Biopolymeric Hydrogel Platforms Integrated with Colorimetric Indicators for Sustainable Intelligent Packaging

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Abstract

Intelligent packaging has emerged as a promising strategy to address global challenges of food safety, quality assurance, and waste reduction. Among the various approaches, colorimetric indicators are particularly attractive due to their ability to provide simple, real-time, and user-friendly visual information to consumers. Recent efforts have focused on integrating these indicators within hydrogels derived from natural and biodegradable polymers. Biopolymeric hydrogels, owing to their high water-retention capacity, tunable porosity, and compatibility with eco-friendly materials, serve as versatile carriers for responsive dyes. When functionalized with natural pigments such as anthocyanins, curcumin, or betalains, hydrogel matrices can effectively respond to food spoilage-associated changes including pH variation, moisture release, and volatile amine generation. These interactions trigger distinct and reproducible color changes that can be readily interpreted without the need for specialized equipment. Advances in material design include the use of polysaccharides (cellulose, starch, chitosan, alginate) and protein-based hydrogels, which not only ensure safety and biodegradability but also improve dye stability. Crosslinking, polymer blending, and incorporation of nanomaterials have further enhanced the sensitivity, durability, and functional versatility of hydrogel-based systems. Nonetheless, challenges persist regarding long-term stability, scalability of production, and regulatory acceptance for commercial applications. Overall, biopolymeric hydrogel–colorimetric platforms represent a sustainable alternative to petroleum-based packaging materials. Their integration into intelligent packaging systems has significant potential to enhance food safety, minimize waste, and contribute to circular economy goals by combining eco-friendly materials with real-time freshness monitoring.

Keywords: Intelligent packaging; Biopolymeric hydrogels; Colorimetric indicators; Natural pigments; Sustainability.