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PREPARATION OF pH-SENSITIVE PACKAGING FILM FROM RED PITAYA (*HYLOCEREUS POLYRHIZUS*) PEEL FOR LAMB MEAT FRESHNESS MONITORING

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Abstract

With growing demands for real-time food freshness monitoring and sustainable packaging, pH-sensitive intelligent films derived from natural pigments have gained significant attention as eco-friendly alternatives. In this study, a pH-sensitive intelligent packaging films were developed using red pitaya (*Hylocereus polyrhizus*) peel pigment–combined with polyvinyl alcohol (PVA) and chitosan (CS). Physicochemical properties, antioxidant activity, and lamb freshness-indicating performance were evaluated. Compared to pure PVA-CS films, PVA-CS-BE films had reduced transparency, mechanical properties, and moisture content, but increased thickness and solubility. In addition, PVA-CS-BE films showed distinct pH-dependent color changes, and 3.6-fold higher DPPH scavenging. In lamb preservation, the films monitored spoilage via visible, distinguishable color changes. PVA-CS-BE films have excellent stability, antioxidant capacity, and color-indicating functionality, demonstrating significant application potential.

Introduction

Food packaging protects food quality and integrity. As a key part of the food industry, it is essential for food safety and quality. Modern types include metal, plastic, glass, and paper-based materials; plastic is the most widely used due to its favorable properties. Yet, environmental concerns and demand for safer food drive a shift to recyclable/eco-friendly materials, with green packaging and nanomaterials becoming key research trends (Ramezani *et al.* 2025).

Active and intelligent packaging are innovative green options, going beyond traditional passive protection to regulate food quality and safety (Dirpan *et al.* 2023). Active packaging extends shelf life via functional components. Zheng *et al.* (2023) developed composite films from fish gelatin and essential oils, effectively prolonging bread's shelf life. Intelligent packaging incorporates sensors that monitor and provide real-time feedback on food conditions, supporting visual quality control. Examples include freshness indicators that change color to signal spoilage, making them ideal for dairy, meat, and produce (Zhao *et al.* 2022, Chen *et al.* 2023). Despite recent advances, pH-sensitive intelligent packaging remains a promising area for further research. Natural food colorants are better than synthetic dyes for indicator films due to safety and bioactivity. For instance, waste peel from pitaya (*H. polyrhizus*) is rich in betacyanin (Mang *et al.* 2025). Natural biopolymers like Chitosan (CS), also play a key role in intelligent film production. Chitosan (CS), derived from chitin, is biocompatible, biodegradable, and nontoxic. It exerts antibacterial action by disrupting cell membranes and genetic material, making it suitable for active biodegradable packaging (Islam *et al.* 2023). Blending CS with essential oils or plant extracts can enhance its antibacterial and antioxidant performance (Siripatrawan and Harte 2010). In contrast, PVA offers high hydrophilicity, chemical stability, and superior film-forming ability, making it advantageous for food packaging.

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Therefore, this study was conducted to utilize pitaya peel pigment as a raw material, combined with PVA and CS, to prepare a pH-sensitive degradable intelligent packaging film for application in monitoring lamb freshness. The pitaya peel used in this project is not only a widely available material source that promotes waste reuse, but the resulting film also possesses characteristics such as biodegradability, eco-friendliness, and good biocompatibility. This project can offer references for the research and development of novel preservation films.

Materials and Methods

Chitosan, Glycerol, acetic acid, PVA and sodium tripolyphosphate was obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). Pitaya (*Hylocereus polyrhizus*) and lamb were purchased from a local supermarket (Bengbu, China).

Pitaya peel pigment was extracted with 30% ethanol using ultrasound (1:30 solid-liquid ratio, 30°C, 25 min) and centrifuged. After centrifugation, the supernatant was concentrated under reduced pressure and stored at 4°C. For film preparation, a CS solution was prepared by dissolving 0.3 g CS in 1% acetic acid, adding sodium tripolyphosphate, and sonicating. Simultaneously, PVA was dissolved in water with heating. After cooling, pitaya pigment, CS solution, and glycerol were added. The mixture was homogenized, sonicated, cast, and dried. All films were done at 43 ± 2% relative humidity, with unpigmented and pigmented films labeled PVA-CS and PVA-CS-BE, respectively.

Color difference and transparency were measured using a colorimeter (NR10QC, 3nh, China) and UV-Vis spectrophotometry, respectively. Mechanical properties including tensile strength (TA) and elongation at break (EAB) were tested according to Yu *et al.* (2022). Moisture content and water solubility were determined gravimetrically after drying and immersion processes. pH sensitivity was measurement by immersing films in buffers (pH 3-11) and measuring color changes. Structural characterization was performed by XRD (4°-80°, 40 kV/40 mA). Antioxidant activity (DPPH scavenging rate) was evaluated using the Nanjing Jiancheng Bioengineering Institute reagent kit following manufacturer protocols.

The pH value of meat samples was measured using a PHs-2F. Fresh mutton (5 g) was packaged in PVA-CS or PVA-CS-BE films, stored at 25°C, and evaluated for color and sensory properties (Table 1).

Table 1. Sensory evaluation criteria.

Parameter	3 points	2 points	1 point	0 point
Meat texture	Elastic muscle tissue	Slightly elastic muscle tissue	Poorly elastic muscle tissue	Soft muscle tissue
Surface color	Vibrant surface color	Moderately lustrous	Slightly dull color	Dull coloration
Odor	Characteristic lamb odor	Slight off-odor	Moderate off-odor	Strong off-odor

Data were analyzed using SPSS 26.0 and GraphPad Prism 9.0.0, with results expressed as mean ± SEM. Statistical significance (p <0.05) was determined by one-way ANOVA.

Results and Discussion

Appearance analysis showed that incorporating pitaya pigment significantly altered the optical properties of PVA-CS films. The PVA-CS-BE film exhibited markedly lower L^* and significantly higher a^* (Table 2), which resulted in reduced lightness and a distinct red tone. Furthermore, the b^* value shifted from 0.46-1.38, indicating a slight blue tint. The ΔE value increased significantly to 19.52, resulting in a light purple color. Transparency was significantly reduced by 36.7% (Fig. 1), indicating enhanced light-shielding and UV barrier performance. These findings corroborate previous studies on plant pigments, which also reduced light transmittance and improved oxidation protection in composite films (Zhuang *et al.* 2019, Yu *et al.* 2022).

Table 2. Δ*E* values of PVA-CS and PVA-CS-BE films.

Film type	*L**	*a**	*b**	△*E*	Color reference
PVA-CS	95.71 ± 0.51[a]	0.04 ± 0.23[b]	0.46 ± 0.54[a]	0[b]	
PVA-CS-BE	78.44 ± 0.60[b]	8.96 ± 0.14[a]	-1.38 ± 0.25[b]	19.52 ± 0.18[a]	

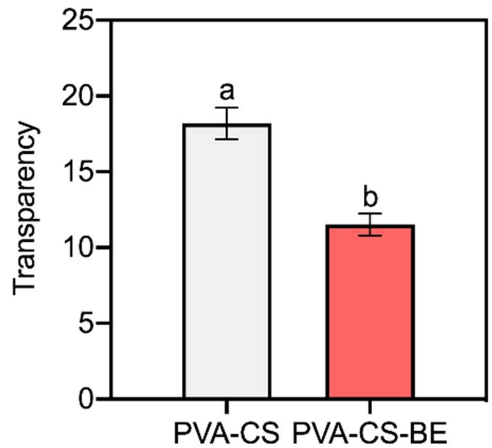


Fig. 1. Transparency of PVA-CS and PVA-CS-BE films.

Mechanical properties analysis showed that the addition of pitaya pigment significantly reduced both TS and EAB of the films, with TS decreased by 12.8% (Fig. 2a), while EAB dropped from 364.9 to 268.7% (Fig. 2b). Film thickness increased significantly from 0.040 mm to 0.051 mm (Fig. 3) which was found consistent with studies reporting thickening effects from plant extracts (Long *et al.* 2024). Moisture content significantly decreased from 28.97 to 14.27% which agree with previous findings that plant extracts reduce water absorption in CS-based films (Wang *et al.* 2019). Conversely, water solubility significantly increased from 7 to 21.67%, attributed to structural loosening induced by the pigment. This observation is supported by existing research, such as the notable increase in water solubility of CS/PVA-based composite films following curcumin addition (Huang *et al.* 2024).

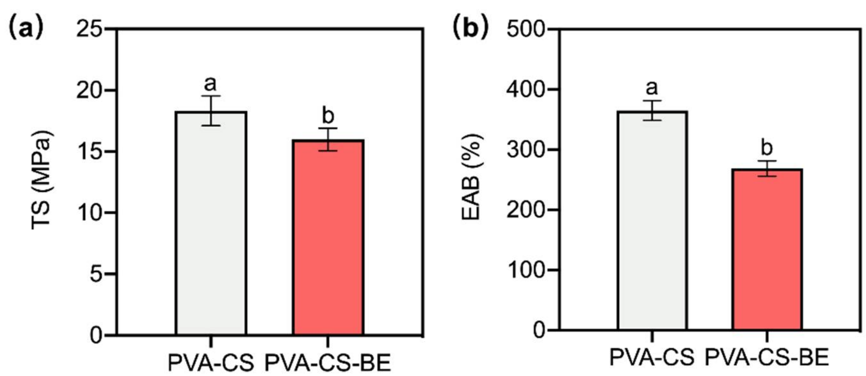


Fig. 2. TS (a) and EAB (b) of PVA-CS and PVA-CS-BE films.

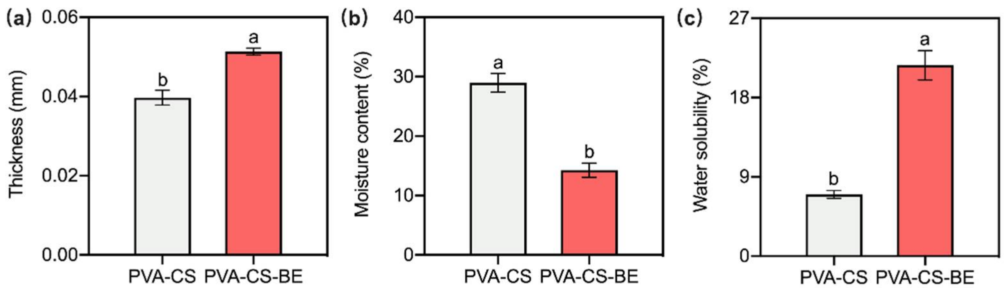


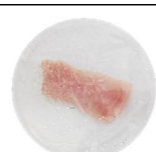
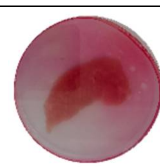
Fig. 3. Thickness (a), moisture content (b), and water solubility (c) of PVA-CS and PVA-CS-BE films.

The PVA-CS-BE films exhibited distinct pH-sensitive color changes. Under acidic conditions (pH 3-5), L^* decreased and a^* slightly increased (Table 3), indicating darker and redder tones. More pronounced shifts occurred in alkaline conditions (pH 7-11), with L^* reaching a minimum (62.62) and b^* increasing significantly, showing stronger yellow hues. The ΔE values increased progressively from 5.73 (pH 3) to 22.9 (pH 11), exceeding the visually detectable threshold (ΔE >5) at pH 7 (18.7). This significant pH-responsive color change demonstrates the film's potential for intelligent food packaging, particularly in the pH range relevant to fresh meat (pH 6-8) (Ma *et al.* 2024).

Table 3. Colorimetric response of PVA-CS and PVA-CS-BE films at different pH conditions.

pH	PVA-CS-BE	L^*	a^*	b^*	$\triangle E$
Control		78.72	8.97	-1.57	0
3		80.72	12.18	2.74	5.73
5		70.61	12.45	3.81	10.3
7		63.16	16.34	5.85	18.7
9		62.62	6.75	10.18	20.1
11		65.53	2.88	16.11	22.9

Table 4. Color response of PVA-CS-BE film to lamb freshness at 25°C after 48 hrs.

Freshness	PVA-CS		PVA-CS-BE	
Fresh		L^*=86.29 a^*=-0.60 b^*=-0.23 $\triangle E$=0		L^*=78.85 a^*=8.97 b^*=8.82 $\triangle E$=0
Spoilage		L^*=82.33 a^*=-1.09 b^*=1.38 $\triangle E$=4.3		L^*=72.27 a^*=-0.11 b^*=10.58 $\triangle E$=32.7

X-ray diffraction analysis revealed that adding pitaya pigment shifted the characteristic diffraction peak from 19.26° to 19.94° and significantly increased intensity from 3,883 to 8,250 CPS (Fig. 4). This may be enhanced crystallinity due to hydrogen bonding between the pigment and PVA/CS polymer matrix, consistent with the observed rise in water solubility (Fig. 3c).

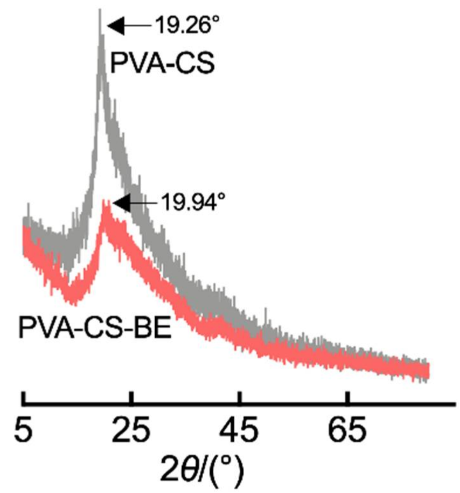


Fig. 4. XRD patterns of PVA-CS and PVA-CS-BE films.

Antioxidant analysis showed that PVA-CS-BE films significantly enhanced DPPH radical scavenging activity from 25 to 89.9% with pitaya pigment addition (Fig. 5). This improvement is attributed to the free amino groups in CS can react with DPPH radicals to form stable NH_3^+ and H^+ radical intermediates the potent radical-scavenging betacyanin present in the pitaya extract (Fogarasi *et al.* 2015, Hafsa *et al.* 2016).

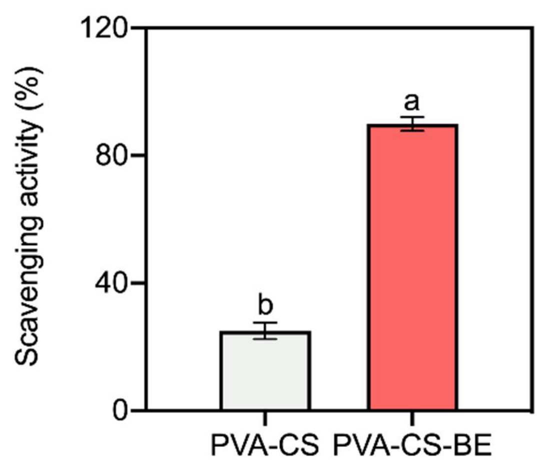


Fig. 5. DPPH radical scavenging rates of PVA-CS and PVA-CS-BE films.

Results demonstrated that 25°C storage caused significant pH increase and rapid sensory decline within just 2 days (Fig. 6), confirming high temperature accelerates spoilage. Within 12-48 h, L^* and a^* values decreased significantly, while b^* increased (Fig. 7). After two days, the ΔE of PVA-CS-BE reached 32.7, far exceeding the control (ΔE = 4.3), indicating visible color shifts. This change is likely due to ammonia volatiles from spoilage dissolving in the film's moisture layer, raising pH and altering pigment color (Alizadeh-Sani *et al.* 2021). The film shows strong potential for real-time mutton freshness monitoring.

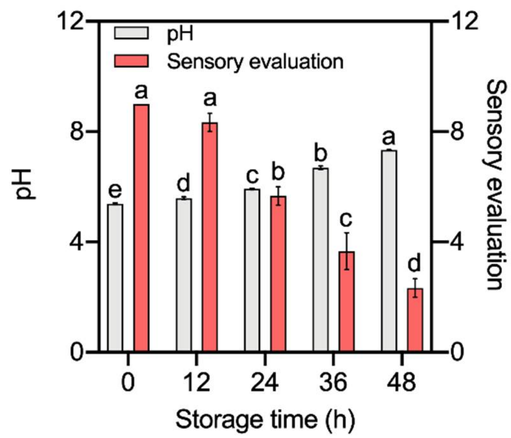


Fig. 6. pH and sensory evaluation score of fresh lamb at 25°C.

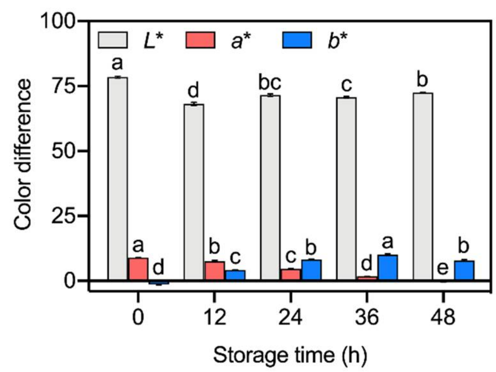


Fig. 7. Color response of PVA-CS-BE film to lamb freshness at 25°C.

In summary, a pH-sensitive intelligent packaging film was developed primarily from pitaya peel pigment, PVA, and CS. The resulting film demonstrated significant colorimetric changes in response to pH shifts and mutton spoilage, in addition to possessing enhanced antioxidant activity and the potential for real-time monitoring of food freshness.

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