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Development of pH-Sensitive Intelligent Indicator Film Based on Cassava Flour /Polyvinyl Alcohol Incorporated with Turmeric Powder (*Curcuma longa* L.) for Pork Freshness Monitoring

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Abstract

This study aimed to develop a biodegradable intelligent indicator film based on cassava flour and polyvinyl alcohol incorporated with turmeric powder for real-time monitoring of pork freshness. The cassava flour (CF) and polyvinyl alcohol (PVA) film were prepared using solution casting with glycerol as a plasticizer and varying turmeric contents (0% - 0.5% (based on the dry weight of CF). The films were evaluated for their physicochemical and functional properties. Results showed that increasing turmeric content slightly increased film thickness (0.19 - 0.29 mm) while decreasing moisture absorption (1.62% - 47.28%), water solubility (6.72% - 44.16%), and water vapor permeability (0.0043 - 0.0293 g/(m^2·kPa·h)), indicating enhanced barrier performance. FTIR spectra suggested possible hydrogen bonding interactions between curcumin and the polymer matrix. The films exhibited a distinct, reversible color transitions in response to pH variation, especially under ammonia exposure and during pork storage at 4 ± 1 °C. The 0.4% turmeric film demonstrated the greatest sensitivity, maintaining structural stability and showing the most pronounced color change. Biodegradability tests revealed 91% - 100% weight loss within 4 weeks, underscoring the films' environmental compatibility. Overall, turmeric-incorporated CF/PVA films represent a promising, eco-friendly alternative for smart packaging, linking biodegradability with pH-sensitivity to enhance food safety and reduce environmental impacts.

Keywords: Intelligent indicator film, Cassava flour, Polyvinyl alcohol, Curcumin, Turmeric, Pork spoilage

Introduction

Intelligent food packaging is designed to actively respond to changes in food quality or the surrounding environment by incorporating sensing elements that signal freshness, safety, or storage conditions [1]. These systems, which may involve indicators or sensors, provide valuable information such as temperature history, pH changes, and microbial spoilage [2]. Despite their potential, most commercial intelligent packaging technologies remain costly, rely on non-biodegradable materials, and contribute to environmental waste, limiting their sustainability [3]. To address these challenges, increasing attention has been given to biodegradable packaging films based on natural biopolymers such as chitosan [4], gelatin [5], lipids [6], and polysaccharides [7]. Among polysaccharides, cassava flour (CF) is an abundant, inexpensive, and locally available raw material with high potential for packaging applications. Its major components, amylose and amylopectin [8], enable film formation and biodegradability [9]. However, pure flour films are typically brittle and highly moisture-sensitive [10], requiring modification or blending to improve functionality.

Polyvinyl alcohol (PVA) is a synthetic polymer that is biodegradable, safe, non-toxic, and highly biocompatible. As a result, it has gained wide acceptance in biomedical, pharmaceutical, and food packaging applications as a composite material [11]. The blending of flour with PVA has been recognized as

an effective approach for improving both the mechanical and physicochemical properties, such as barrier performance against moisture and gas permeability [12]. The resulting composite films demonstrate excellent flexibility, uniform film-forming ability, and strong component adhesion within the matrix [11,12].

In recent years, natural pigments have been explored as colorimetric indicators in pH-responsive films, allowing real-time monitoring of food freshness. Plant-derived pigments such as anthocyanins, flavonoids, and curcumin [12] are especially attractive because they are non-toxic, biodegradable, and environmentally safe. Turmeric (*Curcuma longa* L.) is a rich source of curcumin, a natural polyphenol that exhibits distinct pH-dependent color changes, shifting from yellow/orange under acidic to neutral conditions to reddish-brown in alkaline media [13]. This property makes curcumin particularly suitable for detecting spoilage in pork, which produces volatile basic compounds such as ammonia and trimethylamine during storage [14]. Beyond its pH sensitivity, curcumin also exhibits antioxidant and antimicrobial activities [15,16], which contribute to enhanced food shelf life and safety. Hence, films incorporated with curcumin into biopolymer matrices demonstrate good adhesion and mechanical stability, without significantly compromising physical properties [17]. Such films also add value to natural raw materials and support the development of sustainable and consumer-safe packaging. Although curcumin-based indicator films have been reported, research on films incorporating turmeric powder into cassava flour/PVA matrices remains limited. Moreover, most previous studies focus either on fundamental characterization or on other protein- and polysaccharide-based systems, without demonstrating practical application in pork freshness monitoring.

Therefore, this study aimed to develop an intelligent film based on CF, PVA, and turmeric powder as a natural pH indicator for real-time pork freshness detection. Films containing different turmeric concentrations (0% - 0.5% w/w of cassava flour) were prepared and characterized in terms of physicochemical properties, pH sensitivity, and biodegradability. Particular emphasis was placed on demonstrating practical applicability by testing film responses to pork spoilage under refrigerated storage. This approach not only provides a low-cost, locally sourced, and eco-friendly alternative to synthetic sensors but also adds value to agricultural resources, contributing to the advancement of sustainable intelligent packaging systems.

Materials and methods

Cassava (Saai Dieow Cultivar) tubers, with uniform size and shape, were obtained from a local farm (Lop Buri, Thailand). Polyvinyl alcohol (Degree of Hydrolysis 86 - 90 mol% and M.W = 100,000 g/mol) was supplied by Chem-Supply Pty Ltd, Australia. Turmeric powder (Supaporn, Supaporn Herb Co., Ltd., Thailand) was used. The product is a commercially available natural powder derived from the rhizomes of *Curcuma longa* L., containing approximately 3% - 5% curcumin, with no further purification. Glycerol (food grade) and Ammonium hydroxide (technical grade) were obtained from Scientific Chemical Supply Co., Ltd. Other chemicals used for preparing the buffer solutions were analytical grade. The meat samples (*longissimus dorsi* of pork) were bought from a supermarket and transported on ice to the laboratory within half an hour.

Preparation of flour from cassava tubers (Saai Dieow cultivar)

The flour preparation from cassava tubers (Saai Dieow cultivar) was conducted with slight modifications based on the method of Yonata *et al*. [18]. The tubers were thoroughly washed, peeled, and cut into small pieces. The grated cassava was soaked in deionized (DI) water, filtered, and centrifuged, and the flour sediment was collected. This washing and sedimentation process was repeated 3 times to remove residual fibers and soluble components. The wet flour was then oven-dried at 50 °C for 24 h to reach a residual moisture content of approximately 10% - 12%, resulting in cassava flour (CF) suitable for film preparation. The dried flour was ground and then passed through a 100-mesh sieve and stored in a sealed container with a desiccant.

Indicator film preparation

The indicator film was prepared by modifying the method of Dăescu *et al*. [11]; Wu *et al*. [19]. Dried cassava flour powder (5 g) obtained from the previous step was dissolved in 100 mL of deionized (DI) water at 95 °C with continuous stirring to form a homogeneous gelatinized flour dispersion. Glycerol was then added at 30% (w/w of flour) as a plasticizer, and the mixture was stirred for an additional 30 min to ensure complete homogenization. Separately, 10 g of polyvinyl alcohol (PVA) was dissolved in 100 mL of water at 95 °C. The PVA solution was then gradually added to the CF solution, and the combined solution was stirred continuously for 20 min at the same temperature. Subsequently, turmeric powder was then incorporated at concentrations of 0% (CF/PVA/T0), 0.1% (CF/PVA/T 0.1), 0.2% (CF/PVA/T0.2), 0.3% (CF/PVA/T0.3), 0.4% (CF/PVA/T0.4), and 0.5% (CF/PVA/T0.5) (based on the dry weight of CF), and thoroughly mixed to ensure even distribution. The resulting film-forming solution was sonicated for 20 min to reduce air bubbles and evenly disperse turmeric particles, resulting in a homogeneous film. The mixture was then filtered and cast onto an acrylic plate (20×30 cm^2), followed by drying in a hot air oven at 50 °C for 24 h. Once the film was completely dry, it was peeled off and stored under controlled conditions at 25 ± 2 °C and 50 ± 5% relative humidity for 24 h prior to testing.

Characterization of films

Thickness and color

At each of the 5 distinct positions on the film, the thickness was accurately measured using a digital micrometer (Mitutoyo Co., Japan). The color of the films (2.0×2.0 cm^2) was analyzed using a Hunter Lab colorimeter (ColorFlex Z2, USA), and the color parameters were evaluated in the CIE Lab* system. In this system, the *L** value represents lightness (negative-dark; positive-light), while the a* (negative-green; positive-red) and *b** (negative-blue; positive-yellow) values indicate chromatic coordinates on the horizontal axis [20]. Calibration was performed before each measurement following the standard procedure. The instrument was first calibrated with a black trap, followed by a white standard tile. The color difference (*ΔE**) was determined using Eq. (1) [21], with each measurement recorded at least 3 times for every sample, both before and after light exposure.

$$\Delta E^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad (1)$$

Water activity (a_w), moisture absorption, water solubility and water vapor permeability (WVP)

The water activity (a_w) of the film samples with a diameter of 20 mm was measured using a water activity meter (Aqualab Series 4, Decagon Devices Inc., USA) [22]. The moisture absorption (MA) of the films was measured by modifying the method of Song *et al*. [20]. Film samples from each formulation were cut into 2×2 cm^2 pieces and dried in a hot-air oven at 45 °C for 12 h, after which they were weighed (W_1). Subsequently, the film samples were placed in a desiccator maintained at 95% relative humidity for 48 h and then weighed again (W_2). The MA of the films was calculated based on the weight difference using the following Eq. (2).

$$MA\% = \frac{(W_2 - W_1)}{W_1} \times 100\% \quad (2)$$

The water solubility (WS) of the films was determined with a modified method based on Dăescu *et al*. [11]. Film samples of all formulations were cut into 2.0×2.0 cm^2 pieces and dried in a hot air oven at 105 °C until a constant weight was obtained (M_1). The dried samples were then immersed in 50 mL of distilled water and shaken in a shaker at 120 rpm at a temperature of 30 ± 2 °C for 1 hour. After immersion, the undissolved film residues were carefully filtered using filter paper and weighed (M_2). Subsequently, the filtered samples were re-dried at 105 °C until a constant weight was achieved (M_3). The obtained values were used to calculate the water solubility of the films using the following Eq (3).

$$WS\% = \frac{(M_3 - M_1)}{M_1} \times 100\% \quad (3)$$

The water vapor permeability (WVP) was determined following the ASTM E96/E96M standard method [23], which is a widely accepted procedure for evaluating the transmission of water vapor through film

materials, with modifications based on the method of Martins *et al*. [22]. Film samples (7.0×7.0 cm^2) were used to seal the mouths of aluminum cups containing silica gel (0% relative humidity) inside (internal diameter 45 mm and depth 32 mm). The sealed cups were then placed in a desiccator maintained at 78 ± 2% relative humidity using a saturated sodium chloride solution, at a temperature of 28 ± 2 °C. The weight change of each cup was recorded every hour over 7 h. The WVP was then calculated using Eq. (4) [22].

$$WVP\% = \frac{G.x}{t.A.\Delta P} = \frac{G.x}{t.A.S(R_1 - R_2)} \quad (4)$$

where G/t is the rate of gain in weight over time (the slope of the line, in $g \cdot s^{-1}/h$), A is the permeation area (m^2), x is the thickness of the film (mm), ΔP is the difference in relative humidity between the 2 sides of the film the external side (R_1, 75% R.H.) and the internal side of the cup (R_2, 0% R.H.) expressed in kPa, and S is the partial pressure of saturated water vapor at the test temperature (kPa)

Film characterization by infrared spectroscopy

The FT-IR spectra were recorded using a Spectrum 100 spectrometer (Perkin Elmer) equipped with an ATR cell. The measurement was performed in the spectral band of 4,000 to 500 cm^{-1} and a resolution of 4 cm^{-1} with 32 scans for each film.

The pH response of indicator films

The pH sensitivity of the indicator films was evaluated with modifications based on the method of Shakouri *et al*. [24]. Film samples with dimensions of 2.0×2.0 cm^2 were fully immersed in the buffer solution and gently agitated for 10 min at 28 ± 2 °C. This procedure allowed sufficient time for the film to interact with the buffer, ensuring uniform ion exchange and maintaining a stable pH throughout the film matrix. Equilibration was confirmed by observing that the color change of the film reached a steady state. A digital camera was then used to capture images of the indicator films, allowing for the observation of color changes corresponding to each pH condition. Buffer solutions covering the pH range of 1 - 14 were prepared using standard procedures as follows: pH 1 - 3, hydrochloric acid (HCl) diluted with deionized water; pH 4 - 6, acetate buffer obtained by mixing acetic acid and sodium acetate at appropriate ratios; pH 7, phosphate buffer prepared from sodium dihydrogen phosphate and disodium hydrogen phosphate; pH 8 - 10, carbonate-bicarbonate buffer prepared from sodium carbonate and sodium bicarbonate; and pH 11 - 14, sodium hydroxide (NaOH) diluted with deionized water. All buffer solutions were adjusted to the target pH using a pH meter and stored at room temperature prior to use, to ensure accuracy and consistency during the color response evaluation of the indicator films.

Sensitivity of the colorimetric indicator to ammonia vapor

The sensitivity of the colorimetric indicator film to ammonia vapor was investigated by modifying the method of Tavassoli *et al*. [5]. Sample films (2×2 cm^2) were affixed to the lids of Petri dishes (9×1 cm^2) containing 15 mL of an ammonia solution (8 mM). The setup was maintained at 28 ± 2 °C for 30 min. Subsequently, the overall appearance of the indicator films was recorded using a digital camera to observe color changes induced by exposure to ammonia vapor.

Application of Indicator films in monitoring pork freshness

The application of indicator films for monitoring pork freshness was investigated with modifications based on the method of Dăescu *et al.* [11]. Fresh pork obtained from a local supermarket was packed into foam trays (polystyrene), with each tray containing approximately 60 g of pork of comparable freshness. Indicator films measuring 2×2 cm^2 were attached to the inner side of the plastic wrapping film used to seal the packaging. The packages were then stored at 4 ± 1 °C for a period of 7 days. Changes in the color of the indicator films were observed and recorded throughout the storage period. A control group consisting of similarly wrapped packages with attached indicator films but without pork was also included for comparison.

Biodegradability test

The biodegradability of the indicator films was evaluated using a soil burial method modified from Malekzadeh *et al*. [25]. The films were cut into pieces of 2.0×2.0 cm^2 and their initial weight (W_i) was

recorded. The samples were then buried at a depth of 9 - 10 cm in pots (27×74×21 cm^3) containing loamy soil, composed of a balanced proportion of sand and clay, maintained at room temperature (33 ± 2 °C) and 60% relative humidity. The film weights were monitored weekly for a period of 4 weeks. After each interval, the films were carefully removed, brushed to remove soil residues, and dried at 60 °C for 2 h until a constant weight was achieved. The final weights (W_f) were recorded, and the percentage of weight loss (WL) was calculated to evaluate biodegradation according to Eq. (5) [25].

$$WL\% = \frac{(W_i - W_f)}{W_i} \times 100\% \quad (5)$$

Statistical analysis

All experiments were conducted in triplicate, and the results are presented as mean ± standard deviation (SD). Differences in the properties of the films were analyzed using 1-way analysis of variance (ANOVA) followed by Duncan's multiple range test (DMRT) to identify statistically significant differences. Statistical analyses were performed using SPSS software (version 12, SPSS Inc.), with significance set at $p \leq 0.05$.

Results and discussion

The intelligent pH indicator films prepared from CF and PVA, incorporated with turmeric powder at concentrations of 0%, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% (w/w based on CF), exhibited distinct physical appearances depending on the turmeric content. The CF/PVA film without turmeric (0%) (**Figure 1(a)**) appeared thin, transparent, and flexible, and could be formed into a complete, intact film. The CF/PVA film containing 0.1% - 0.3% turmeric (**Figures 1(b) - 1(d)**) exhibited flexibility, a yellow color, and smooth surfaces on both sides without wrinkles, forming uniform and defect-free films. At higher turmeric concentrations (0.4% and 0.5%) (**Figures 1(e)** and **1(f)**), the films retained good flexibility, showed no brittleness, and displayed a more intense yellow color, with smooth surfaces and intact structures similar to those of the lower concentrations. These findings are consistent with the previous study of Tavassoli *et al*. [5], which demonstrated that the incorporation of pigments into biopolymer networks enhances the flexibility and softness of films while, at the same time, reducing their mechanical strength. In addition, Yong *et al*. [26] reported that the incorporation of pigments into chitosan matrices could similarly improve film flexibility but lead to a reduction in mechanical strength. In the present study, increasing the concentration of turmeric led to a higher curcumin content in the CF/PVA film matrix. Curcumin is a natural polyphenolic compound with prominent chromophoric groups [27], and its higher content enhances light absorption in the visible range, resulting in a deeper yellow color of the film. Moreover, the formation of hydrogen bonds between curcumin molecules and the hydroxyl groups of flour and PVA also helps maintain the structural stability of the film, even at high levels of turmeric incorporation. These observations are in agreement with previous reports, which indicated that the addition of curcumin enhances the color intensity of flour- or polymer-based films while preserving their mechanical properties [28].

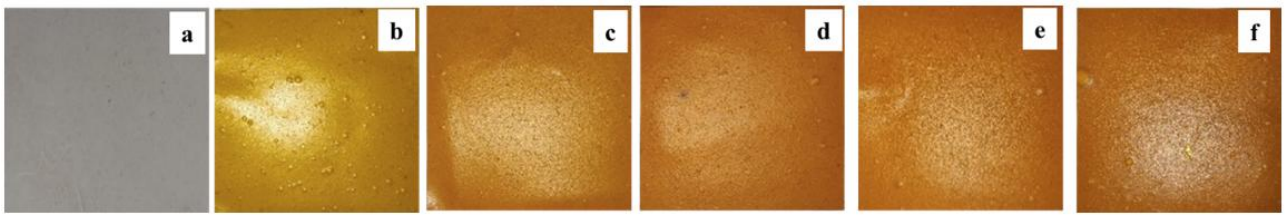


Figure 1 Intelligent indicator films based on CF/PVAwith turmeric concentrations of 0% (a), 0.1% (b), 0.2% (c), 0.3% (d), 0.4% (e), and 0.5% (f).

Table 1 presents the thickness values of CF/PVA-based indicator films prepared with varying turmeric concentrations. A significant increase in thickness ($p \leq 0.05$) was observed with higher turmeric content, which can be attributed to hydrogen bonding interactions between curcumin molecules and the abundant hydroxyl

groups of CF and PVA. In addition, curcumin may act as a filler or interfere with the packing of polymer chains, contributing to the observed increase in film thickness. Similar trends have been reported in other studies on flour- or PVA-based films incorporated with natural pigments, such as gelatin - basil seed gum films with saffron petal extract [24] and flour - PVA films with anthocyanins [25], where pigment - polymer interactions also resulted in enhanced film thickness.

The color parameters of the indicator films based on CF/PVA with varying turmeric concentrations showed that the L^* value tended to decrease ($p \leq 0.05$), while the a^* and b^* values tended to increase ($p \leq 0.05$) with increasing turmeric content. This shift reflects the higher curcumin loading and more homogeneous pigment dispersion, which enhances light absorption in the visible region and imparts a deeper yellow coloration [27]. The ΔE^* values were calculated to evaluate color differences at each turmeric concentration. Higher ΔE values indicate more pronounced color differences between the films. Therefore, films with higher turmeric concentrations exhibited more distinct color changes, making them suitable for application in intelligent packaging to effectively monitor food freshness. These results are consistent with the previous study by Etxabide *et al*. [29] who investigated biopolymer films with the addition of colorants containing curcumin at different concentrations, and found that the ΔE^* value increased with the amount of colorant incorporated into the films.

The water activity (a_w) of the indicator films based on CF/PVA with turmeric concentrations ranged from 0.43 to 0.35, which is well below 0.60. Such low a_w values are critical for film stability and microbial resistance, as most microorganisms require an a_w of approximately 0.70 - 0.99 to grow [22]. Therefore, these films are expected to remain stable and resistant to microbial spoilage under typical storage conditions. Furthermore, the effects of turmeric incorporation on film properties are likely influenced by interactions between CF, PVA, glycerol, and curcumin, which together contribute to the observed stability and functional performance of the films.

Table 1 The thickness, color and water activity (a_w) properties of the indicator films based on CF/PVA with turmeric.

Sample	Thickness (mm)	Color				Water activity (a_w)
		L^*	a^*	b^*	ΔE^*	
CF/PVA/T0	0.19 ± 0.01^{e}	39.16 ± 0.02^{a}	-0.33 ± 0.03^{d}	0.24 ± 0.04^{f}	-	0.43 ± 0.01^{a}
CF/PVA/T0.1	0.22 ± 0.01^{d}	37.34 ± 0.04^{b}	-0.19 ± 0.02^{d}	19.30 ± 0.76^{e}	19.15 ± 0.76^{e}	0.41 ± 0.01^{b}
CF/PVA/T0.2	0.24 ± 0.01^{c}	33.56 ± 0.09^{c}	-0.16 ± 0.03^{d}	23.55 ± 0.87^{d}	23.97 ± 0.85^{d}	0.39 ± 0.01^{c}
CF/PVA/T0.3	0.26 ± 0.01^{b}	35.41 ± 0.06^{d}	2.22 ± 0.11^{c}	28.49 ± 0.20^{c}	28.61 ± 0.20^{c}	0.38 ± 0.01^{c}
CF/PVA/T0.4	0.27 ± 0.01^{b}	28.86 ± 0.08^{e}	4.79 ± 0.54^{b}	30.78 ± 0.12^{b}	32.63 ± 0.15^{b}	0.36 ± 0.01^{d}
CF/PVA/T0.5	0.29 ± 0.01^{a}	22.96 ± 0.10^{f}	7.81 ± 0.58^{a}	32.26 ± 0.52^{a}	36.80 ± 0.47^{a}	0.35 ± 0.01^{d}

Values (mean ± SD) with different superscripts (a-f) in the same column indicate significant differences among treatment groups ($p \leq 0.05$).

Based on the analysis of moisture content and solubility of CF/PVA-based indicator films with varying turmeric concentrations, both parameters decreased significantly ($p \leq 0.05$) as the turmeric content increased. Specifically, the moisture content decreased from 47.28 ± 1.03% to 1.62 ± 0.96%, corresponding to a 96.58% reduction, while solubility decreased from 44.16 ± 1.37% to 6.72 ± 0.81%, a 84.78% reduction. This reduction can be explained not only by hydrogen bonding between the hydroxyl groups of CF and PVA with curcumin molecules but also by the physical contributions of fibers and pigments present in whole turmeric powder, which limit water penetration and solubilization within the polymer network [30]. Water vapor permeability (WVP) is another important property of films and the values are presented in **Table 2**. The results indicated that WVP decreased significantly ($p \leq 0.05$) with increasing turmeric incorporation, from

0.0293 ± 0.0002 to 0.0043 ± 0.0001 g/(m^2·kPa·h), representing a 85.32% reduction. This effect is primarily attributed to the hydrophobic components of turmeric, including curcumin and other associated compounds, which introduce a tortuous diffusion pathway within the biopolymer matrix. The dispersed turmeric particles act as fillers or barriers that hinder the direct movement of water molecules through the film structure, thereby reducing WVP [31]. These findings are consistent with the study of Liu *et al.* [15], which reported that films based on *k*-carrageenan incorporated with curcumin exhibited a decrease in WVP with increasing curcumin content.

Table 2 Moisture absorption (MA), water solubility (WS), and water vapor permeability (WVP) of the indicator films based on CF/PVA with turmeric.

Sample	MA (%)	WS (%)	WVP (g/(m^2·kPa·h))
CF/PVA/T0	47.28 ± 1.03^{a}	44.16 ± 1.37^{a}	0.0293 ± 0.0002^{a}
CF/PVA/T0.1	31.73 ± 1.07^{b}	29.95 ± 0.33^{b}	0.0235 ± 0.0001^{b}
CF/PVA/T0.2	20.37 ± 1.84^{c}	19.73 ± 1.72^{c}	0.0216 ± 0.0001^{c}
CF/PVA/T0.3	05.27 ± 1.95^{d}	13.69 ± 2.53^{d}	0.0126 ± 0.0001^{d}
CF/PVA/T0.4	03.68 ± 1.57^{de}	09.53 ± 0.78^{e}	0.0059 ± 0.0001^{e}
CF/PVA/T0.5	01.62 ± 0.96^{e}	06.72 ± 0.81^{f}	0.0043 ± 0.0001^{f}

Values (mean ± SD) with different superscripts (a-f) in the same column indicate significant differences among treatment groups ($p \leq 0.05$).

The FTIR spectra of CF (**Figure 2(a)**), PVA (**Figure 2(b)**), turmeric (**Figure 2(c)**), glycerol (**Figure 2(d)**), and the indicator films based on CF/PVAcontaining turmeric at 0% (**Figure 2(e)**), 0.1% (**Figure 2(f)**), 0.2% (**Figure 2(g)**), 0.3% (**Figure 2(h)**), 0.4% (**Figure 2(i)**), and 0.5% (**Figure 2(j)**) are presented in **Figure 2**. The FTIR spectra of CF showed characteristic peaks at 3,300 cm^{-1} (O-H stretching), 2,930 cm^{-1} (C-H stretching in the polymer chain), and approximately 1,097 cm^{-1} (C-O stretching), which is consistent with the findings reported by Chamorro *et al*. [32]. For PVA, peaks were observed at 3,400 cm^{-1} and 1,360 cm^{-1}, corresponding to the stretching and bending vibrations of hydroxyl groups; at 2,930 cm^{-1}, corresponding to C-H stretching; and at 1,050 cm^{-1}, corresponding to symmetric C-O stretching [33]. The FTIR spectrum of turmeric powder (**Figure 2(c)**) exhibited characteristic peaks of curcumin at 3,480 cm^{-1} (phenolic O-H stretching), 1,627 cm^{-1} (C=O stretching), 1,590 and 1,510 cm^{-1} (C=C stretching in the benzene ring), and 1,150 cm^{-1} (C-O stretching) [15]. It should be noted that turmeric powder also contains fibers, oils, and polysaccharides, which may influence the spectral profile. Glycerol exhibited a broad O-H stretching band at 3,280 cm^{-1} and aliphatic C-H bands at 2,930 and 2,870 cm^{-1} [34]. In the FTIR spectra of the CF/PVA-based indicator films with turmeric, all characteristic peaks of the components were observed. Importantly, the phenolic O–H stretching of curcumin shifted from 3,480 cm^{-1} in pure turmeric to 3,320 cm^{-1} in the films, indicating the formation of hydrogen bonds between curcumin and the polymer matrix. This interaction likely contributes to enhanced film properties, such as increased flexibility and reduced solubility. Comparative analysis showed that the shift in -OH stretching became more pronounced with increasing turmeric concentration, suggesting greater incorporation and compatibility of curcumin within the CF/PVA network. These observations are consistent with prior studies on starch- or PVA-based films incorporating phenolic compounds, which reported similar -OH band shifts associated with hydrogen bonding and improved matrix compatibility [35].

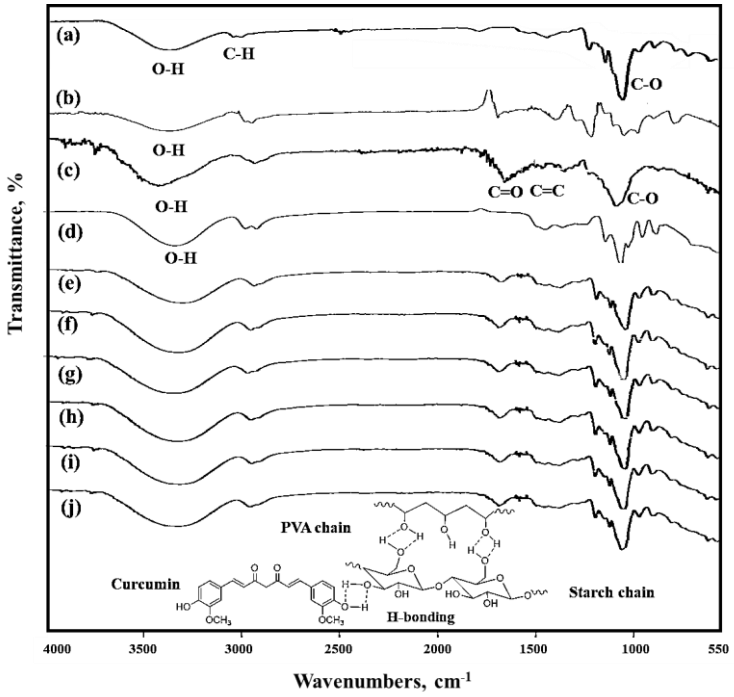


Figure 2 The FTIR spectra of CF (a), PVA (b), turmeric (c), glycerol (d), and the indicator films based on CF/PVA containing turmeric at 0% (e), 0.1% (f), 0.2% (g), 0.3% (h), 0.4% (i), and 0.5% (j).

The colorimetric response of CF/PVA indicator films with varying turmeric concentrations under acidic, neutral, and alkaline conditions is summarized in **Table 3**. The color changes can be observed from the photographs: The film appears yellow at pH < 8, reddish-brown at pH 8 - 10, and dark brown at pH 12 - 14. **Figure 3** shows a schematic of the reversible structural changes of curcumin at different pH values [36]. In acidic and neutral solutions, curcumin exists predominantly in the keto form, whereas at pH values above 8, it exists mainly in the enol form. This color change is due to the deprotonation of curcumin's phenolic hydroxyl groups under alkaline conditions, which alters electronic conjugation and increases intramolecular charge transfer, thereby intensifying the color [37].

Table 3 Color change of the film upon exposure to buffer solutions of different pH values of the indicator films based on CF/PVA with turmeric.

Sample	Color changes of the indicator films at different pHs.													
	pH1	pH2	pH3	pH4	pH5	pH6	pH7	pH8	pH9	pH10	pH11	pH12	pH13	pH14
CF/PVA/T0														
CF/PVA/T0.1														
CF/PVA/T0.2														
CF/PVA/T0.3														
CF/PVA/T0.4														
CF/PVA/T0.5														

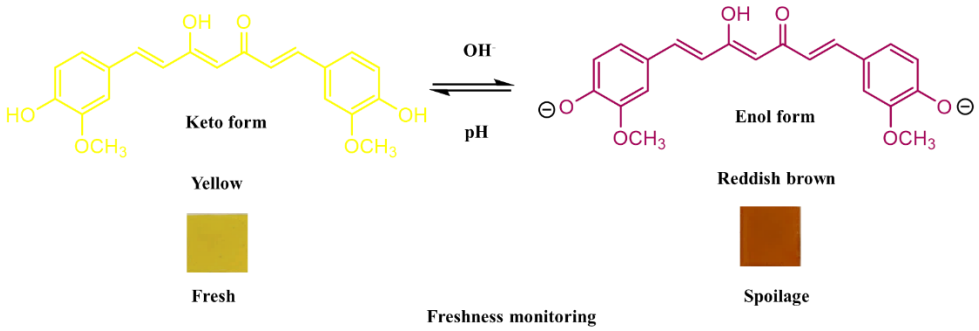


Figure 3 Chemical structure changes of the curcumin molecule in the different pH conditions.

To evaluate the sensitivity of the indicator films to volatile alkaline compounds generated during pork spoilage, the response of the films to ammonia vapor at a concentration of 8 mM was tested [5], which corresponds to the levels of ammonia typically produced during pork spoilage (**Table 4**). The observed color change resulted from the deprotonation of the phenolic hydroxyl groups in curcumin molecules under alkaline conditions, caused by the reaction of NH_3 with water on the film surface to form NH_4^+ and OH^-, rather than from reactions with the polymer matrix itself [38]. Films with higher turmeric content exhibited more pronounced color changes due to increased pigment density and more uniform dispersion within the CF/PVA matrix. The film color shifted from yellow to reddish-brown and finally to dark brown. According to the proposed mechanism illustrated in **Figure 3**, the films show a yellow color when ammonia volatilization is low. As ammonia release increases, the corresponding pH rise triggers the response of curcumin molecules, leading to a distinct color change of the film. This mechanism aligns with the observed color transitions of the films under both fresh and spoiled pork conditions.

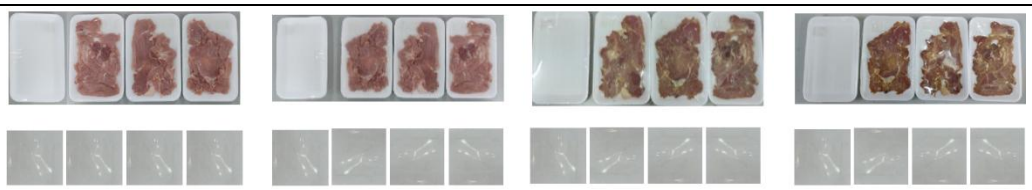
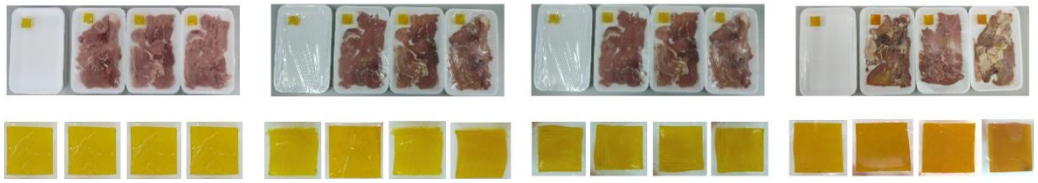
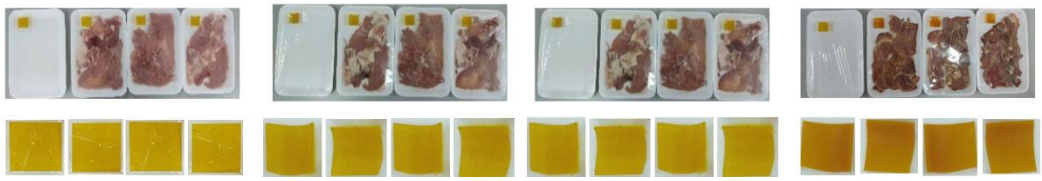
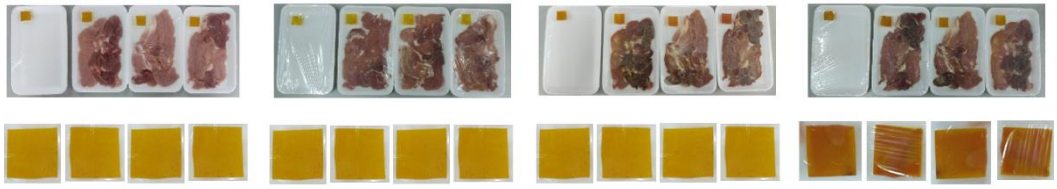
Table 4 Color response to volatile NH_3 of the indicator films based on CF/PVA with turmeric.

Sample	Color Response of the indicator films to volatile ammonia [8 mM]		
	0 min	15 min	30 min
CF/PVA/T0			
CF/PVA/T0.1			
CF/PVA/T0.2			
CF/PVA/T0.3			
CF/PVA/T0.4			
CF/PVA/T0.5			

The CF/PVA indicator films incorporated with different concentrations of turmeric were investigated for monitoring pork freshness, with a control group consisting of films stored without pork. All samples were stored at 4 °C for 7 days (**Table 5**). The results demonstrated that, as pork quality deteriorated, microorganisms decomposed proteins and generated volatile nitrogen compounds such as ammonia and

amines. These compounds induced deprotonation of the phenolic hydroxyl groups in the curcumin structure of the films, thereby triggering a pH-responsive reaction to the alkaline volatiles produced during spoilage [37,38]. Consequently, the films gradually changed color from brown to reddish-brown on days 5 - 7, whereas the control films exhibited no color change. This color transition corresponded to the pH range of 5 - 8. These findings are consistent with the study of Mohseni-Shahri *et al*. [39], who reported that an intelligent film incorporated with anthocyanins from roselle and curcumin effectively monitored shrimp freshness at 4 °C. The shrimp pH increased from 6.29 to 7.73 within 10 days, while total volatile basic nitrogen (TVB-N) values rose from an initial 12.96 mg/100 g to levels exceeding the spoilage threshold of 28.72 mg/100 g on day 8. Notably, TVB-N accumulation reflects the generation of low-molecular-weight alkaline compounds, particularly ammonia and trimethylamine, which are directly associated with off-odors and sensory rejection. Similarly, Liu *et al*. [15] developed a carrageenan - curcumin film for freshness monitoring of pork and shrimp. Their findings showed that TVB-N levels in pork increased from 4.91 to 31.11 mg/100 g, with pH shifting from 5.6 to 7.6. For shrimp, TVB-N rose from 7.15 to 41.53 mg/100 g, accompanied by a pH change from 6.7 to 7.7. These results further confirm the potential of curcumin-based films as effective freshness indicators for animal protein foods.

Table 5 Color changes in the indicator films based on CF/PVA with turmeric attached to packages in monitoring pork freshness.

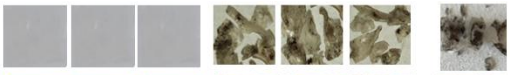
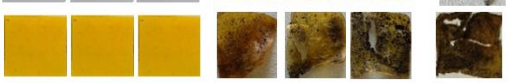
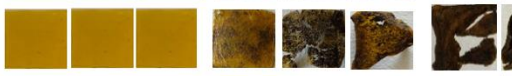
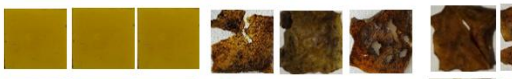
Sample	Time (Day)			
	0	3	5	7
CF/PVA/T0				
CF/PVA/T0.1				
CF/PVA/T0.2				
CF/PVA/T0.3				
CF/PVA/T0.4				

Sample	Time (Day)			
	0	3	5	7
CF/PVA/T0.5				

The biodegradability of CF/PVA indicator films containing different turmeric concentrations is summarized in **Table 6**. After 4 weeks, the films exhibited weight loss ranging from 91% to 100%, with values of 100 ± 0.00% for CF/PVA/T0, CF/PVA/T0.1, CF/PVA/T0.2, and CF/PVA/T0.3, 94.05 ± 2.69% for CF/PVA/T0.4, and 91.92 ± 1.36 % for CF/PVA/T0.5. Degradation became apparent in the second week, when some samples fragmented into smaller pieces, and proceeded rapidly between the second and third weeks. By the fourth week, several films (CF/PVA/T0, CF/PVA/T0.1, CF/PVA/T0.2, and CF/PVA/T0.3) were fully degraded and could not be recovered. To better illustrate the degradation behavior across turmeric concentrations, a biodegradation curve was plotted (**Figure 4**), which clearly visualizes the slower degradation trend in turmeric-rich films compared to turmeric-free films.

Films with higher turmeric content showed slower degradation, likely due to the increased turmeric loading enhancing film thickness and structural stability (**Table 1**). In addition, curcumin, the main bioactive compound in turmeric, has been reported to act as a microbial inhibitor [40], which may further suppress microbial activity during the degradation process. This effect, combined with reduced moisture absorption, solubility, and water vapor permeability (**Table 2**), decreases the hydrophilicity of the films and limits microbial adhesion and colonization. Collectively, these structural and physicochemical factors explain the slower degradation observed in turmeric-rich films.

Table 6 Biodegradable of the indicator films based on CF/PVA with turmeric.

Sample	Physical appearance					weight loss (%)
	Time (Weeks)					
	0	1	2	3	4	
CF/PVA/T0						100 ± 0.00[a]
CF/PVA/T0.1						100 ± 0.00[a]
CF/PVA/T0.2						100 ± 0.00[a]
CF/PVA/T0.3						100 ± 0.00[a]
CF/PVA/T0.4						94.05 ± 2.69[b]
CF/PVA/T0.5						91.92 ± 1.36[b]

Values (mean ± SD) with different superscripts (a,b) in the same column indicate significant differences among treatment groups ($p \leq 0.05$).

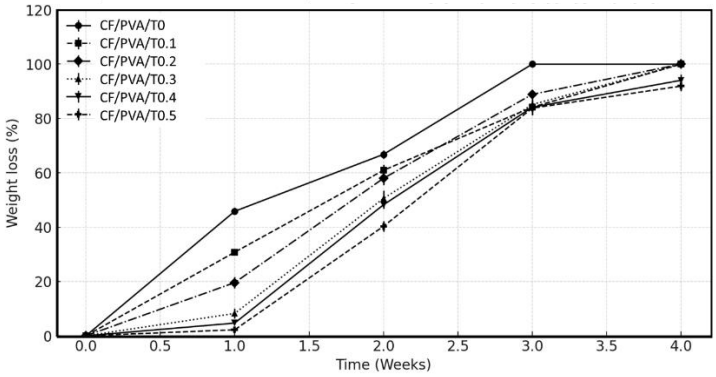


Figure 4 Biodegradability of CF/PVA indicator films incorporated with different turmeric concentrations during 4 weeks of soil burial.

Conclusions

This study successfully developed intelligent pH-sensing indicator films from cassava flour (CF)/polyvinyl alcohol (PVA) incorporated with curcumin for monitoring pork freshness. The films exhibited desirable physicochemical properties, including reduced moisture absorption, water solubility, and water vapor permeability with increasing curcumin content. The improved performance of the films was attributed to hydrogen bonding between curcumin and the polymer matrix, as well as reduced hydrophilicity, and the films also demonstrated high biodegradability (91% - 100% weight loss within 4 weeks). In particular, the 0.4% curcumin-incorporated film exhibited the most distinct color change, making it the most effective for real-time freshness monitoring. However, some limitations should be noted. This study did not assess the long-term stability of the films, their mechanical performance under practical packaging conditions, or their applicability to other perishable food systems. Testing was conducted only at 4 °C, and turmeric powder was used instead of pure curcumin. Despite these limitations, the findings confirm the potential of cassava flour/PVA-based curcumin films as eco-friendly smart packaging materials, showing promising applications for enhancing food safety and reducing environmental impact.

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Declaration of generative AI in scientific writing

The authors certify that generative AI tools were used in the preparation of this manuscript solely for language improvement and grammar correction. AI was not used to generate content or analyze data in any way. The use of these tools was conducted under human oversight and supervision. The authors take full responsibility for the content, scientific accuracy, and all conclusions presented in this research.

CRediT author statement

Pawinee Theamdee: Conceptualization, Methodology, Validation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, **Chanthakan Klinson**: Investigation, Visualization.

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