydrogel matrix without affecting gel formation.

3. pH-Responsive Color Change

The hydrogel exhibited clear and visible color changes under different pH conditions, confirming its pH-sensitive behavior.

4. Curcumin Indicator Performance

Curcumin changed from yellow to orange-brown/reddish-brown as pH increased, enabling easy detection of alkaline spoilage conditions.

[Comments]		SAMIKSHA-1.jws	
Sample name	SAMIKSHA	[Detailed Information]	
Comment		Creation date	21-04-2026 14:37
Username		Date modified	21-04-2026 14:38
Division		Data array type	
Organization	B.K. Birla College	Linear data array	
[Measurement Information]		Horizontal axis	Wavenumber [cm-1]
Model name	FT/IR-4X1typeA	Vertical axis	%T
Serial No.	A150562111	Start	399.193 cm-1
Accessory	ATR PRO 4X	End	4000.6 cm-1
Accessory S/N	A081862126	Data interval	0.964233 cm-1
Incident angle	45 deg	Data points	3736
Measurement date	21-04-2026 14:37		
Light source	Standard		
Detector	TGS		
Accumulation	16		
Resolution	4 cm-1		
Zero filling	On		
Apodization	Cosine		
Gain	Auto (8)		
Aperture	Auto (7 mm)		
Scan speed	Auto (2 mm/sec)		
Filter	Auto (12800 Hz)		

5. Betalain Indicator Performance

Betalain showed a transition from bright red/pink to faded brownish colors with increasing pH, demonstrating effective spoilage indication.

6. Detection of Microbial Activity

The hydrogel successfully responded to metabolic products produced by *Proteus mirabilis* and *Bacillus subtilis*, indicating bacterial growth through color variation.

7. FTIR Confirmation of Crosslinking

FTIR peaks at approximately 3381.8 cm^{-1} , 1653.3 cm^{-1} , and 1101.1 cm^{-1} confirmed hydroxyl groups, alginate-calcium interactions, and polysaccharide backbone formation within the hydrogel.

8. Milk Freshness Monitoring

Fresh milk showed red/pink (betalain) and yellow (curcumin) colors, whereas spoiled milk exhibited fading and color variation, indicating spoilage progression.

9. Paneer Spoilage Detection

Fresh paneer maintained its original indicator colors, while spoiled paneer caused significant color changes to purple-brown and orange-brown, demonstrating practical freshness monitoring capability.

10. Potential for Sustainable Smart Packaging

The developed hydrogel proved to be biodegradable, low-cost, eco-friendly, and capable of providing real-time visual spoilage indication, making it a promising intelligent food-packaging material.

V. CONCLUSION

A biodegradable pH-sensitive hydrogel indicator was successfully developed using sodium alginate as the polymer matrix and natural pigments extracted from beetroot (betalain) and turmeric (curcumin). The hydrogel exhibited distinct color changes in response to pH variations associated with microbial growth and food spoilage. FTIR analysis confirmed the successful crosslinking of sodium alginate with calcium ions and the incorporation of natural indicator compounds within the hydrogel network. The developed material effectively responded to the growth of *Proteus mirabilis* and *Bacillus subtilis*, demonstrating its ability to detect microbial activity through visible color transitions. Furthermore, the hydrogel successfully monitored freshness changes in food samples such as milk and paneer, indicating its practical applicability in intelligent food packaging systems. Owing to its biodegradability, low cost, non-toxic nature, and eco-friendly characteristics, the developed hydrogel represents a promising alternative to synthetic spoilage indicators and has significant potential for sustainable food quality monitoring and smart packaging applications.

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