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BIODEGRADABLE *pH*-RESPONSIVE COLOURIMETRIC INDICATORS FOR SMART PACKAGING APPLICATION

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Abstract. Increasing interest in more sustainable and intelligent smart packaging has promoted the use of organic dyes as simple freshness indicators. In this research, two ideas were applied: first, the use of plant-based, sensitive pigments for spoilage detection, and second, comparing biodegradable indicators with synthetic ones for packaging purposes. At the same time, the transition to biodegradable insulation and packaging materials is becoming increasingly important, especially for the food sectors that rely on temperature-controlled transport. Conventional synthetic *pH* indicators as phenolphthalein and bromothymol, are difficult to recycle and cause long-term environmental waste, while novel biobased materials manufactured from plant fibers can provide similar thermal insulation with substantially lower environmental effect. Red cabbage anthocyanins and turmeric curcumin natural indicators were extracted and applied onto filter-paper absorbents, which then described the substance's acidity, neutrality, and basicity (or alkalinity). The absorbents showed clear, easily observable color transitions – anthocyanin changed from red to green-blue, while curcumin changed from yellow to a darker reddish- brown under alkaline conditions. These quick laboratory tests confirm that such natural indicators can function as cost-effective visual sensors for freshness monitoring. The findings demonstrate distinct differences across the indicators: curcumin responds weakly in basic conditions, bromothymol blue shows limited color changes around neutral to slightly alkaline *pH* (7–8), and phenolphthalein only reacts in extremely alkaline conditions (*pH* 9–10). When these biodegradable materials are combined with printed indicators using screen printing, extrusion, or additive manufacturing, the packaging can actively signal early spoilage or temperature-related changes.

Keywords: anthocyanins, curcumin, freshness monitoring, intelligent packaging, natural color indicators, *pH*-sensitive films, sustainable food packaging.

1. Introduction

In contemporary food supply chains, preserving product quality, freshness, and safety during storage remains a major concern, particularly for temperature-sensitive products such as fish, fresh fruits, and meat. Traditional packaging solutions protect products from external factors but do not provide real-time monitoring of internal conditions (Rais et al., 2025; Ghosh et al., 2024). In response to growing consumer demand for safe, fresh, and minimally processed food products, together with increasing environmental awareness, the development of intelligent and sustainable packaging systems has accelerated in recent years. Smart packaging incorporating natural *pH*-responsive indicators offers a practical approach for real-time monitoring of food quality, enabling early detection of spoilage and reducing food waste. The integration of such systems within circular economy principles promotes resource efficiency, waste reduction, and the use of biodegradable materials, supporting environmentally responsible packaging strategies (Hou et al., 2023; Kumar et al., 2025). Recent studies have underscored the potential of colorimetric food freshness indicators for intelligent packaging, demonstrating both progress and limitations in real-time spoilage detection (Zhai et al., 2025; Zhang et al., 2025).

pH variation is widely recognized as a reliable indicator of freshness and spoilage in food products, including meat, fish, dairy, and fermented beverages. In fresh meat and fish, *pH* typically ranges from 5.5 to 6.5 but increases above 7.0 during spoilage due to microbial protein degradation and the formation of volatile basic compounds such as ammonia and amines. In dairy products such as yogurt, *pH* decreases from approximately

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6.5 to 4.0–4.5 during fermentation as a result of lactic acid production, while deviations from this range during storage may indicate quality deterioration. Similar *pH*-dependent changes are observed in fermented beverages, where stable acidification reflects proper fermentation, whereas unexpected shifts may signal instability or contamination (Liu et al., 2022; Dodero et al., 2021; Peydayesh et al., 2024).

Biodegradable polymers have emerged as a promising approach for laboratory-scale *pH* monitoring, enabling environmental protection while allowing visual detection of *pH* changes. These materials combine functional colourimetric indicators with biodegradable matrices such as chitosan, starch, alginate, and cellulose (Rocha et al., 2025). Among these, *pH*-sensitive systems based on anthocyanins are particularly appealing due to their visible color responses and antioxidant properties. Red Cabbage Anthocyanins (RCAs) show distinct colour transitions across a wide *pH* range, making them versatile indicators for laboratory-scale evaluation. Curcumin, derived from Curcuma longa, serves as a *pH*-sensitive pigment and antioxidant, shifting from yellow to red under alkaline conditions, and hybrid anthocyanin-curcumin films demonstrate synergistic color responses with improved stability (Abedi-Firoozjah et al., 2022; Li et al., 2023; Khezerlou et al., 2023; Cvek et al., 2022; Zhou et al., 2023; Rais et al., 2025; Ghosh et al., 2024; Li et al., 2024).

pH-sensitive systems based on anthocyanins are particularly promising because they allow visual monitoring of spoilage-related *pH* changes caused by the release of organic nitrogen compounds during degradation. Anthocyanins extracted from natural sources such as red cabbage (*Brassica oleracea var. capitata f. rubra*), purple tomato (*Solanum lycopersicum*), saffron petals (*Crocus sativus*), and barberry (*Berberis vulgaris*) shows outstanding *pH* sensitivity and antioxidant capacity, and chitosan-enhanced anthocyanin films have been successfully applied for accurate monitoring of meat freshness (Abedi-Firoozjah et al., 2022; Li et al., 2023; Khezerlou et al., 2023; Ma et al., 2024; Rais et al., 2025).

Synthetic dyes, such as bromothymol blue, phenolphthalein, methyl red, and bromocresol green, are widely used for laboratory *pH* monitoring due to their reproducible color changes and serve as references for evaluating natural indicators (Wang & Liu, 2024; Chen et al., 2020; Ran et al., 2021; Al Obaidi et al., 2022). Hybrid systems combining natural pigments with polymers or mineral supports have been shown to improve thermal and optical stability, enabling rapid and reversible color responses upon *pH* shifts while supporting circular economy principles and laboratory-scale reproducibility (Szadkowski et al., 2025; Tavassoli et al., 2022; Zeng et al., 2023; Demirtas et al., 2025).

This research aims to develop a low-cost, reproducible methodology for laboratory-scale *pH* monitoring using cellulose strips impregnated with natural pigments. Quantitative evaluation is achieved through spectrophotometric and imaging analysis, avoiding complex polymer matrices or gelatin, providing a simplified and reproducible approach to evaluate the performance of natural *pH*-sensitive pigments under controlled conditions.

2. Materials and methods

Natural indicator preparation was conducted using cellulose-based filter strips, *pH* buffer solutions, and plant-derived pigment extracts. Curcumin and red cabbage were sourced from local markets in Vilnius, Lithuania. Anthocyanins were extracted from fresh red cabbage using a standardized procedure: approximately 50 g of cabbage was weighed using a digital scale and finely minced, then blended with 100 mL of distilled water until homogeneous suspension was obtained. The mixture was filtered through multiple layers of gauze to remove solids, yielding a clear anthocyanin extract (Figure 1c).

Curcumin was extracted from 5 g of turmeric powder mixed with 50 mL of 70% ethanol or boiled distilled water. The mixture was stirred thoroughly at room temperature (22 ± 1°C) for 15 minutes and then filtered to collect the curcumin-rich solution (Figure 1c).

Filter paper strips measuring approximately 1 × 5 cm were prepared and immersed in the corresponding pigment solutions for 2–3 minutes to ensure complete saturation (Figure 1a). Strips were then removed and dried at room temperature for 24 hours on a drying rack, protected from direct sunlight. This drying procedure ensured reproducibility and minimized pigment degradation across strips.

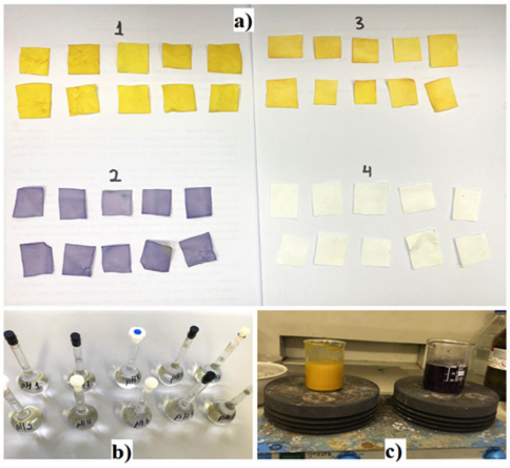

Figure 1. Preparation and pH response of cellulose strips with natural indicator: a) Cellulose filter strips soaked in natural anthocyanin solution extracted from 1 – curcumin 2 – red cabbage 3 – bromothymol blue 4 – phenolphthalein; b) strips immersed in a series of pH buffer solutions ranging from pH 1 to 10; c) anthocyanin extraction by boiling in water followed by filtration. Numbers 1–10 correspond to different pH values (1: strongly acidic, 2–6: mildly acidic, 7: neutral, 8–10: basic), showing the characteristic color changes of the indicator from red to purple to blue, reflecting its pH sensitivity

A series of buffer solutions covering the pH range 1–10 was prepared for testing (Figure 1b). Acidic buffers included hydrochloric acid (HCl, 37%), glacial acetic acid (CH_3COOH, 100%), and orthophosphoric acid (H_3PO_4, 85%). Alkaline buffers were prepared using sodium hydroxide (NaOH) and aqueous ammonia (NH_3, ~25%). Buffer salts were added to stabilize solutions: sodium acetate (CH_3COONa) for pH 3–5, sodium carbonate (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$) for pH 9–10, and phosphate salts (NaH_2PO_4 and Na_2HPO_4) for pH 5.8–8. Optional sodium chloride (NaCl) was used to adjust ionic strength.

Synthetic indicator preparation was performed using analytical-grade dyes purchased from laboratory suppliers. Bromothymol blue, phenolphthalein, were dissolved 70% ethanol at concentrations of 0.1–0.5% (w/v), ensuring complete dissolution. Filter paper strips of 1 × 5 cm were immersed in these solutions for 2–3 minutes and dried under the same conditions as the natural indicators. For dual-indicator strips, two dyes were mixed in equal volumes to expand the detectable *pH* range (Figure 1a). These synthetic indicators provided a comparative standard to evaluate natural pigments.

For qualitative color assessment, both natural indicators (red cabbage extract in Figure 2a and curcumin in Figure 2b) and synthetic strips (bromothymol blue in Figure 2c and phenolphthalein in Figure 2d) were immersed in each buffer solution for 30–60 seconds and then immediately placed on a horizontal surface for photography (Figure 2a–d). Images were taken under constant illumination, with a fixed smartphone camera distance, and standardized white balance.

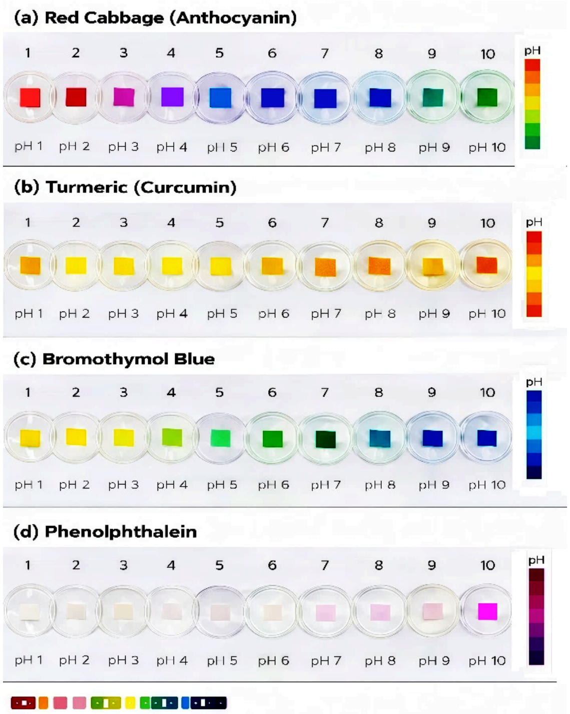

Figure 2. *pH*-dependent color spectra of: a) red cabbage; b) curcumin; c) bromothymol blue; d) phenolphthalein

Quantitative analysis was performed with red cabbage anthocyanins using a spectrophotometer, due to their broad, well-defined, and reproducible spectral response across a wide *pH* range. Their clear, monotonic bathochromic shift in maximum absorbance wavelength (λ_{max}) enables reliable regression modeling and accurate *pH* calculation using linear regression (Eqs. 1–2). In contrast, synthetic indicators, such as curcumin, show narrower *pH* response ranges, less distinct color transitions, or limited λ_{max} shifts, making quantitative analysis challenging. These synthetic indicators were therefore evaluated qualitatively using a camera, providing visual comparison data. By focusing on red cabbage anthocyanins for quantitative measurements and synthetic dyes for qualitative observations, the study ensures methodological rigor, reproducibility (n = 3), and robust reference data for assessing natural *pH*-sensitive pigments.

Spectrophotometric analysis was performed using a UV-1900 spectrophotometer within the 200–800 nm wavelength range at a resolution of 1 nm. Full absorbance spectra were recorded in scan mode over the visible range (400–700 nm) to capture all pH-dependent color transitions of the red cabbage anthocyanins. The maximum absorption wavelength (λ_{max}) was determined as the highest peak in each recorded spectrum and used as a quantitative reference for *pH* estimation (Figure 3). All measurements were conducted in triplicate (n = 3) using matched quartz cuvettes with an optical path length of 1 cm. Baseline correction was performed against the corresponding blank solution prior to each measurement. Reproducibility was ensured by repeating spectrophotometric measurements for each replicate and confirming consistency in λ_{max} values. Standard deviations and standard errors were calculated to assess variability between measurements. Overlay comparison of replicate spectra further verified measurement consistency.

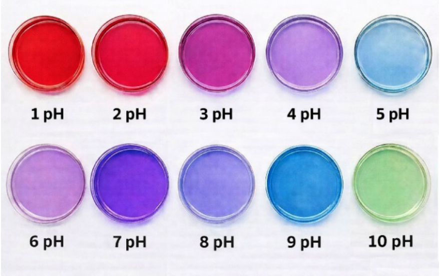

Figure 3. Red cabbage indicator solutions for spectrophotometric measurements

Laboratory equipment included a blender, mortar and pestle, filtration setup (filter paper), glassware (beakers, flasks, pipettes), digital balance and drying rack. All procedures were conducted at room temperature (22 ± 1°C) following standard laboratory practices for handling pH-sensitive pigments. A smartphone camera was used separately for documentation of the experiments. UV–Vis absorption measurements were performed using a

UV-1900 spectrophotometer manufactured by Shimadzu Corporation. The instrument operates over a wavelength range of 190–1100 nm with a 1 nm spectral bandwidth and utilizes a deuterium lamp (UV region) and tungsten-halogen lamp (visible region) as light sources. Regression model for *pH* calibration. The relationship between $\lambda_{\max}$ and *pH* was modeled using linear regression, as shown in Eq. (1):

$$\lambda_{\max} = a \times pH + b. \qquad (1)$$

$\lambda_{\max}$ – maximum absorption wavelength of the *pH*-sensitive compound, *a* – slope of the regression line, representing the change in $\lambda_{\max}$ per unit *pH*, *b* – intercept, representing the extrapolated $\lambda_{\max}$ at *pH* 0.

The *pH* of unknown samples was calculated by inverting the Eq. (2):

$$pH = \frac{\lambda_{max} - b}{a}. \qquad (2)$$

The coefficient of determination (R^2) was calculated to evaluate the accuracy of the regression model. An R^2 value close to 1 indicates that the majority of variation in $\lambda_{\max}$ is explained by solution *pH*, confirming the reliability of $\lambda_{\max}$ as a quantitative measure of *pH*.

The linear regression model (Eq. (1) was used to describe the relationship between the maximum absorption wavelength ($\lambda_{\max}$) of red cabbage anthocyanin and solution *pH*. The slope (*a*) indicates the change in $\lambda_{\max}$ per *pH* unit, while the intercept (*b*) represents the theoretical $\lambda_{\max}$ at *pH* 0. Using Eq. (2), the *pH* of unknown solutions was calculated from measured $\lambda_{\max}$ values. Application of this formula allowed for accurate determination of solution *pH*, with results closely matching the nominal buffer values. This demonstrates the reliability and reproducibility of the method, confirming that the red cabbage anthocyanin strips provide a predictable spectral response suitable for quantitative *pH* assessment. Other indicators, including curcumin and synthetic dyes, were analyzed qualitatively to compare visible color transitions, response ranges, and reproducibility, with red cabbage anthocyanin serving as the reference for quantitative evaluation.

3. Data analysis

The prepared indicator strips showed distinct and reproducible color changes when exposed to buffer solutions of different *pH* levels, demonstrating their effectiveness as laboratory-scale colorimetric *pH* sensors (Figure 3).

Anthocyanin-impregnated filters showed a wide color range, transitioning from red under acidic conditions to violet at near-neutral *pH* and green-blue under alkaline conditions. This broad chromatic response confirms the sensitivity of anthocyanin to *pH* variation across the investigated range (*pH* 1–10).

Red cabbage extract (anthocyanin) covered the entire tested *pH* range (1–10), showing a gradual color transition from bright red/red (*pH* 1–2) to pink–purple (*pH* 3–4), purple (*pH* 5–7), blue (*pH* 8–9), and finally green (*pH* 10).

Turmeric-derived curcumin exhibited a narrower response range. It remained yellow under acidic and neutral conditions (*pH* 1–6), shifted to yellow–orange at slightly alkaline *pH* (*pH* 7–8), and further changed to orange and reddish-brown under more alkaline conditions (*pH* 9–10).

Bromothymol Blue displayed its characteristic transition over a limited range. It was yellow under acidic conditions (*pH* 1–6), green at neutral *pH* (*pH* 7), and gradually changed to blue at alkaline *pH* (*pH* 8–9), becoming deep blue at *pH* 10.

Phenolphthalein remained colorless in acidic and neutral solutions (*pH* 1–8). A faint pink color appeared at *pH* 9, intensifying to bright pink at *pH* 10, reflecting its typical transition in strongly alkaline conditions.

Overall, bromothymol blue and phenolphthalein showed more restricted operational ranges, consistent with their known *pH* transition intervals. Red cabbage anthocyanin demonstrated the broadest and most continuous color change across the studied *pH* range and was therefore selected as the reference indicator for spectrophotometric analysis due to its wide *pH* sensitivity and gradual, well-defined spectral shifts.

Experimental UV–Vis analysis confirmed that anthocyanins from red cabbage shows strong absorption in the visible range, with peak wavelengths ($\lambda_{\max}$) shifting systematically with *pH*. These shifts correspond to visible color changes, highlighting their suitability as a natural colorimetric *pH* indicator under controlled laboratory conditions (Figure 2a).

Figure 4 shows the UV-spectrophotometric analysis of the maximum absorption wavelength ($\lambda_{\max}$) of red cabbage anthocyanin extract. At *pH* 1, a dominant absorption peak at approximately 525 nm was observed, corresponding to the flavylium cation form. As *pH* increased to 6, $\lambda_{\max}$ shifted toward approximately 590 nm, consistent with conversion to quinoidal base structures and the observed purple–blue coloration.

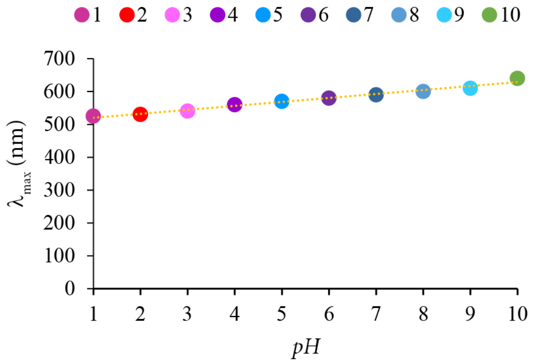

Figure 4. Red cabbage indicator: *pH*-dependent absorption spectrum

Figure 4 presents the UV–Vis spectrophotometric analysis of red cabbage anthocyanin extract, demonstrating a clear bathochromic shift in the maximum absorption wavelength (λ_{max}) with increasing *pH* under standardized buffer conditions. The absorption maximum progressively shifts from acidic to alkaline environments, corresponding to visible color transitions from red/pink through purple and blue to green. This spectral behavior reflects well-established structural transformations of anthocyanin molecules: the flavylium cation predominates under strongly acidic conditions, the quinoidal base form becomes dominant near neutral *pH*, and anionic or chalcone forms are favored in alkaline media.

The magnitude and direction of the observed λ_{max} shifts confirm the *pH* sensitivity of the extract across the investigated laboratory range (*pH* 1–10). Minor deviations in λ_{max} may result from variations in anthocyanin concentration, extraction procedure, solvent composition, or instrumental parameters. The obtained spectral trends are consistent with previously reported studies on red cabbage anthocyanin (Becerril et al., 2021; Wang & Liu, 2024; Rais et al., 2025), supporting the reproducibility of the present findings.

These results were obtained exclusively under controlled buffer conditions. The behavior, stability, and responsiveness of the indicator in real food matrices or after incorporation into packaging materials remain to be investigated. Accordingly, the present findings provide laboratory-scale optical characterization of the pigment rather than confirmation of practical spoilage detection performance or packaging functionality.

3.1. Discussion

The present study investigates the *pH*-dependent spectral behavior of red cabbage anthocyanin extract under controlled laboratory conditions using standardized buffer solutions. The experimental results demonstrate a clear and statistically significant relationship between solution *pH* and the absorbance properties of the extract. Across the investigated *pH* range (1–10), the maximum absorption wavelength (λ_{max}) increases progressively from 525 nm to 640 nm, corresponding to a total bathochromic shift of 115 nm. This shift is monotonic throughout the tested interval, with no abrupt discontinuities, indicating stable optical responsiveness of the anthocyanin extract under both acidic and alkaline conditions within the laboratory system.

Linear regression analysis confirms a strong correlation between *pH* and λ_{max} ($R^2 = 0.9788$), demonstrating that approximately 98% of the variance in λ_{max} is explained by changes in *pH*. The calculated slope of 12.09 nm per *pH* unit, with a 95% confidence interval of 10.64–13.54 nm/*pH*, indicates high spectral sensitivity within the investigated range. The associated p-value (5.62×10^{-8}) confirms the statistical significance of the observed trend. A standard deviation of 0.725 nm/pH (≈6% relative to the slope) is reasonable and indicates your *pH* sensor has a precise, stable response. These calibration parameters demonstrate that the indicator shows predictable optical behavior under standardized buffer conditions. Although minor deviations from perfect linearity are observed at higher *pH* values, the overall response remains well described by a linear model and is suitable for semi-quantitative optical calibration in laboratory systems. These calibration parameters (Table 1) demonstrate that the indicator shows predictable optical behaviour under standardised buffer conditions.

Table 1. Linear regression parameters for *pH* sensor response (nm versus *pH*)

Parameter	Value
Slope, nm/*pH*	12.09
Intercept, nm	508
R^2	0.979
p-value	5.62×10^{-8}
Standard Error, nm	0.63
Standard deviation, nm/*pH*	0.725
95% CI (Lower Bound) nm/*pH*	10.64
95% CI (Upper Bound) nm/*pH*	13.54

The spectral progression corresponds closely to visible color transitions. Under strongly acidic conditions (*pH* 1–2), red coloration reflects the predominance of the flavylium cation. Near neutral *pH* (5–7), purple and blue tones correspond to increasing contributions of quinoidal base structures. In alkaline media (*pH* 9–10), greenish coloration is associated with anionic and chalcone-type species. The strong agreement between λ_{max} progression and visible color transitions supports the molecular interpretation of anthocyanin structural transformations as a function of *pH*.

Quantitative analysis was limited to red cabbage anthocyanins due to their well-characterized spectral behavior, broad *pH* response, and reproducibility, providing a reliable reference for linear regression modeling. Other indicators, including curcumin and synthetic dyes (bromothymol blue, phenolphthalein), were evaluated qualitatively. Curcumin displayed lower color stability and sensitivity, particularly under near-neutral conditions, while synthetic dyes showed narrower response ranges. These differences underscore both the advantages of red cabbage anthocyanins for quantitative applications and the limitations of alternative pigments for precise spectral monitoring.

All measurements were conducted exclusively in standardized buffer solutions. The reproducible spectral response, strong statistical correlation, and broad *pH* sensitivity demonstrated under laboratory conditions provide a well-defined calibration framework. Future studies are required to evaluate performance in real food systems, assess matrix effects, and determine practical applicability under realistic storage and packaging conditions.

Comparison with literature indicates that the observed λ_{max} shifts and color transitions of red cabbage anthocyanins are consistent with previous studies (Becerril et al., 2021; Wang & Liu, 2024; Rais et al., 2025). Overall, findings demonstrate the potential of red cabbage anthocyanin strips as reliable *pH*-sensitive indicators under controlled laboratory conditions. They establish a foundation for future research aimed at applying natural pigments in smart and sustainable packaging, emphasizing the need for validation in real food systems.

4. Conclusions

Red cabbage (anthocyanin) extract demonstrated clear and reproducible *pH*-dependent color changes in standard buffer solutions (*pH* 1–10), transitioning from bright red at *pH* 1–2 to purple at *pH* 6–7 and finally to green at *pH* 10, accompanied by a bathochromic shift in λ_{max} from approximately 525 nm to 640 nm.

The observed spectral shifts correspond to structural transformations of anthocyanins: the flavylium cation under acidic conditions, the quinoidal base near neutral *pH*, and anionic/chalcone forms under alkaline conditions.

Linear regression analysis confirmed a strong correlation between *pH* and λ_{max} (slope = 12.09 nm/*pH*; intercept = 508 nm; $R^2 = 0.979$; p-value = 5.62×10^{-8}), with a 95% confidence interval of 10.64–13.54 nm/*pH*, indicating high spectral sensitivity within the investigated range.

Curcumin-based indicator strips showed a narrower response range, remaining yellow at *pH* 3–7 and shifting toward a reddish-brown color at *pH* 8–10, confirming their selective sensitivity to basic environments.

The results provide a laboratory-scale optical calibration and characterization of natural pigment-based *pH* indicators. Further research is required to validate their stability, selectivity, and practical applicability in real food systems and under realistic storage conditions.

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