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Creating Smart Packaging Film with *Garcinia Mangostana* L. Pericarp Powder for Fish Fillets Monitoring

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Abstract

Ensuring the freshness of food products is a critical factor influencing consumer perception and acceptance, which directly relates to food safety and quality. To support responsible consumption and minimize food waste, this study introduces smart packaging technology designed to monitor the freshness of perishable goods. Specifically, smart packaging films were developed by incorporating mangosteen pericarp powder (MPP) and anthocyanin extract (ATH) from *Garcinia mangostana* L. to assess the freshness of fish fillet. Among the formulations, the starch-MPP film demonstrated superior pH sensitivity, making it more suitable as a smart packaging indicator due to its distinct color change response. Furthermore, the starch-MPP film exhibited the highest antioxidant activity at 96.88%, compared to the Starch-ATH film (85.83%), contributing to the preservation of food quality. When applied to fish fillet stored at 5 °C for two days, the starch-MPP film showed visible color shifts in response to pH changes caused by the release of nitrogenous compounds, indicating spoilage. This underscores the potential of starch-MPP films as an eco-friendly innovation for real-time freshness monitoring, contributing to both public health and sustainable food systems.

Keywords

Garcinia mangostana L. pericarp, smart packaging film, anthocyanins, pH sensitivity, fish fillet

1 Introduction

Smart packaging is a type of packaging that can monitor the quality or freshness of the food encompassed *via* colour change [1]. The smart packaging film is developed by incorporating compounds which are sensitive to the change of environment condition. It acts as an indicator with the capability to sense and assess the state of the food product. Changes in factors such as pH or carbon dioxide levels within the food can be detected and used to gauge the food's freshness based on the provided information. These indicators may involve substances that convey specific data through alterations in their physical and chemical characteristics. Numerous research studies have been undertaken involving various compounds, such as anthocyanins [2–4], betalains [2, 3], carotenoids [3], chlorophyll [3], and curcumin [3, 5], sourced from plant materials for the purpose of creating smart packaging films. Amongst, anthocyanins are the most widely sought compounds for this purpose [6]. Anthocyanins are natural pigments belonging to the flavonoid group, widely known for their vivid coloration and sensitivity to pH changes. Their molecular structures undergo significant alterations in response to varying pH environments, which directly influence their chromatic properties. These structural transitions are primarily responsible for the hyperchromic effect – an increase in absorption intensity – and the bathochromic shift, where the absorption maximum moves to a longer wavelength. As a result, anthocyanins exhibit a distinctive and progressive color transformation as the pH increases, typically shifting from red in strongly acidic conditions (pH ~2.0), to violet around neutral pH, and eventually to blue and green under alkaline conditions (up to pH ~9.0) [7]. Due to their non-toxic nature,

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biodegradability, and visual appeal, anthocyanins are increasingly incorporated into smart films and coatings designed for food packaging. These intelligent films function as real-time freshness indicators, signalling spoilage or quality degradation of perishable products through visible color changes, thus enhancing food safety and reducing waste [7]. To extract these versatile pigments, researchers have explored a variety of agricultural and food industry by-products as sustainable and cost-effective sources. Anthocyanins have been successfully obtained from blueberry residue, a by-product of juice and jam production [8]; dragon fruit skin, which is typically discarded after flesh extraction [9, 10]; purple sweet potato, known for its high anthocyanin yield [11]; and grape skin, a significant residue from wine processing [12]. Other notable sources include black bean seed coat [13], red cabbage, which contains high levels of acylated anthocyanins known for improved stability [13, 14]; purple and black eggplant, especially the peel [15]; Chinese bayberry, a native fruit rich in cyanidin-3-glucoside [16]; and roselle, which provides vibrant red pigments from its calyces [17, 18].

Anthocyanins are found in mangosteen (*Garcinia mangostana* L.) rind pericarp. The mangosteen is a tropical fruit known for its sweet and tangy flavor. The mangosteen pericarp, which is the thick outer rind of the fruit, is an abundant agricultural waste commonly discarded in tropical country such as Malaysia. It is rich in anthocyanins, which impart a deep purple or reddish color. Both anthocyanins and xanthones found in mangosteen rind have been widely reported for their health benefits such as antioxidant [19, 20] and antitumoral [21] properties. According to Fu et al. [7] and Palapol et al. [22], the predominant anthocyanin present in mangosteen pericarps is cyanidin-3-sophoroside, with a lower quantity of cyanidin-3-glucoside. Although these compounds have been extensively studied for pharmaceutical applications [23], their use as film indicators remains limited. By incorporating anthocyanins extracted from mangosteen rind pericarp into smart packaging films, this study explores a sustainable packaging innovation that may support several targets within the United Nations Sustainable Development Goals (SDGs). For instance, smart indicators that provide real-time information about food freshness could help reduce food spoilage across the supply chain, contributing to more responsible consumption and production patterns (SDG12). Utilizing agricultural by-products in packaging materials adds value to crop waste and supports sustainable agricultural practices (SDG2). Moreover, this work aligns with efforts to promote innovation and sustainable industrial practices (SDG9), as it contributes to the development of bio-based, functional packaging systems. While such packaging alone cannot achieve these global goals, it can be part of broader strategies that promote environmental sustainability and food system resilience.

Therefore, the objective of this study was to explore how the inclusion of mangosteen rind pericarp powder and extract in cassava starch affects the development of smart packaging films. The film structural analysis was evaluated using Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM). Film thickness, water solubility (*WS*), antioxidant property and pH sensitivity were assessed. Additionally, films made from cassava starch containing mangosteen rind pericarp powder were assessed for their feasibility in monitoring fish fillet storage at 5 °C for two days.

2 Materials and methods

2.1 Preparation of mangosteen (*Garcinia mangostana* L.) pericarp powder and anthocyanins extract

The preparation of mangosteen pericarp powder (MPP) and anthocyanins extract is illustrated in Fig. 1. Mangosteen rind waste was collected from the private orchard located in Sungai Gadut, Negeri Sembilan, Malaysia. It was washed

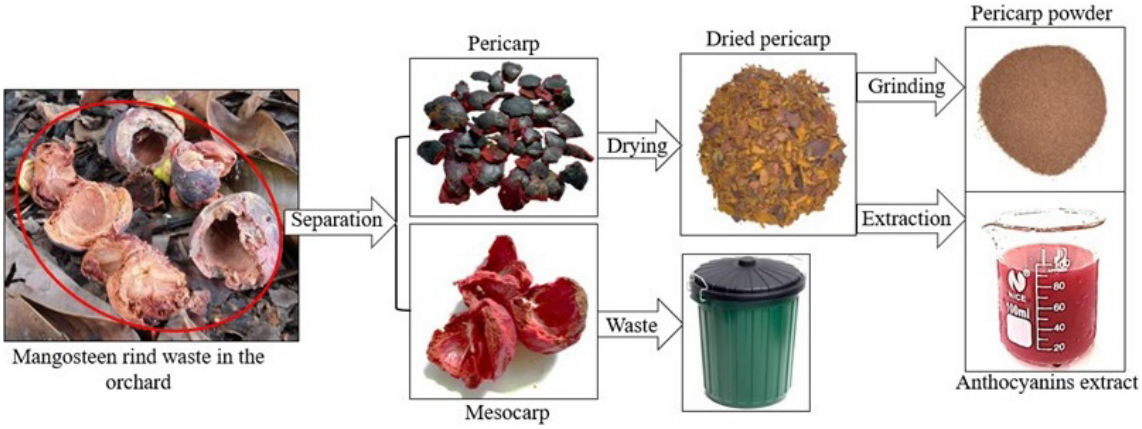


Fig. 1 Preparation of mangosteen pericarp powder and anthocyanins extract

with tap water to remove dirt from the surface after transferring to University College Sedaya International (UCSI) laboratory. After removing the excess water on the peel surface by wiping it with tissue paper, the pericarp (the outer layer) was peeled and separated from the soft rind (mesocarp) using forceps. The mangosteen pericarp was dried through natural convection at room temperature (25 ± 2 °C) for 48 h. The dried MPP was obtained by grinding with a blender (MX-M200, Panasonic, Malaysia). Anthocyanins extract was obtained by performing extraction of mangosteen pericarp using 30% (v/v) ethanol aqueous solvent [24]. 5 g of mangosteen pericarp was added into 50 mL of ethanol aqueous solvent in a 50-mL centrifuge tube. Then, 1 g of citric acid solution of 20 g/L concentration was added and the mixture was shaken at 100 rpm using an orbital shaker (OS-20, JoanLab, China) for 15 h. The mixture was filtered using filter paper to separate anthocyanin extract (ATH) from the pericarp residue.

2.2 Development of films

Three different types of films were prepared: starch film, starch-MPP film and starch-ATH film, as illustrated in Fig. 2. Cassava starch powder (4 g) was mixed with 100 mL of distilled water in a beaker and stirred at 350 rpm using a magnetic stirrer (C-MAG HS 7, IKA, China) for 30 min. Starch slurry was then mixed with 1.2 g of glycerol on a hot plate where heat was supplied slowly from room temperature (25 ± 2 °C) to 95 °C [25]. The heating was halted one minute after reaching the temperature of 95 °C. The film solution (40 mL) was poured into a plastic petri dish and dried at 60 °C in an oven (Carbolite AX120, Chempharm, Australia) for 5 h. The film was kept in plastic zip bag and stored at 5 °C in the refrigerator until further analysis. To create the starch-MPP film, one gram of pericarp powder was blended into the starch slurry, followed by the addition of 1.2 g of glycerol. Subsequently, the film solution was subjected to heating and casting under identical conditions as those employed for preparing the starch film. The starch-ATH film was generated using the identical procedure, wherein 1 mL of anthocyanins extract was incorporated instead of 1 g of pericarp powder.

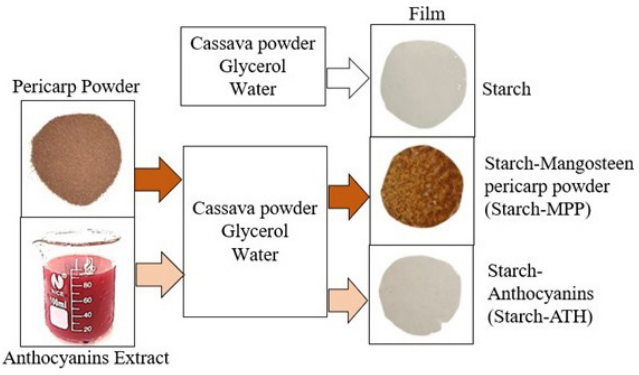


Fig. 2 Preparation of starchfilm, starch-MPP film, and starch-ATH film

2.3 Characterizations of the films

FTIR spectra through attenuated total reflection was recorded using a Spectrum Two FTIR Spectrometer (PerkinElmer, USA) with scanning resolution of 16 cm^{-1} in the absorbance mode from 4000 to 400 cm^{-1}. Functional groups of the synthesized films were identified from the FTIR spectrum. The surface morphological characterization of the films was captured by SEM (Tescan Vega Compact, Czech Republic) [26].

2.4 Physical and antioxidant properties of the films

The films were cut into dimensions of 10 × 10 mm and their thickness was measured using a micrometer screw gauge, ensuring careful handling while securing the films. The *WS* of the films was evaluated using method in previous studies [19, 27]. The films were cut into dimensions of 10 × 10 mm and placed into a petri dish filled with 30 mL of distilled water at room temperature (25 °C ± 2 °C), where they were left to soak for 6 h. Then, the films were dried at 60 °C in an oven for 15 min until reaching a constant weight. The *WS* of the films was calculated using Eq. (1):

$$WS(\%) = \frac{m_1 - m_2}{m_1} \times 100, \tag{1}$$

where m_1 is the initial dry mass, m_2 is the final dry mass.

The antioxidant property of the films was investigated using 1,1-diphencyl-2-picryl-hydrazyl (DPPH) method [18, 28, 29] in triplicate. The films were resized to 10 × 10 mm and submerged in 10 mL of a 20% (v/v) aqueous methanol solution. They were then gently agitated by hand until a uniform mixture was achieved. Subsequently, 10 mL of the supernatant was combined with 3 mL of 150 µM of DPPH methanol solution in a centrifuge tube and subjected to gentle agitation manually. The mixture was kept in the dark at ambient temperature (25°C ± 2 °C) for 15 min, after which its absorbance (A_{sample}) was measured at 517 nm using a UV-Vis spectrophotometer (Bk-V1000, Biobase Biointudstry, China). The absorbance value of the control solution ($A_{control}$) that only consisted of 4 mL of 150 µM of DPPH methanol solution was recorded. DPPH radical scavenging activity (%) was calculated using Eq. (2):

$$\text{DPPH radical scavenging activity}(\%) = \frac{(A_{control} - A_{sample}) \times 100}{A_{control}}. \tag{2}$$

2.5 pH Sensitivity property of the films

The pH sensitivity of the films was investigated by submerging them in various buffer solutions spanning pH values from 2.0 to 12.0 for a duration of 2 min [20]. The alteration in color of the films was assessed using a portable digital colorimeter (FRU WR10QC, ShenZhen Wave Optoelectronics Technology Co., Ltd., China) by recording the L^*, a^* and b^* value, which indicate lightness, redness and yellowness, respectively. The total color difference (ΔE) was calculated using Eq. (3):

$$\Delta E = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2}, \quad (3)$$

where ΔL^*, Δa^*, and Δb^* denote the differences in the values of the color parameters between the films and the films before the test. L^*, a^*, and b^* refer to lightness, redness and yellowness, respectively.

2.6 Fish fillet freshness monitoring with starch-MPP film

The starch-MPP film was cut into dimensions of 10 × 10 mm and sticked to the inner surface of the lid of plastic container using masking tape as shown in Fig. 3. Fresh Spanish mackerel (*Scomberomorus niphonius*) was purchased from a local supermarket located in Cheras, Kuala Lumpur, Malaysia. Subsequently, the Spanish mackerel fillet was positioned within the polypropylene (PP) container and secured with the lid, which was affixed with the starch-MPP film. Fish fillet enclosed within these PP containers were prepared for 2 days storage evaluation in a chiller at 5 °C, as this temperature reflects typical household refrigerator conditions. The color alteration of the starch-MPP film was measured at every 24 h interval using a digital colorimeter and the total color difference (ΔE) was calculated using Eq. (3) [30].

3 Results and discussion

3.1 Functional groups of flms

Fig. 4 illustrates the FTIR spectra of starch film, starch-ATH film and starch-MPP film. All the films exhibited consistent characteristic pattern across the absorption band spanning from 4000 to 500 cm^{-1}. The presence of functional group stretching vibrations was indicated by peaks observed at absorption bands of 3282 cm^{-1}, 2927 cm^{-1}, 1645 cm^{-1}, 1149 cm^{-1}, 1077 cm^{-1}, and 926 cm^{-1}. These vibrations corresponded to O–H, C–H, O–H of bound water, C–O, C–O–H, and C–O–C functional groups [2]. The formation of all the films occurred through the polymerization of glucose *via* glucoside bonding, as evidenced by the existence of ether bonds (C–O–C) 926 cm^{-1} band [14]. Moreover, the C–O–C bond can be found through the 926 cm^{-1} band that represents the skeletal mode vibrations of the α-1,4-glycosidic [2]. Similar peaks of the spectra were reported by Otálora González et al. [2], Yun et al. [16], and Zhai et al. [17].

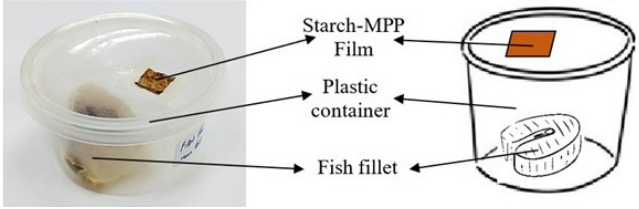


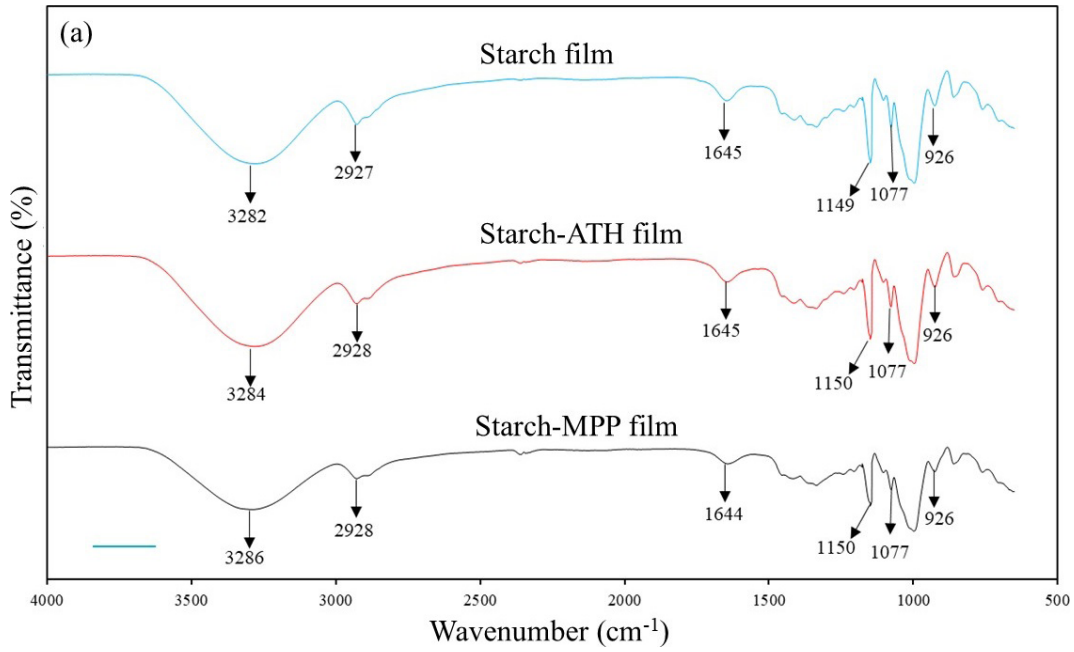
Fig. 3 Schematic of fish fillet freshness monitoring with starch-MPP film

It is worth noting that inclusions of ATH or MPP into the film did not lead to the occurrence of new absorption band. Nevertheless, there was a slight shift of O–H stretching from 3282 cm^{-1} to 3284 cm^{-1} after incorporating the ATH into the starch film. This can be explained through the formation of hydrogen binding between hydroxyl group and the amino group of the starch [16]. Similar phenomenon can be found for starch-MPP film that the O–H stretching was shifted from 3282 to 3286 cm^{-1}. While referring to the other bands of the spectrum, the bands of starch film that incorporated ATH or MPP did not show any significant changes which indicated the good compatibility of cassava starch after adding ATH and MPP.

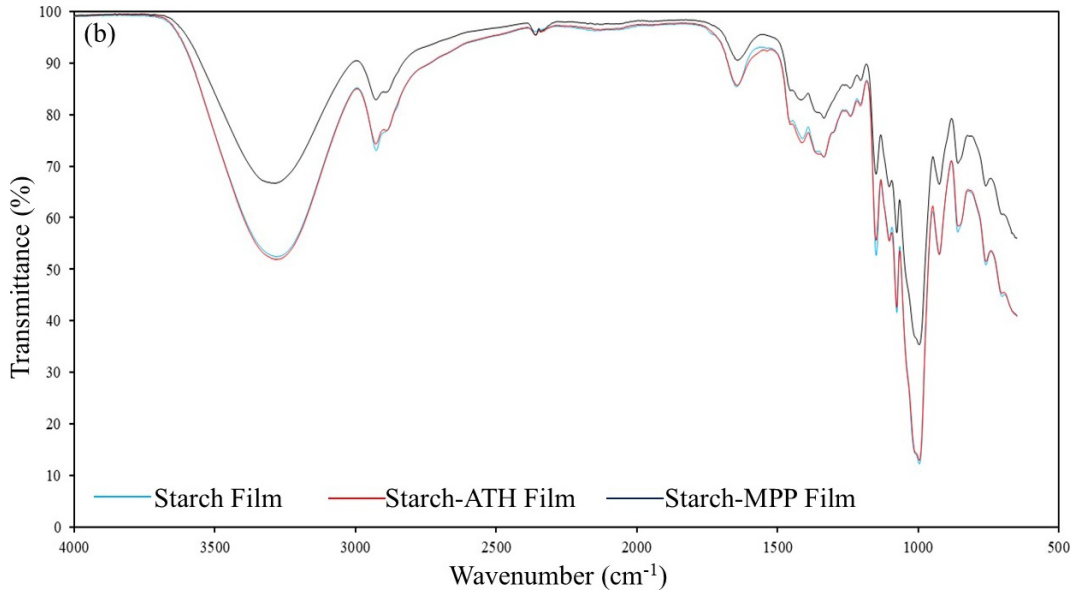
Starch film and starch-ATH film showed the similar peak intensity for all the absorption bands. This might have been because the quantity of ATH integrated into the film was insufficient to modify O–H group within the films [15]. Nevertheless, starch-MPP film exhibited a reduction in peak intensity within the wavelength range of 3700–3000 cm^{-1}. This phenomenon was ascribed to the substitution reaction involving the modified groups attached to hydroxyl (–OH) moieties [14]. The presence of MPP may interact with the glycerol-starch matrix that leads to the change in O–H availability within the polymer network of the film [31].

3.2 Scanning electron icroscopy micrographs analysis

It can be observed that the surface morphology of the starch film had significant protrusion and wrinkles and was not relatively smooth compared to the starch-ATH film (Fig. 5). This was likely a result of the starch slurry solution not being properly homogenized before undergoing gelatinization. As a result, the distribution of glycerol and starch within the film matrix was uneven and not uniform [16]. The starch-ATH film mostly even surface with minor protrusions in its surface morphology. The smooth nature of the starch-ATH



(a)



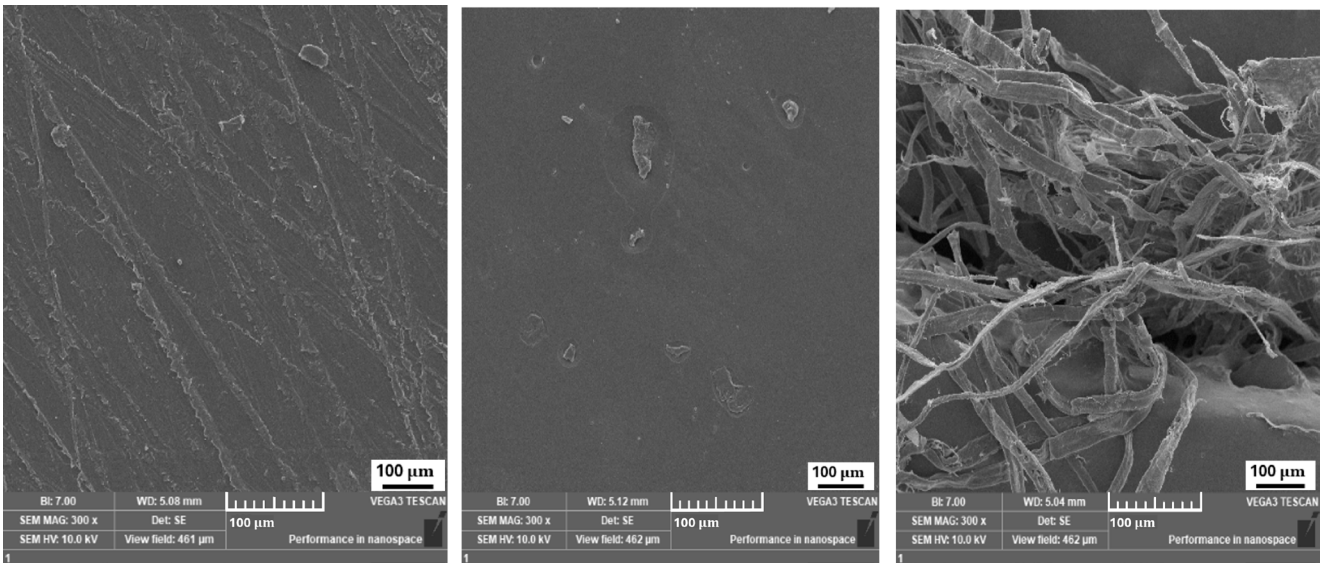
(b)

Fig. 4 FTIR spectra of starch film, starch-ATH film, and starch-MPP film: (a) Characteristic absorption peaks and functional group interactions; (b) Overlaid comparative analysis of transmittance patterns and molecular structure modifications after incorporation of ATH and MPP

film indicates strong compatibility and miscibility between the cassava starch and ATH components [17]. The appearance of these protrusions was likely attributed to the persistence of undissolved cassava starch particles during the formation of the starch-ATH film. Conversely, the SEM image for the starch-MPP film revealed loosely arranged untreated cellulose fibers (Fig. 5). The presence of cellulose fibers in the SEM micrograph can be attributed to the inclusion of a significant portion of MPP in the starch slurry, which comprises plant fibers [32].

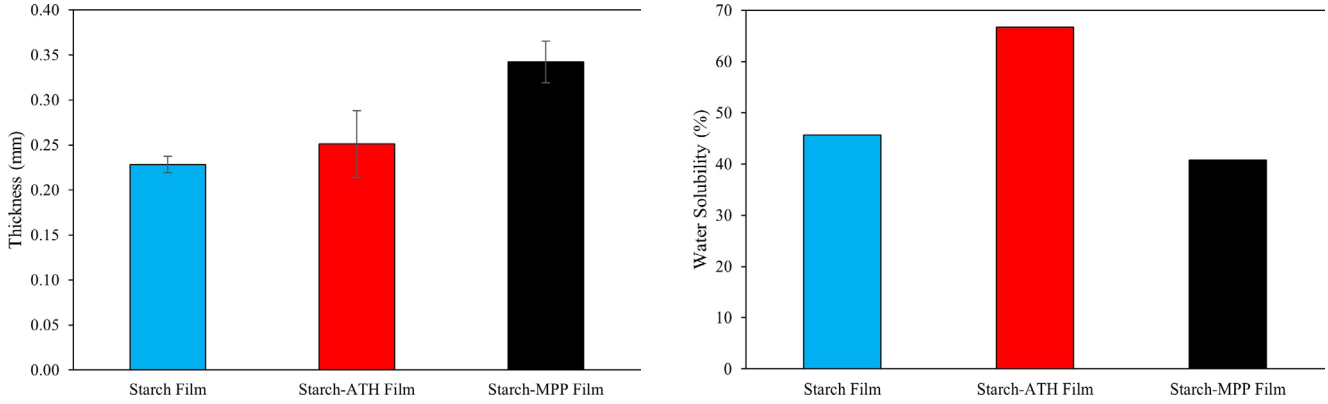
3.3 Physical and antioxidant properties of the films

Fig. 6 presents the thickness of starch film, starch-ATH film and starch-MPP film. Result revealed that the thickness between starch film and starch-ATH film has no significant difference ($P > 0.05$). This could be due to relatively small amount of ATH that was added to the film, which did not have a substantial impact to the film thickness. The findings of this study contradict those of a previous study conducted by Azlim et al. [9]. In their study, they observed that the thickness of the film increased as they incorporated more



(a) (b) (c)

Fig. 5 SEM micrograph of films at magnification of 300× (100 µm): (a) Strach-film; (b) Strach-ATH film; (c) Strach-MPP film



(a) (b)

Fig. 6 Tickness (a) and water solubility (b) of the films

ATH extract, particularly in films enriched with dragon fruit extract. Among the developed films, the starch-MPP film exhibited the greatest thickness, likely due to the presence of cellulose fibers within the MPP. This observation aligns with findings from a previous study done by Putra et al. [10]. They observed that the increase of the total solid from the dragon fruit skin extract in the solution increased the thickness of the bioplastic synthesized.

The water solubility of the films was calculated after the films immersing in water for 6 h. Among the films, starch-ATH film showed the highest water solubility (66.67%), followed by starch film (45.71%) and starch-MPP film (40.74%). This phenomenon might be a result of incorporating anthocyanins-rich extract, which could have reduced the interactions between polymeric chains in the film. As a consequence, the film could have become more water-soluble [4].

When comparing the starch film to the starch-MPP film, the findings revealed that the starch film exhibited greater water solubility than the starch-MPP film. This could be attributed to the substantial amount of MPP that was integrated into the starch slurry, consequently leading to an elevated cellulose fiber content within the produced film. High cellulose fiber content in the film facilitated water uptake and therefore, led to high water solubility. This finding is in agreement to previous work conducted by Andretta et al. [8]. They observed that film of cassava starch with high fibrous compounds content of blueberry residue up took substantial amount of water, consequently, led to increase in water solubility.

3.4 Antioxidant properties of the films

The presence of free radicals and reactive oxygen species in food products can accelerate oxidative spoilage, leading

to quality deterioration, off-flavors, and a reduction in nutritional value [33]. Incorporating food packaging films with enhanced antioxidant property could assist in extending the shelf-life of enclosed food by delaying these oxidative processes. In this study, the antioxidant capacity of the films was evaluated using the DPPH radical scavenging method, which serves as a standard indicator of free radical scavenging potential, rather than a direct measure of oxygen absorption within packaging systems. The results, expressed as scavenging activity percentages, are presented in Fig. 7. Among the tested formulations, the starch-MPP film displayed the most potent scavenging activity at 96.88%, outperforming the starch-ATH film (85.83%). The elevated scavenging activity exhibited by the starch-MPP film might be attributed to its abundant presence of secondary metabolites, such as anthocyanins, xanthones, proanthocyanidins, and flavonoids, derived from the mangosteen pericarp. These compounds contribute to a range of bioactive functions, including antioxidant properties [34]. There was no notable distinction ($P > 0.05$) between the scavenging activity of the starch film and the starch-ATH film. This lack of difference might be attributed to the relatively small quantity of ATH extract incorporated into the film formulation, which seemingly did not lead to a substantial improvement in antioxidant property.

3.5 pH-sensitivity of the films

Color of starch-ATH and starch-MPP films prior to immersion in pH buffer solutions was recorded in Table 1. Result obviously showed that the lightness (L^*) of starch-ATH film is higher than starch-MPP film. The lower L^* value of the starch-MPP film primarily resulted from the addition of MPP to the film composition. Conversely, the inclusion of MPP in the film formulation led to elevated a^* and b^* values, indicating increased levels of redness and yellowness.

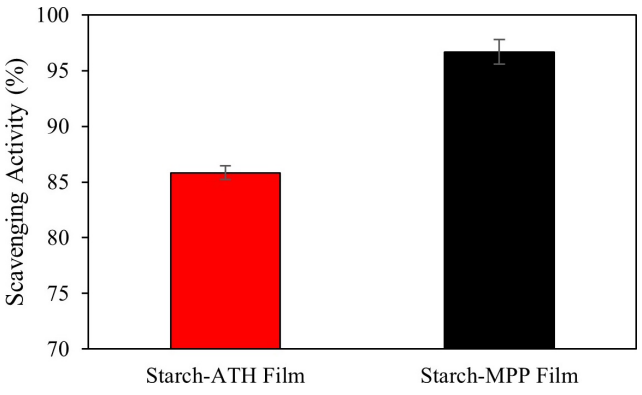
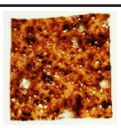


Fig. 7 Scavenging activity of the films

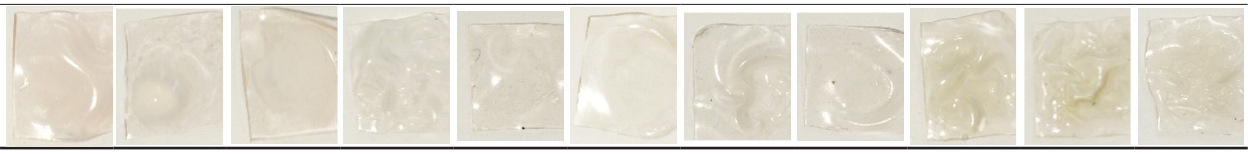
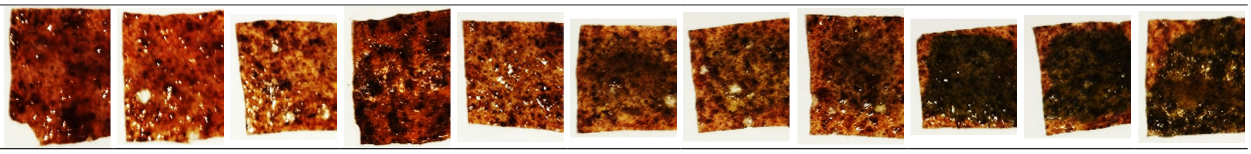
Table 1 Color of starch-ATH and starch-MPP films prior to immersion in pH buffer solutions

	Starch-ATH film	Starch-MPP film
		
L^*	76.14	43.32
a^*	2.24	17.19
b^*	−1.23	12.92

Color responses of starch-ATH and starch-MPP films corresponding to color parameters (L^*, a^*, b^*, and ΔE) over the pH range from 2 to 12 are presented in Table 2. The starch-ATH film became slightly darker (L^*) when immersed in both lower and higher pH buffer solutions, compared to pH 7. The redness (a^*) of starch-ATH film decreases when the film is immersed in buffer solutions with increasing pH, ranging from pH 2 to pH 12. This observation aligns with a previous work conducted by Choi et al. [11]. They reported that the redness of agar/potato starch film, which incorporated with ATH from purple sweet potato, decreased when it was immersed in increasing buffer solutions, ranging from pH 2 to pH 10. It appears that there was no significant trend observed in the yellowness (b^*) of the starch-ATH film when it was immersed in buffer solutions with increasing pH, ranging from pH 2 to pH 12 (Table 2). When the starch-ATH film was immersed in buffer solutions with decreasing pH, there was an increase in the total color difference (ΔE) compared to pH 7. However, no clear trend was observed when the film was immersed in buffer solutions with increasing pH, also compared to pH 7. This implies that the film is more sensitive to changes of redness in acidity or alkalinity. The structure of ATH of the film changed to flavylium cation (red) when it was immersed in an acidic conditions, and changed to chalcone base (yellow) when the film immersed in alkaline conditions [15].

The L^* of the starch-MPP film exhibited a similar trend to the starch-ATH film, as it became darker when immersed in both decreasing and increasing pH buffer solutions, compared to pH 7. The a^* of starch-MPP film decreases when the film is immersed in buffer solutions with increasing pH, ranging from pH 2 to pH 12. It appears that there was no significant trend observed in the b^* and total color difference (ΔE) of the starch-MPP film when it was immersed in buffer solutions with increasing pH, ranging from pH 2 to pH 12. However, when immersed in a pH 2 buffer solution, the film exhibited an increase in

Table 2 Color change of the starch-ATH film and starch-MPP film after immersing in buffer solutions

	Starch-ATH film										
	pH 2	pH 3	pH 4	pH 5	pH 6	pH 7	pH 8	pH 9	pH 10	pH 11	pH 12
											
L^*	63.78	67.62	69.86	68.62	72.07	73.27	66.72	72.36	66.18	66.18	67.37
a^*	5.29	2.06	2.60	1.49	1.96	1.72	1.62	1.40	1.35	1.48	1.12
b^*	1.77	−0.26	−1.13	−1.10	−0.88	−0.73	−0.18	−0.93	1.35	2.43	2.72
ΔE	13.08	8.58	6.29	7.56	4.10	2.96	9.50	3.88	10.33	10.64	9.68
	Starch-MPP film										
	pH 2	pH 3	pH 4	pH 5	pH 6	pH 7	pH 8	pH 9	pH 10	pH 11	pH 12
											
L^*	28.06	33.12	42.23	40.62	36.90	36.03	39.49	35.48	31.67	31.89	33.13
a^*	26.74	23.28	17.66	16.01	17.24	12.99	12.56	13.69	6.88	6.70	9.73
b^*	29.31	24.97	14.14	16.02	18.95	18.58	13.79	17.89	17.84	16.57	20.61
ΔE	24.34	16.92	1.70	4.27	8.81	10.14	6.07	9.92	16.31	15.93	14.78

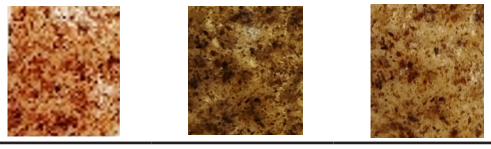
yellowness and a higher ΔE value compared to its appearance in a pH 7 solution. This finding contrasts with the results of a prior study conducted by Choi et al. [11]. They found that the incorporation of ATH from purple sweet potatoes into agar/potato starch film led to a reduction in its yellow hue when subjected to immersion in pH buffer solutions within the range of pH 2 to pH 10.

As Prietto et al. [13] indicated, films with a ΔE value exceeding five can be readily discerned by the naked eye, and a ΔE value greater than 12 results in a pronounced color alteration, easily noticeable even by untrained panellists. Given that the starch-MPP film contains a significant number of samples with high total color differences ($\Delta E > 12$), it becomes more practical for application as a smart film in monitoring the freshness of food products. The film's elevated total color difference enhances its visibility to consumers, further justifying its suitability for this purpose.

3.6 Color change of starch-mangosteen pericarp powder film during fish fillet storage

The starch-MPP film was employed to oversee the storage of fish fillets within a chiller at 5 °C for a duration of two days, and the changes in film color are detailed in Table 3. Following a single day of storage, the L^* and a^* values of the film experienced a significant decline, as measured by the colorimeter and evident even to the naked eye due to high value of ΔE. This phenomenon can be elucidated by the alteration in the structure of anthocyanins within the film, which shifts from carbine pseudobase (colorless under slightly acidic conditions) to chalcone (yellow under strongly alkaline conditions) upon encountering an alkaline environment, which was facilitated by nitrogen compounds released from the fish fillet during storage [15]. As noted by Becerril et al. [6], the progressive rise in spoilage microorganisms during the storage of raw fish leads to the generation of nitrogen compounds, ultimately contributing to the formation of an alkaline environment. It is important to note, however, that anthocyanin stability can be influenced by prolonged storage factors such as light exposure, temperature, and oxygen, which may cause

Table 3 Color change of starch-MPP film during fish fillet storage in a chiller at 5 °C

	Day 0	Day 1	Day 2
			
L^*	39.88	31.35	31.24
a^*	14.13	6.89	6.54
b^*	9.85	16.87	19.21
ΔE	0.00	13.55	14.90

pigment degradation and color fading over time [35]. Furthermore, volatile amines, lipids, and other food-derived compounds present in complex matrices may interfere with color perception or reaction kinetics, potentially affecting indicator precision [35]. Beyond fish fillets, the film also shows promise for monitoring freshness in other perishable foods, including poultry, seafood, and meat products, although matrix-specific calibration would be necessary to account for differences in spoilage metabolites and pH evolution [6].

4 Conclusions

This study demonstrated the use of MPP as a natural pH indicator for the formation of a smart packaging film, designed to assess its performance through pH-sensitivity and freshness indicators in monitoring the freshness of fillet fish. The starch-ATH Film had an initial light pink color and the redness of film decrease when pH increase. When pH reduces, the redness of the film increase. For starch-MPP Film, the initial color is brown, the decrease of the pH causes the increase of the redness of the film and vice versa. The color change of starch-ATH Film was not easy to differentiate by naked eye. In contrast, the colour change of starch-MPP was noticeable when exposed to various pH environments. The yellowness of the film increased when the pH environment of the film increased. This may be due to the transformation of the structure of ATH to flavylium cation (red) in acidic medium and chalcone (yellow) in alkaline medium. During storage at 5 °C for two days, the freshness of the fillet fish declined, as indicated by the increased yellowness of the starch-MPP film. This change corresponded with the formation of alkaline compounds, such as nitrogenous metabolites produced by spoilage microorganisms. These results demonstrate that the starch–MPP film has strong potential as an intelligent packaging material capable of providing a visual, real-time indication of food freshness.

Beyond its laboratory validation, the potential application of this film lies in its integration into active food packaging systems for perishable products such as fish, poultry, and meat. By providing immediate visual feedback on product quality, it could help reduce food waste and enhance consumer confidence in food safety. However, challenges remain before large-scale implementation can be realized. These include improving the mechanical strength and moisture resistance of the film, ensuring color stability under variable lighting and humidity conditions, and validating its long-term performance across diverse storage environments. Future research should therefore focus on optimizing film formulation, testing under industrial storage and distribution conditions, and assessing regulatory compliance to advance the practical use of such bio-based intelligent packaging films in the food industry.

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