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Development of pH-Responsive Smart Colorimetric Biobeads from *Gomphrena Globosa* Flower for Food Quality Monitoring

V Manivasagan[1], M Dhanalakshmi[2], J Divya[3], P Thiruvasuki[4]
[1,2,3,4] *Department of Biotechnology Adhiyamaan College of Engineering (Autonomous), Hosur, Tamil Nadu, India*

Abstract- The replacement of synthetic dyes with natural pigments in food packaging has gained significant attention due to environmental and safety concerns. In this study, pH-responsive colorimetric biobeads were fabricated using betalain pigments extracted from *Gomphrena globosa* (Globe Amaranth) flowers and encapsulated within a sodium alginate–calcium chloride hydrogel matrix. Betalains were extracted through Soxhlet extraction using 75% ethanol, concentrated, and characterized by UV–Visible spectroscopy, showing a major absorption peak at 538 nm, confirming the presence of betacyanin. The extract demonstrated pH-dependent color transitions from deep pink in acidic media to yellow in alkaline environments, confirming its suitability as a natural pH indicator. The pigment was successfully entrapped in calcium-crosslinked alginate beads, producing uniform, magenta- colored spheres of 2.5–3.2 mm diameter. Phytochemical screening confirmed the presence of betalains, phenols, and alkaloids. The biobeads exhibited high stability under dark, cool storage conditions and biodegraded naturally within 15 days when buried in soil. When tested with milk, fish, and meat samples, the beads displayed visible color changes corresponding to spoilage stages, shifting from pink (fresh) to yellow (spoiled). These results demonstrate that *G. globosa*-based pH-responsive biobeads provide a biodegradable, eco-friendly, and low-cost solution for real-time food freshness monitoring and intelligent packaging applications.

Keywords: *Gomphrena globosa*, betalains, sodium alginate, colorimetric indicator, pH- responsive biobeads, food freshness.

1. INTRODUCTION

The increasing global demand for safe, sustainable, and environmentally responsible food packaging materials has encouraged the development of natural pigment-based sensing systems. Conventional synthetic dyes used in foods and packaging pose genotoxic, mutagenic, and ecological risks (Slimen et al., 2017; Polturak & Aharoni, 2018). In contrast, natural colorants such as betalains, anthocyanins, and curcuminoids are biodegradable, non-toxic, and exhibit strong bioactivity, making them ideal candidates for smart packaging and freshness indicators (Martins et al., 2024).

Betalains are water-soluble nitrogenous pigments found primarily in the Amaranthaceae family. They are divided into betacyanins (red-violet) and betaxanthins (yellow-orange), both exhibiting strong antioxidant and antimicrobial activities (Lavanya & Thamaraiselvi, 2023). *Gomphrena globosa* L. (Globe Amaranth), a widely cultivated ornamental plant, is rich in betacyanin pigments such as gomphrenin-I, offering bright coloration and biological functionality (Roriz *et al.,* 2017). However, betalains are highly sensitive to pH, temperature, light, and oxygen, which limits their industrial application (Chaari *et al.,* 2024; Majdinasab *et al.,* 2018).

Encapsulation using biodegradable biopolymers like sodium alginate enhances pigment stability and enables pH- responsive color change suitable for intelligent food packaging (Pawar & Edgar, 2012). The present study aims to develop and characterize pH-responsive colorimetric biobeads based on *G. globosa* betalains entrapped within a sodium alginate–calcium chloride matrix for real- time food freshness monitoring.

II. MATERIALS AND METHODS

2.1 Materials

Fresh *Gomphrena globosa* flowers were obtained from local gardens. Analytical- grade sodium alginate, calcium chloride, ethanol, HCl, and NaOH were used. Equipment included a Soxhlet extractor, tray dryer, UV–Vis spectrophotometer, pH meter, and blender.

2.2 Sample Collection and Drying

Fresh flowers were cleaned with distilled water, air-dried, and then oven-dried at 60°C for 24 h. The dried material retained a deep magenta color, indicating pigment stability. Dried petals were ground into a fine powder and stored in airtight containers.

2.3 Extraction of Betalain Pigments

Ten grams of the powdered sample was extracted with 150 mL of 75% ethanol using Soxhlet extraction for 4–6 h. The extract was concentrated using a rotary evaporator and stored in amber bottles at 4°C to prevent photodegradation.

2.4 pH Measurement and Phytochemical Screening

The extract's pH was recorded as 7.2 using a calibrated digital pH meter. Qualitative tests confirmed the presence of bioactive compounds:

Table 2.1. Qualitative Phytochemical Tests

Test	Observation	Inference
NaOH Test	Pale yellow coloration	Indicates the presence of betalains
$FeCl_3$ Test	Blue-green coloration	Confirms the presence of phenolic compounds
Tannic Acid Test	Formation of precipitate (in para form)	Suggests the presence of alkaloids and tannins

2.5 Preparation of Sodium Alginate–Calcium Chloride Biobeads

A 4% (w/v) sodium alginate solution was prepared and mixed with the pigment extract for uniform dispersion. The mixture was dropped slowly into 2% (w/v) calcium chloride solution under stirring. The calcium ions crosslinked the alginate via the "egg-box" mechanism, forming hydrogel beads. The beads were hardened for 15–20 min, rinsed, and air-dried.

2.6 Spectrophotometric Analysis

UV–Vis absorption spectra were recorded from 350–700 nm. The betalain extract exhibited a strong absorption peak at 538 nm, characteristic of betacyanin.

2.7 pH-Responsiveness and Stability Tests

Color transitions were recorded across pH 3–9 using buffer solutions. Bead stability was assessed under light, dark, and refrigerated conditions over 30 days. Biodegradability was tested by burying beads in moist soil for 15 days.

2.8 Application in Food Freshness Detection

The biobeads were placed in proximity to milk, fish, and meat samples at ambient temperature. Color changes were monitored visually during storage to evaluate spoilage detection capability.

III. RESULTS AND DISCUSSION

3.1 Collection and Preparation of Raw Material

Fresh *Gomphrena globosa* flowers were collected, cleaned, and dried at 60°C for 24 hours. The dried flowers showed a deep magenta color, indicating good pigment retention and suitability for extraction.

Figure 3.1 Collected flowers

Figure 3.2 Dried flowers

3.2 Grinding and Sample Preparation

The dried *Gomphrena globosa* flowers were finely ground using a blender to increase surface area for efficient extraction. About 10 gm of the powdered sample was accurately weighed for bioactive compound extraction, ensuring uniformity and consistency in the extraction process.

Figure 3.3 Powder flower

3.3 Extraction and Pigment Characterization

Soxhlet extraction with hydroethanolic solvent yielded a bright violet-pink pigment, confirming efficient betalain recovery. The UV–Vis spectrum displayed a maximum absorbance at 538 nm (1.624 A.U.), validating the presence of betacyanin, the dominant betalain component (Calva-Estrada *et al.,* 2022).

Figure 3.4 Extraction of Pigment using a Soxhlet apparatus

Figure 3.5 Extracted pigment

Table 3.1 UV–Vis Analysis of *Gomphrena globosa* Pigment

Test	Observation	Compound Confirmed
NaOH test	Pale yellow	Betalains
$FeCl_3$ test	Blue-green	Phenolic compounds
Tannic acid test	Precipitate	Alkaloids

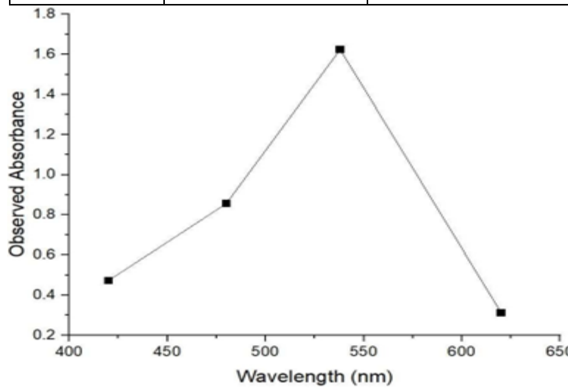

Figure 3.6 UV–Vis Analysis of *Gomphrena globosa* Pigment

3.4 Phytochemical Composition

Qualitative tests confirmed betalains, phenolic compounds, and alkaloids aligning with previous findings that *G. globosa* contains antioxidant and antimicrobial phytochemicals contributing to its stability and bioactivity (Lavanya *et al*., 2023).

Table 3.2 Phytochemical profile of *G. globosa* extract

Wavelength (nm)	Observed Absorbance (AU)
420 nm	0.472
480 nm	0.856
538 nm	1.624
600 nm	0.312

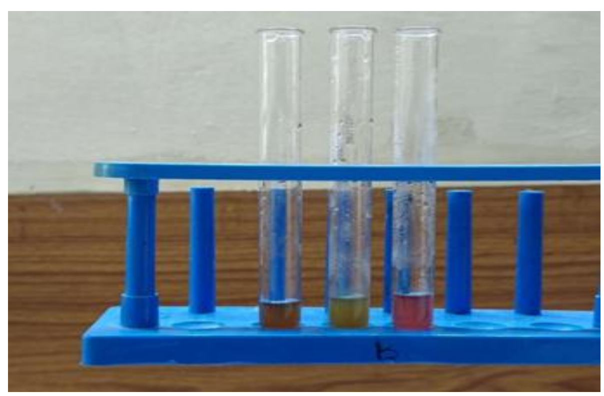

Figure 3.7 Phytochemical Analysis of *Gomphrena globosa* Extract

3.5 Formation of Sodium Alginate– Calcium Chloride Bio beads

Cross-linking between alginate chains and Ca^{2+} ions formed uniform spherical hydrogel beads (2.5–3.2 mm diameter) with vivid pink coloration. The beads exhibited good mechanical integrity and minimal pigment leaching, confirming successful encapsulation. Similar crosslinking behavior has been reported by Mohammadalinejhad *et al.* (2024) in anthocyanin-based indicator beads.

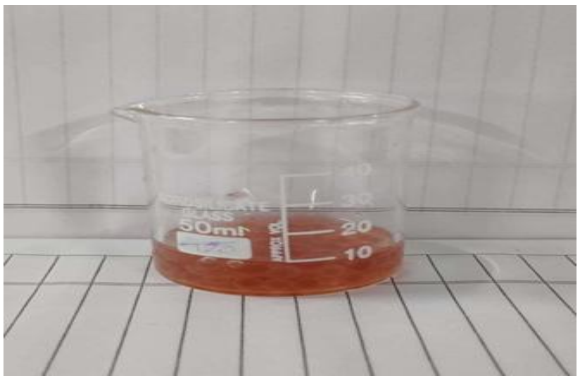

Figure 3.8 Crosslinking of beads

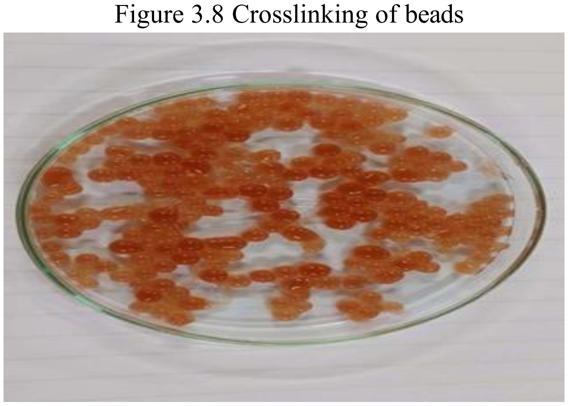

Figure 3.9 Beads formation

3.6 pH-Responsive Colorimetric Behaviour

The bio beads displayed distinct colour changes (Table 2) with increasing pH deep pink (pH 3–5) to light pink/violet (pH 6–7.5) to yellow-orange (pH 8–9). This reversible color transition results from protonation and deprotonation of chromophoric groups within the betalain molecule (Calva-Estrada *et al.,* 2022). Such responsiveness enables rapid, visible detection of food spoilage, as microbial metabolism raises pH through ammonia and amine release.

Table 3.3 pH-dependent color variation of bio beads

pH Range	Observed Color
3.0–5.0	Deep Pink
6.0–7.5	Light Pink to Violet
8.0–9.0	Yellowish Orange

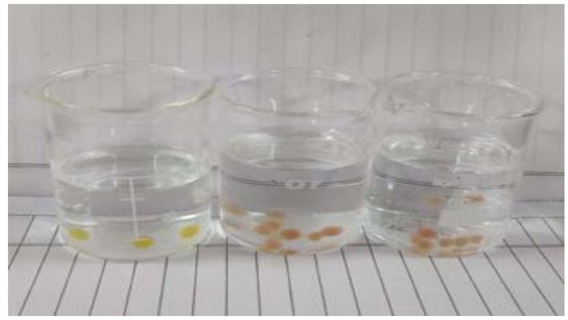

Figure 3.10 pH-Responsive Behaviour of Bio beads

3.7 Stability and Biodegradability

The biobeads maintained color stability for 30 days under dark refrigeration, while mild fading occurred under light exposure. Biodegradability was evident after 15 days in soil, with visible disintegration and weight loss. These properties confirm environmental safety and suitability for eco-friendly packaging applications.

3.8 Application in Food Freshness Monitoring

When applied to perishable foods, the biobeads effectively indicated spoilage through visible color shifts. In fish and meat samples, the beads remained pink during freshness and turned yellow upon spoilage, correlating with pH increase from microbial decomposition. This finding is consistent with prior studies employing anthocyanin- based indicators for similar applications (Ahmad *et al.,* 2019; Mohammadalinejhad *et al.,* 2024).

Overall, the *G. globosa* biobeads demonstrated reproducible colorimetric behavior, good storage stability, and rapid visual response to spoilage-related pH changes key features for practical intelligent packaging systems.

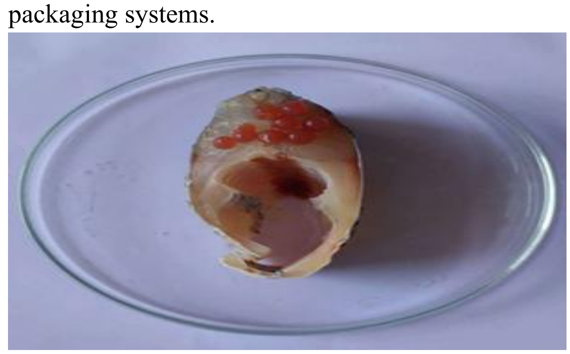

Figure 3.11 Freshness detection in fish

Figure 3.12 Spoilage detection in fish

IV. CONCLUSION

This study successfully formulated pH- responsive colorimetric biobeads using betalain pigments extracted from *Gomphrena globosa* flowers, encapsulated within a sodium alginate–calcium chloride hydrogel matrix. The biobeads exhibited clear pH-dependent color transitions, high stability under dark conditions, biodegradability, and strong performance in real-time food freshness detection. These results establish *G. globosa* betalains as promising natural alternatives to synthetic indicators, offering an eco-friendly, non- toxic, and cost-effective approach to intelligent food packaging and spoilage monitoring.

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