



Editorial

Intelligent Packaging Systems with an Emphasis on Natural Pigment-Based Colorimetric Indicators: Curcumin and Anthocyanins

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Intelligent food packaging can be defined as a system that monitors and communicates information about the condition of packaged food from the production chain to the point of consumption; these systems aim to provide real-time information regarding quality and safety. Intelligent packaging doesn't alter the food itself; instead, it employs sensors or signaling components to report on factors such as temperature or spoilage that may affect quality. The objective for contemporary intelligent packaging is to minimize the waste by notifying the consumers about spoilage before expiry date and monitoring freshness and storage history (Azeredo and Correa, 2021; Kalpana et al., 2019; Schaefer and Cheung, 2018; Wang et al., 2025). In order to achieve these goals, smart packaging uses three main mechanisms:

1. Sensors: Instruments for detecting physical or chemical values (gas content, temperature, moisture, etc.) within or in a package. For example, gas sensors detect decomposition gases (O_2 , CO_2 , NH_3 , H_2S , and volatile organic compounds) to measure freshness. Time-Temperature Indicators (TTIs) are used to measure the thermal history of sensitive, perishable foods. Sensors sense the humidity to avoid molding or desiccation. Biosensors (usually enzyme- or DNA-based) mark pathogens or microbial metabolites but are not yet widely found in commercial packaging. Such sensors continuously monitor the following areas: for instance, the O_2 sensor states whether in modified atmosphere packaging, packaging integrity is maintained, or an NH_3 sensor can indicate spoilage on meat/fish (Palanisamy et al., 2025).

2. Indicators: Visual devices or labels that change color or appearance in response to environmental changes or byproducts of decomposition. Examples of common

indicators are freshness indicators (dyes that change color as they react with amines and volatile sulfides), time-temperature indicators (films that darken in response to cumulative exposure to heat), pH indicators (dyes sensitive to pH changes due to fermentation or decomposition), and gas indicators (inks or labels that respond to O_2 or CO_2). For instance, incorporated anthocyanin dye-based labels shift color (purple to green) as the pH increases due to fish spoilage, and a commercial "Fresh-Check" label darkens one spot with an increasing unit of time and temperature passed (Shao et al., 2021). These indicators create an intuitive color response, e.g., bromophenol blue from yellow to blue with the increase of ammonia (Total Volatile Basic Nitrogen [TVB-N]) in meat spoilage. (Palanisamy et al., 2025; Zhai et al., 2025).

3. Data carriers: Elements that store and transmit product information. These include barcodes (1D or 2D) and Radio-Frequency Identification (RFID)/ Near-Field Communication (NFC) tags. A barcode or QR code printed on the packaging transmits product, batch, and traceability data to scanners. RFID tags can contain detailed data (temperature history, location) and be read wirelessly during shipping. For example, RFID tags have been used to monitor cold chain temperature and gas sensors in transported food, improving product recall speed and reducing waste. QR codes on packaging often link to websites that offer nutritional information, allergen information, or supply chain traceability for greater consumer transparency. These data carriers do not detect spoilage themselves, but they communicate monitored data or control supply chain processes, thus complementing sensors and indicators. Together, these components create a smart packaging system (Heo and Lim, 2024; Palanisamy

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et al., 2025).

Natural color indicators

Among freshness indicators, natural pigments (curcumin, anthocyanins, betalains, and alizarin) are gaining increasing popularity as safe and biodegradable sensor colorants. These pigments undergo color changes depending on pH or react to spoilage compounds, enabling visible colorimetric monitoring of food quality (Abedi-Firoozjah et al., 2023; Zhai et al., 2025).

1. Curcumin

Curcumin is the bright yellow pigment found in the rhizomes of turmeric (*Curcuma longa*). It is a hydrophobic polyphenol widely used as a natural colorant and food additive. Curcumin is almost insoluble in water but soluble in ethanol. It contains enol hydroxyl groups in which ionization induces a color change. In neutral or slightly acidic solutions (pH \approx 3–7), curcumin solutions appear bright yellow. As the pH rises above \sim 8, curcumin deprotonates, and the solution turns orange-red and eventually brown at high alkalinity. The curcumin chromophore is also sensitive to certain volatile amines (e.g., NH_3 from spoiled meat), which raise the local pH and trigger color changes. Chemically, curcumin offers antioxidant and antimicrobial activity, which can, on its own, slow spoilage (Chen et al., 2020; Lv et al., 2023; Zhai et al., 2025).

Color behavior: In practical tests, curcumin-impregnated films remained yellow under initial conditions but turned orange/red upon accumulation of ammonia (Total Volatile Basic Nitrogen [TVB-N]). This color change (yellow \rightarrow red) is easily noticeable. However, curcumin is highly photosensitive and unstable: it degrades under UV light, heat, or in humid/alkaline conditions. Its low water solubility also results in slow diffusion within the films (Lv et al., 2023; Zhai et al., 2025).

Use in packaging: Curcumin can be incorporated into biopolymer films (chitosan, gelatin, starch, and Polyvinyl Chloride [PVC]) by casting or extrusion. In these films, it acts as a pH indicator dye (Lv et al., 2023; Zhai et al., 2025).

Advantages and limitations: The bright color and biological activity (antioxidant and antibacterial) of curcumin are advantages. It provides a clear visual signal and, as an antioxidant, can slightly extend shelf life. However, its disadvantages include low solubility and photo-instability.

2. Anthocyanins

Anthocyanins are water-soluble flavonoid pigments abundant in many fruits, vegetables, and flowers (berries,

red cabbage, grapes, purple corn, etc.). They are responsible for the red, purple, and blue hues found in nature and are easily extracted with hot water or ethanol (Lv et al., 2023; Rawdkuen et al., 2020). Anthocyanins exist in different ionic/structural forms depending on the pH. In strongly acidic media (pH $<$ 3), they predominantly form the red flavylium cation. As the pH increases, they convert to a colorless carbinol pseudobase and then to purple/blue quinonoidal bases around neutral pH. At even higher pH ($>$ 7–8), further deprotonation and ring opening occur, often producing greenish or yellow chalcone forms. Thus, anthocyanin solutions visually progress from red (pH \approx 1–2) to violet/blue (pH \approx 4–6) to green/yellow (pH $>$ 8), as shown by Lv et al. (2023). Chemically, anthocyanins are polyphenols (anthocyanidin glycosides) and have antioxidant activity. They are generally stable under moderate acidity (pH 3–5) but degrade under high pH, heat, or light (Chen et al., 2020; Fei et al., 2021; Kang et al., 2020; Lv et al., 2023; Yong and Liu, 2020).

Color behavior: In packaging tests, anthocyanins produce dramatic color changes. The vivid shift from red to blue and then to green provides a strong visual indicator. However, at a pH above 8, they typically turn brown or completely colorless (unstable chalcone), which limits their dynamic range. Anthocyanins also interact with metal ions or sugars, which can alter their color or stability (Lv et al., 2023).

Use in packaging: Anthocyanins are the most widely used natural indicators in smart packaging. They have been incorporated into gelatin, chitosan, starch, and other edible films. Numerous studies report the use of anthocyanin films in packaging for fresh meat, dairy products, and agricultural products (Lv et al., 2023; Palanisamy et al., 2025; Remedio et al., 2024).

Advantages and limitations: Anthocyanins are non-toxic, readily available, and exhibit strong color changes depending on pH. Their antioxidant and antimicrobial effects are beneficial. However, their stability is a concern; they degrade with light, high temperatures, or at neutral/alkaline pH. Furthermore, they discolor if not properly fixed to the film (Lv et al., 2023).

In summary, natural color indicators offer a safe and visual method for monitoring food freshness. Incorporated into smart packaging films or labels, they provide a direct color reading of chemical changes related to spoilage. For example, a change in the color of a fish package film from yellow to purple immediately alerts the retailer to a pH increase due to ammonia. By making spoilage visible, these indicators help prevent the accidental consumption of spoiled food and allow for disposal only when absolutely necessary. In this way, they improve food safety and reduce waste. Ongoing research focuses on improving pigment

stability and color response (e.g., through polymer matrices or nano-encapsulation). Overall, natural indicators such as curcumin, anthocyanins, betalains, and alizarin are promising tools in smart packaging, combining intense color change, biocompatibility, and functionality to help maintain food safety and keep consumers informed.

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