Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Cite this: *Sustainable Food Technol.*, 2025, **3**, 2032

Active food packaging development: rambutan (*Nephelium lappaceum* L.) peel extract incorporated into starch-protein blend films

T. Nurul Azlin, [abc] F. Han Lyn [a] and Z. A. Nur Hanani *[ad]

Natural biopolymers, including carbohydrates, proteins, and fats, have gained significant interest in this emerging phase of a circular economy and sustainable environment. Blending multiple polymers helps overcome their poor mechanical and barrier properties, consequently enhancing their resemblance to commercially used synthetic plastics. This study develops biodegradable active packaging by incorporating rambutan peel extract (RPE) into corn starch-soy protein isolate blend films. Different concentrations of RPE (0%, 1%, 3%, and 5%) were added to the blend films and analysed for their physicochemical, mechanical, barrier, microstructure, and antioxidant properties. The incorporation of RPE produced significantly ($p < 0.05$) darker films with increased thickness while exhibiting similar ($p \geq 0.05$) moisture content and water solubility. The extract significantly reduces ($p < 0.05$) the light transmittance and develops a more opaque film than the control. Even though the addition of 5% RPE showed a significant ($p < 0.05$) improvement in tensile strength (6.36 MPa) and flexibility (7.10%), the highest water vapour permeability (1.63 10^{-10} g m^{-1} s^{-1} Pa^{-1}) was recorded. Small voids and a heterogeneous internal structure were observed from the microstructure morphology of the active film in comparison to the smooth and homogeneous structure of the control film. A gradual increase in the RPE concentration has increased the antioxidant activities, including ABTS radical scavenging activity (24.32–77.98%), DPPH radical scavenging activity (11.05–66.75%), and ferric reducing antioxidant power, FRAP (26.41–73.59 mM Fe_2SO_4 per g sample), of the active starch-protein biodegradable films. The starch-protein blend films prepared in this study showed promising potential as a low-cost active biodegradable film material to improve the shelf life and quality of food products.

Received 1st July 2025
Accepted 21st August 2025

DOI: 10.1039/d5fb00343a

rsc.li/susfoodtech

Sustainability spotlight

This study emphasizes the sustainable valorization of tropical fruit by-products through the incorporation of rambutan peel extract into corn starch-soy protein isolate blend films. By upgrading agricultural by-products as functional ingredients in eco-friendly plastic materials, this research contributes directly to the circular economy, transforming potential waste into high-value materials and thereby reducing food waste and environmental impact. Additionally, the inclusion of natural bioactive compounds from rambutan peel aligns with the objectives of the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 3 (Good Health and Well-being). Through the development of eco-friendly alternatives to synthetic additives in food packaging, this study advances sustainable food and environmental systems, offering innovative strategies to address global health and a sustainable environment.

1 Introduction

Sustainable active packaging has garnered significant attention globally as an alternative to conventional petrochemical-based plastic materials to overcome plastic pollution. Over the years, increased awareness of environmental sustainability and advancements in packaging technology have led to the evolution of traditional packaging that is not only biodegradable but also provides additional functions, including antimicrobial and antioxidant properties.[1,2] Sustainable active packaging is developed from biopolymer materials incorporated with active compounds, serving not only as packaging but also effectively

[a]*Department of Food Technology, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 Serdang, Selangor Darul Ehsan, Malaysia. E-mail: hanani@upm.edu.my*

[b]*Alliance of Research & Innovation for Food (ARIF), Universiti Teknologi MARA Cawangan Negeri Sembilan (Kampus Kuala Pilah), 72000 Kuala Pilah, Negeri Sembilan Darul Khusus, Malaysia*

[c]*Department of Food Technology, Faculty of Applied Sciences, Universiti Teknologi MARA Cawangan Negeri Sembilan (Kampus Kuala Pilah), 72000 Kuala Pilah, Negeri Sembilan Darul Khusus, Malaysia*

[d]*Institute Nanoscience and Nanotechnology (ION2), Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*

extending the shelf-life of food products, thereby contributing to food waste reduction.[3] Biodegradable plastics derived from carbohydrates, proteins, and lipids have emerged as promising natural alternatives due to their environmental sustainability, low food safety concerns, renewability, and ease of waste management. This situation has led to an increasing demand for innovative and eco-friendly food packaging solutions. Fats, due to their hydrophobic structure, can reduce water transmission through films. Long polysaccharide chains are effective in controlling oxygen and other gas permeability, while proteins, composed of amino acids, offer structures with high intermolecular binding potential, contributing to the mechanical stability of the film.[4] By understanding their properties and their respective functions, biopolymer films with optimised performance can be developed.

At the commercial level, an ideal alternative to petrochemical-based packaging must not only be environmentally friendly but also demonstrate excellent mechanical and barrier properties.[5] As each biopolymer has its own strengths and weaknesses, many biopolymer-based films tend to show relatively poor barriers and mechanical properties. Studies have found that blending protein-based polymers with other biomaterials can enhance the mechanical and functional properties of the resulting films.[5] Such blend films often exhibit synergistic behaviour, where each polymer compensates for the limitations of the other, resulting in a multifunctional composite. Corn starch and soy protein isolate, known for their film-forming ability and mechanical strength, can be a great blend for producing biodegradable plastics due to their biodegradability, renewability, and cost-effectiveness. Since packaging is paramount in maintaining the safety and quality of food products during storage, it is crucial to understand their mechanical and barrier properties that will affect their stability during storage and handling.[6]

Rambutan (*Nephelium lappaceum* L), a tropical fruit native to Southeast Asia, produces a peel that accounts for more than 50% of its total fruit weight.[7] Rambutan peels are typically discarded after consumption or industrial processing.[6,8] The high volume of rambutan-based production results in significant amounts of agricultural waste.[8] According to Tingting *et al.*,[9] the phenolic compounds in the rambutan peel possess bioactivities properties, including antioxidant and antimicrobial activities, making them ideal candidates as key ingredients in active packaging systems. Geraniin, ellagic acid, and corilagin are among the important phenolic compounds found in rambutan peels, as reported by numerous studies.[8,10–12] Bioactive films incorporating such compounds can serve not only as physical barriers but also extend shelf life and improve food quality by actively interacting with the packaged product. Despite its bioactive potential, the application of rambutan peel extract (RPE) as an active compound in corn starch-soy protein isolate is still underexplored. Therefore, this study aims to evaluate the physicochemical, mechanical, and antioxidant properties of a corn starch-soy protein isolate blend film integrated with RPE as a potential active biodegradable film for food applications.

The findings from this research will not only add value to the underutilised agricultural waste such as rambutan peel but also align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 3 (Good Health and Well-being). Additionally, this study will contribute to the development of sustainable packaging materials as part of efforts to support the principles of the circular economy.

2 Materials and methods

2.1. Chemicals

Rambutan (*Nephelium lappaceum* L.) fruits were collected from Tampin, Negeri Sembilan, Malaysia. Ethyl alcohol (95%), potassium persulfate, and hydrochloric acid were purchased from Chemiz (Shah Alam, Selangor, Malaysia). Folin-Ciocalteu's reagent, sodium carbonate (anhydrous), corn starch, and sodium acetate trihydrate were purchased from R&M Chemicals (Petaling Jaya, Selangor, Malaysia). Gallic acid (anhydrous) was supplied by Sigma-Aldrich (St. Louis, Missouri, United States). The 1,1-diphenyl-2-picrylhydrazyl (DPPH) free radical and 2,2′-azinobis (3-ethylbenzothiazoline-6-sulfonic acid) radical cation ($ABTS^{\bullet+}$) were bought from TCI (Nihonbashi-honcho, Chuo-ku, Tokyo) and Calbiochem (Shah Alam, Selangor, Malaysia), respectively. Glacial acetic acid-and iron(III) chloride-anhydrous were supplied by Syterm-ChemAR (Shah Alam, Selangor, Malaysia). 2,4,6-Tri-(2-pyridyl)-1,3,5-triazine was purchased from Acros Organics (New Jersey, United States). Trolox was purchased from Solarbio (Beijing, China) and soy protein isolate was purchased from Tong Sheng Shidai Biotechnology (Beijing, China).

2.2. Rambutan peel extract preparation

The rambutan peels were cut into slices, washed, and treated using blanching and cooling according to a patented method (PI 2024005868) before being oven-dried at 50 °C for 24 h. The dried rambutan peels were ground and sieved using a 300 μm mesh with the average moisture content around 5.84 ± 0.12%. The rambutan peel powder was treated with 50% ethanol using ultrasound-assisted extraction (UAE) at a constant temperature of 25–30 °C and 40 kHz frequency for 15 min. The ratio between rambutan peel powder and solvent was 1 : 20, following Torgbo *et al.*[13] The solvent was removed from the extract using rotary evaporation (40 °C) and freeze-dried to form a stable powdery rambutan peel extract (RPE) for further usage.

2.3. Corn starch-soy protein isolate blend film preparation

The corn starch-soy protein isolate blend films were prepared according to Yun *et al.* with some modifications as presented in Table 1.[14] The ratio between corn starch and soy protein isolate (SPI) was 60 : 40, with the addition of glycerol (25%) as a plasticizer and RPE (0%, 1%, 3%, and 5%) as the active ingredient, in amounts relative to the total weight of SPI and corn starch. Briefly, corn starch was dissolved in distilled water, followed by SPI and glycerol. The film-forming solution was stirred at 70 ± 5 °C for 30 min and cooled down before casting. Meanwhile, for active films, the film-forming solutions were cooled down to 40 ± 5 °C before adding the RPE, followed by 15 min of stirring.

Table 1 Formulations for corn starch–soy protein isolate blend films

Ingredient	C-SPI	C-SPI 1	C-SPI 3	C-SPI 5
Distilled water	200 mL	200 mL	200 mL	200 mL
Corn starch	2.964 g	2.964 g	2.964 g	2.964 g
Soy protein isolate	1.976 g	1.976 g	1.976 g	1.976 g
Glycerol	1.235 g	1.235 g	1.235 g	1.235 g
RPE	0 g	0.0494 g	0.1482 g	0.2470 g

40 mL of film-forming solution was poured onto Plexiglas plates (14 cm × 14 cm) and dried using a fan at room temperature (23 ± 5 °C) with RH (50 ± 5%) for 2 days. The films containing 0%, 1%, 3%, and 5% of RPE were denoted as C-SPI, C-SPI 1, C-SPI 3, and C-SPI 5, respectively. The dried films were peeled off and conditioned in a dry cabinet until further analysis.

2.4. Physicochemical analysis of the film

2.4.1. Colour. The mean values for L^*, a^*, and b^* were reported as average values of five random spots on the films measured using a CR-400 Chroma Meter (Konica Minolta, New Jersey, USA), adopted from Go and Song.[15]

2.4.2. Film thickness. Film thickness was measured using a hand-held micrometer (Mitutoyo No. 547–401, Tokyo, Japan). Five random points were measured on each sample, and the average value was calculated.[16]

2.4.3. Moisture content and water solubility. The moisture content and water solubility of the film were measured according to Maryam Adilah *et al.*[16] Blended films (2 cm × 2 cm) were weighed (initial wet weight, W1) and oven dried (100 ± 5 °C) for 24 h to a constant weight which is denoted as dry weight for moisture content or initial dry weight for water solubility (W2) using a Memmert ULM 500, Germany. The moisture content was calculated using eqn (1). The dried film was then immersed in 50 mL of distilled water at room temperature for 24 h. The insoluble portion was re-dried (100 ± 5 °C) for 24 h to a constant weight which is labelled as final dry weight (W3).[16] The water solubility of the film was calculated using eqn (2):

$$\text{Moisture content}(\%) = \frac{\text{Wet weight(W1)} - \text{Dry weight(W2)}}{\text{Wet weight(W1)}} \times 100 \quad (1)$$

$$\text{Solubility}(\%) = \frac{\text{Initial dry weight(W2)} - \text{Final dry weight(W3)}}{\text{Initial dry weight(W2)}} \times 100 \quad (2)$$

2.4.4. Light transmittance and opacity. The light transmittance and opacity of the films were measured using a Genesys 10 UV-Vis spectrophotometer (Thermo Fisher Scientific, Madison, WI USA) following Maryam Adilah *et al.*[16] Two film strips (1 cm × 4 cm) were inserted into opposite sides of a cuvette, and the percentage of light transmittance was recorded at 200, 280, 400, 500, 600, and 800 nm. The analysis was conducted in triplicate. The opacity and transparency of the films were calculated using eqn (3) and (4), respectively:

$$\text{Opacity}(\text{AU mm}^{-1}) = \frac{\text{Absorbance at } \lambda = 600\text{nm(AU)}}{\text{Film thickness(mm)}} \quad (3)$$

$$\text{Transparency} = \log\left(\frac{\text{Transmittance at } \lambda = 600 \text{ nm}}{\text{Film thickness(mm)}}\right) \quad (4)$$

2.4.5. Water vapour permeability (WVP). The WVP of the film was analysed according to the modified procedure by Maryam Adilah *et al.*[16] First, a crucible was filled with 6 mL of distilled water and the film was positioned over the opening of the crucible to cover it completely. Vacuum grease was applied to ensure a tight seal. Subsequently, the samples were placed in the desiccator (50 ± 5% RH and 23 ± 2 °C). The weight of the samples was recorded hourly (9 h) until a constant weight was achieved. The WVP was calculated using eqn (5):

$$\text{WVP}(\text{g m}^{-1}\text{s}^{-1}\text{Pa}^{-1}) = \frac{\text{Weight difference} \times \text{Film thickness}}{\text{Exposed area} \times \text{Time} \times \text{Pressure difference}} \quad (5)$$

2.5. Mechanical property analysis of the film

A standard method of ASTM D 882 (ASTM, 2002) was used to determine the mechanical properties of the films using an Instron universal testing machine (Instron Engineering Co., Canton, Mass., USA). The conditioned films were cut into rectangular strips (1.5 cm × 9 cm). The grip separation was set at 5 cm with a crosshead speed of 50 mm min^{-1}, and a total load of 5 kN was used. The analysis was measured with three replications.

2.6. Film microstructure analysis

A 10 kV voltage scanning electron microscope, SEM (JSM-IT100, Jeol, Tokyo, Japan), was used to visualise the surface and cross-sectional morphology of the film. Approximately 1 cm × 1 cm of the film was mounted onto a stub and coated with gold by using a sputter coater SCD 005 (BAL-TEC AG, Balzers, Liechtenstein). Then, the films were visualised at 500× and 1000× magnification.

2.7. Antioxidant activities of the film

2.7.1. Total phenolic content. A piece of the film sample (1 g) was immersed in distilled water for two hours, and the supernatant was collected as film extract.[15] About 0.4 mL of film extract was mixed with 2 mL of 10% Folin–Ciocalteau Reagent (FCR) and 1.6 mL of 7% (w/v) sodium carbonate. After two hours of incubation in the dark at room temperature, the absorbance was measured at 760 nm using a UV-Vis spectrophotometer (Thermo Scientific Genesys 10S UV-VIS, United States). Gallic acid (400 μg mL^{-1}) was diluted with distilled water to prepare a series of standard solutions, and the absorbance was used for the standard calibration curve. The concentration of TPC in the film extract was expressed as milligrams of gallic acid equivalents per gram (mg GAE mg^{-1}) of film.

$$\text{TCP}(\text{mg GAE mg}^{-1}) = \frac{C \times V \times \text{DF}}{m} \quad (6)$$

where C is the concentration of the sample from the standard curve, V is the volume of solvent used during the extraction, m is the mass of the sample used during the extraction, and DF is the dilution factor.

2.7.2. 2,2′-azinobis-(3-ethylbenzothiazoline)-6-sulphonic acid (ABTS) radical scavenging activity. The ABTS radical scavenging assay was performed following the methods by Go and Song, with slight modifications.[15] ABTS stock solution (7 mM) was mixed with 2.45 mM potassium persulfate solution in a 1 : 1 ratio and incubated in the dark at room temperature for 16 h. The solution was then diluted with ethanol until it reached an absorbance of 0.70 ± 0.02 at 734 nm. 60 μL of film extract was mixed with 2.94 mL of ABTS solution and incubated for 10 min in the dark at room temperature and the absorbance was measured at 734 nm. The radical scavenging activity of ABTS was calculated using the following equation:

$$\text{Radical scavenging activity}(\%) = \frac{(\text{Abs ABTS} - \text{Abs sample})}{\text{Abs ABTS}} \times 100 \quad (7)$$

2.7.3. 2,2-Diphenyl-2-picrlhydrazyl (DPPH) radical scavenging activity. The free radical scavenging activity of the extracts was determined using a stable free radical, 2,2-diphenyl-2-picrylhydrazyl (DPPH), assay following the method described by Phuong *et al.*[17] with slight modifications. An aliquot of the diluted crude extract (100 μL) was mixed with 2 mL of 0.1 mM DPPH solution and incubated for 15 min in the dark room at room temperature. The absorbance was measured at 517 nm. The following equation was used to determine the radical scavenging activity:

$$\text{Radical scavenging activity}(\%) = \frac{(\text{Abs DPPH} - \text{Abs sample})}{\text{Abs DPPH}} \times 100 \quad (8)$$

2.7.4. Ferric reducing antioxidant power (FRAP) assay. The FRAP assay was performed according to Mistriyani *et al.* with some modifications.[17] The FRAP reagent was prepared by mixing 300 mmol per L acetate buffer, 10 mmol L^{-1} of 2,4,6-Tri-(2-Pyridyl)-1,3,5-Triazine (TPTZ) (in 40 mmol per L hydrochloric acid), and 20 mmol per L of ferric chloride solution (in distilled water) with a ratio of 10 : 1:1. 300 mmol L^{-1} of acetate buffer was prepared by dissolving sodium acetate trihydrate with acetic acid until the pH reached 3.6 and 1 M of sodium hydroxide was used for pH adjustments. A volume of 150 μL of the diluted crude extract was mixed with 2.85 mL of FRAP reagent and incubated in the dark at room temperature for 5 min for the reaction to occur. The absorbance was recorded at 595 nm. The antioxidant capacity was obtained using a standard curve obtained using standard solutions of ferrous sulfate (0.1 to 1.0 mM) and was expressed as μM of Fe(II) g^{-1} of sample. The FRAP reagent was used as the blank sample.

2.8. Statistical analysis

All data obtained from each analysis were analysed statistically using analysis of variance (ANOVA) using Minitab software (Version 21, PA, USA), and the values were expressed as mean ± standard deviation. The Tukey test was used to analyse the significant difference between means, and the differences were considered significant when $p < 0.05$.

3 Results and discussion

3.1 Colour of the films

Based on Table 2, increasing the rambutan peel extract resulted in a decrease in L^* (lightness) and an increase in b^* (yellow/blue) value. Meanwhile, the a^* (red/green) values increased with the addition of RPE from 1% to 3% but significantly decreased when 5% RPE was added. Incorporation of RPE into the biodegradable film resulted in a lower ($p < 0.05$) lightness value than the control film due to the presence of abundant phenolic compounds.[14,15]

The colourless control film exhibited a higher ($p < 0.05$) lightness value and lower opacity due to higher transparency than the active film. Meanwhile, in the active films, increasing the concentration of RPE from one to five percent significantly increased the b^*.[14,15] This might be due to the interaction between the red RPE and pigment from film materials, especially SPI powder, which is yellowish. According to Mendes *et al.*,[18] the increase in the b^* value could also be contributed to by the Maillard reaction that occurred during film making.

3.2 Thickness, moisture content, and water solubility of the films

The physical properties of the films are presented in Table 3. The addition of 5% RPE into the film matrix (C-SPI 5) resulted in a significant ($p < 0.05$) increase in film thickness due to the presence of a higher solid content. Similarly, Yun *et al.*,[14] Go and Song,[15] and Zhuang *et al.*[19] reported an increase in film thickness with the addition of extracts. Previous studies reported that the addition of phenolic-rich plant extracts reduced the moisture content in chitosan films.[14] In this study, the addition of RPE up to 5% did not show a substantial effect on the moisture content of starch-protein blend films, which could indicate a homogeneous incorporation of RPE into the starch-protein film matrix, without changing the water absorption and solubility properties of the film. The starch-protein blend films in this study have a relatively low water solubility (17–19%)

Table 2 L^* (lightness), a^* (redness/greenness), and b^* (yellowness/blueness) values of corn starch-soy protein isolate (C-SPI) blend films incorporated with different concentrations (0, 1, 3, and 5%) of rambutan peel extract (RPE)[a]

Film	L^*	a^*	b^*
C-SPI	92.56 ± 0.13[a]	−0.55 ± 0.02[d]	10.32 ± 0.08[d]
C-SPI 1	88.31 ± 0.07[b]	0.68 ± 0.01[a]	17.95 ± 0.08[c]
C-SPI 3	86.46 ± 0.10[c]	0.51 ± 0.06[b]	25.43 ± 0.31[b]
C-SPI 5	85.49 ± 0.20[d]	0.36 ± 0.02[c]	30.47 ± 0.36[a]

[a] Values are given as mean ± standard deviation. Means with different letters in the same column indicate a statistically significant difference ($p < 0.05$) between films.

Table 3 Thickness, moisture content, solubility, and water vapour permeability of corn starch-soy protein isolate (C-SPI) blend films incorporated with different concentrations (0, 1, 3, and 5%) of rambutan peel extract (RPE)[a]

Film	Thickness (μm)	Moisture content (%)	Solubility (%)	Water vapour permeability (10^{-10} g m^{-1} s^{-1} Pa^{-1})
C-SPI	64.00 ± 1.00[b]	14.16 ± 0.33[a]	17.40 ± 0.09[a]	1.46 ± 0.05[b]
C-SPI 1	66.00 ± 2.00[b]	13.08 ± 0.88[a]	18.17 ± 0.67[a]	1.46 ± 0.05[b]
C-SPI 3	66.00 ± 1.00[b]	12.82 ± 0.11[b]	17.45 ± 0.58[a]	1.48 ± 0.06 [ab]
C-SPI 5	73.00 ± 3.00[a]	13.32 ± 0.25 [ab]	17.19 ± 0.34[a]	1.63 ± 0.09[a]

[a] Values are given as mean ± standard deviation. Means with different letters in the same column indicate a statistically significant difference ($p < 0.05$) between films.

compared to pure carbohydrate films, which have a higher (46–55%) water solubility,[14] demonstrating the advantage of using a starch-protein combination, which strengthens its structural integrity, especially in aqueous environments.

3.3 Water vapour permeability (WVP)

Barrier properties are one of the important key quality parameters for packaging, as they influence the transmission of moisture from the storage environment to the film atmosphere, impacting the product's quality. Based on Table 3, the starch-protein blend film enriched with 5% RPE shows a slight increase ($p < 0.05$) in water vapour permeability (WVP) compared to the control film. Even though RPE exhibits a strong affinity for water, it did not cause noticeable moisture uptake and an increase in water solubility of the blend film. An increase in WVP might be due to the reduction in the crystallinity of the polymers. This aligned with the previous study, revealing that the incorporation of RPE increased the WVP due to changes in the film structure by the plasticizing effect of unpurified RPE that disrupted the compactness of the film.[15] Meanwhile, the addition of pomegranate peel extract into gelatin-based films shows the formation of alternative pathways and cracks in the matrix chemical bonds.[20] In contrast, Chollakup *et al.*[3] reported that active films acquire hydrophobicity enhancement from the dispersion of cinnamon oil and RPE that leads to a reduction in WVP as the water vapour diffusion through matrices has been slowed down. Similarly, Yun *et al.*[14] mentioned that the addition of 5% RPE reduced WVP when a strong interaction between RPE and film matrices developed a more compact microstructure, avoiding moisture transmission in chitosan-based films added with RPE and cinnamon oil.

3.4 Optical properties of the film

According to Table 4 and Fig. 1B, the addition of RPE has gradually reduced the UV (200–400 nm) and visible light transmittance (500–700 nm) of the films. This is due to the interaction of the phenolic compounds and film materials, which increases the opacity, decreasing light penetration. A packaging material with a higher opacity might lower the visibility of its contents, therefore affecting consumers' acceptance.[21] C-SPI 5, which contains the highest RPE concentration, exhibited the lowest transmittance and the highest opacity values among the samples. The C-SPI film showed the highest ($p < 0.05$) transmittance percentage at all wavelengths due to its transparency (Fig. 1A), which was in good agreement with the observations reported by Xu *et al.*[2] and Maryam Adilah *et al.*[16] This can be attributed to the light scattering properties of the phenolic compounds in the RPE.[14,15] The barrier protects food from photodeterioration, especially within the UV light region.[20] In terms of opacity value, active films had a higher value than the control film, providing light-blocking properties in conjunction with promising active packaging properties.[22]

3.5 Mechanical properties of the films

The inner microstructures and intermolecular interactions between film components highly influenced the mechanical properties of the films.[14] The tensile strength, elongation at break, and Young's modulus of the starch-protein blend films are recorded in Table 5. Based on the results, adding RPE significantly ($p < 0.05$) increased the tensile strength of starch-protein blend films. The hydrogen bonds are likely formed between the hydroxyl (–OH) groups in RPE, particularly polyphenols, and the starch-protein matrix.[3] Consequently, the active blend film effectively reinforces the interaction with the film matrix and can

Table 4 Light transmittance and opacity of corn starch-soy protein isolate (C-SPI) blend films incorporated with different concentrations (0, 1, 3, and 5%) of rambutan peel extract (RPE)

	Light transmittance (%) at different wavelengths (nm)						
Film	200 nm	280 nm	400 nm	500 nm	600 nm	800 nm	Opacity value (Au mm^{-1})
C-SPI	62.05 ± 0.03[a]	33.55 ± 0.50[a]	59.32 ± 0.11[a]	73.34 ± 0.46[a]	76.84 ± 0.02[a]	81.63 ± 0.26[a]	1.78 ± 0.02[c]
C-SPI 1	47.45 ± 0.16[b]	20.41 ± 0.04[b]	30.94 ± 0.02[b]	64.44 ± 0.31[b]	74.18 ± 0.08[b]	80.24 ± 0.06[b]	2.00 ± 0.03[b]
C-SPI 3	38.84 ± 0.05[d]	17.65 ± 0.18[c]	11.41 ± 0.13[d]	55.18 ± 0.04[c]	69.75 ± 0.26[c]	79.65 ± 0.05[c]	2.31 ± 0.04[a]
C-SPI 5	40.65 ± 0.34[c]	15.74 ± 0.14[d]	13.12 ± 0.12[c]	53.97 ± 0.53[c]	67.35 ± 0.10[d]	77.21 ± 0.05[d]	2.31 ± 0.14[a]

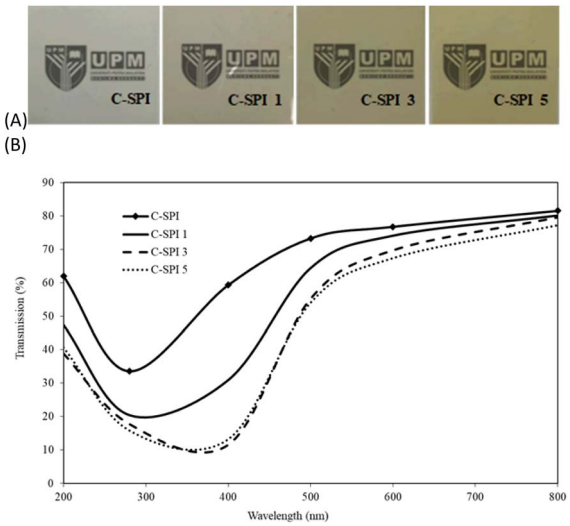

Fig. 1 Colour (A) and UV-visible light transmittance (B) of corn starch-soy protein isolate (C-SPI) blend films incorporated with different concentrations (0, 1, 3, and 5%) of rambutan peel extract (RPE).

withstand stress better than the control film. On the other hand, incorporating 5% RPE into the film matrix significantly ($p < 0.05$) enhanced the flexibility of the film as indicated by the increase in elongation at break (EAB) values. Along with an improvement in tensile strength, the addition of RPE resulted in a plasticizing effect, making films more flexible and promising for active packaging. However, the film with 3% RPE displayed the lowest EAB ($p < 0.05$), indicating a brittle film, possibly due to extract aggregation that disrupted the polymer network. The interaction between phenolic compounds and functional groups in the polymer could lead to a stronger film structure that increased the tensile strength and Young's modulus, but it reduced the flexibility, EAB.[23] Young's modulus measures a film's ability to resist deformation under stress. Typically, active blend films showed higher values than the control film. Overall, the 5% RPE formulation offered the most favourable mechanical balance for food packaging applications, as the addition of extract improves the strength and film's stretchability due to a reduction in rigidity and stiffness. This finding aligned with that by Yun *et al.*,[14] who reported that a chitosan film embedded with 5% RPE could be the best candidate for effectively protecting packaged food during transportation and storage with the highest mechanical properties.

Table 5 Mechanical properties of corn starch-soy protein isolate (C-SPI) blend films incorporated with different concentrations (0, 1, 3, and 5%) of rambutan peel extract (RPE)[a]

Film	Tensile strength (MPa)	EAB (%)	Young's modulus (MPa)
C-SPI	4.89 ± 0.31^{b}	2.62 ± 0.51^{c}	795.50 ± 27.30^{c}
C-SPI 1	6.02 ± 0.36^{a}	5.20 ± 0.51^{b}	928.70 ± 72.20^{ab}
C-SPI 3	5.76 ± 0.31^{a}	2.11 ± 0.62^{c}	976.50 ± 53.60^{a}
C-SPI 5	6.36 ± 0.27^{a}	7.10 ± 0.52^{a}	851.29 ± 14.14^{bc}

[a] Values are given as mean ± standard deviation. Means with different letters in the same column indicate a statistically significant difference ($p < 0.05$) between films.

3.6 Microstructures of films

The information related to the arrangement of film materials can be obtained through microstructure testing.[14] The surface (A–D) and cross-sections (E–H) of starch-protein blend films are shown in Fig. 2. Based on SEM images, small, empty spaces that appeared within the film material are called microvoids. Meanwhile, the breaks or fractures observed in the SEM images refer to the cracked structure, and the air pockets filled with air represent material defects of the composite or porous structure of the material. Based on the surface morphologies, the control film (C-SPI) revealed a smooth, homogeneous surface without visible pores, cracks, or aggregated particles. This indicates strong compatibility between corn starch and soy protein isolate, producing a uniform film. The smooth and clean surface morphology might have decreased the rate of moisture transmission, corroborating its low WVP. In contrast, a gradual increment of RPE into the film matrix produced more heterogeneous surface morphologies with rougher and more irregular surfaces, leading to higher WVP values. This could be due to the hydrophilic phenolic compounds that disrupt the uniformity and compactness of the starch-protein matrix.

On the other hand, the cross-section morphology for the control film (C-SPI) exhibited a dense, tightly packed, layered

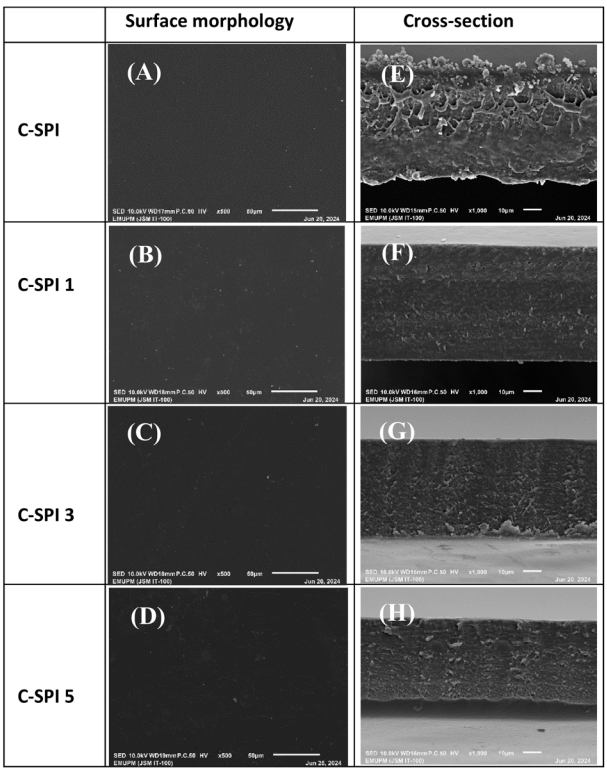

Fig. 2 SEM micrographs on the surface (500× magnification) of corn starch-soy protein isolate (C-SPI) film (A–D) and cross-section (1000× magnification) of the C-SPI film (E–H).

structure with minimal visible voids, directly correlating with enhanced barrier properties. This control film matrix is strongly integrated and tightly attached to the casting plate during the drying process. Addition of RPE into the film matrix helped reduce the tightly bound surfaces between the film and casting plate, as it has a plasticizing effect that can enhance the film's flexibility and texture. The cross-section microstructure of the active films displays a more porous and heterogeneous internal structure with small voids and uneven regions compared to the control film and, consequently, provides a lower water vapour permeability value.

3.7 Antioxidant activities of the film

Measuring the antioxidant availability in the film incorporated with a bioactive-rich extract is crucial to ensure that it serves the purpose of active food packaging. Antioxidants in the film scavenge free radicals found in the food system to slow down the oxidation process and prevent product deterioration within the stipulated period. As shown in Fig. 3, the trend of total phenolic content released from the films after two hours of water immersion increased with the concentration of RPE from 1 to 5% (4.46–14.65 mg GAE per g film). A similar trend was observed in DPPH and ABTS radical scavenging activities, as shown in Fig. 4 and 5 which illustrates the relationship between

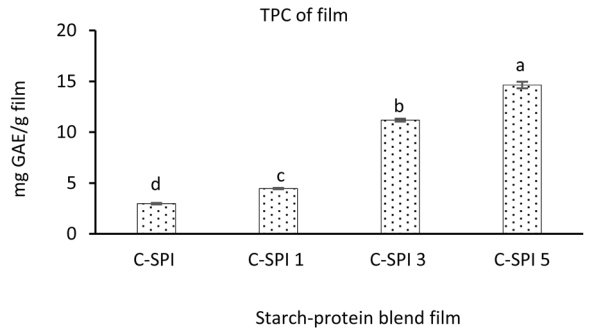

Fig. 3 Total phenolic content (TPC) of corn starch-soy protein isolate (C-SPI) blend films incorporated with different concentrations (0, 1, 3, and 5%) of rambutan peel extract (RPE).

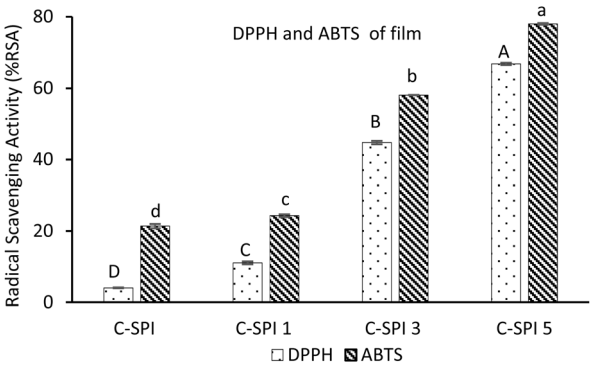

Fig. 4 DPPH and ABTS scavenging activities of corn starch-soy protein isolate (C-SPI) blend films incorporated with different concentrations (0, 1, 3, and 5%) of rambutan peel extract (RPE).

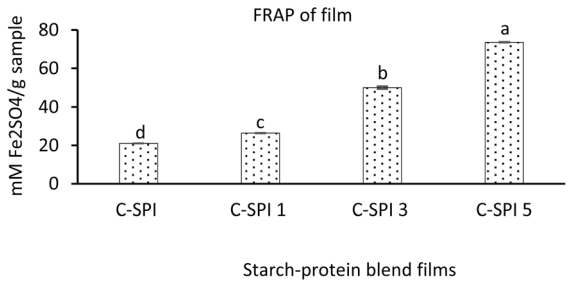

Fig. 5 Ferric reducing antioxidant power (FRAP) of corn starch-soy protein isolate (C-SPI) blend films incorporated with different concentrations (0, 1, 3, and 5%) of rambutan peel extract (RPE).

phenolic compounds and antioxidant activities. This shows that the starch-protein blend film allows the active compound embedded in the film matrix to migrate into the food system, as the FRAP assays recorded an increasing value in the active film compared to the control. Based on all four antioxidant assays, increasing the amount of RPE will proportionately enhance the antioxidant activities of the starch-protein blend films. This is in good agreement with previous studies conducted by Go and Song[15] and Chollakup *et al.*[3] The bioactive compounds in RPE, particularly geraniin, ellagic acid, and gallic acid, are known as electron and hydrogen donors contributing to effective radical scavenging and reducing power.[8,10–12] Therefore, starch-protein blend films incorporated with RPE can be a promising active food packaging material as an alternative for petrochemical-based food packaging.

4 Conclusions

Incorporating the RPE powder has increased ($p < 0.05$) the thickness of corn starch-soy protein isolate blend films without a noticeable change ($p \geq 0.05$) in moisture content and water solubility. However, the addition of 5% RPE has significantly ($p < 0.05$) increased the water vapour permeability of the blend film. This aligned with the microstructure properties of the C-SPI 5 film, which displayed a more heterogeneous and porous internal morphology. Meanwhile, the control film (C-SPI) exhibited a homogeneous surface without visible pores, cracks, or aggregated particles. On the other hand, the addition of 5% RPE into the starch-protein blend film has significantly reduced the lightness value and increased the film's opacity. Therefore, the light transmittance from the UV and visible light spectrum has been significantly reduced. Furthermore, incorporating the RPE up to 5% also showed a significant ($p < 0.05$) effect on the mechanical properties of the film blend, with an increase in tensile strength and flexibility. Evaluating another important criterion for this active blend, which is the antioxidant properties, has shown that the blend film with 5% RPE (C-SPI 5) demonstrated the highest ($p < 0.05$) antioxidant activities among the other films. Overall, the corn starch-soy protein isolate blend film incorporated with 5% RPE (C-SPI 5) showed promising potential as an active food packaging material to extend the shelf life and maintain the quality of food products.

Author contributions

T. Nurul Azlin conducted the formal analysis, investigation, and methodology and wrote the original draft. F. Han Lyn reviewed and edited it, and Z.A. Nur Hanani reviewed, validated, and supervised the project.

Conflicts of interest

There are no conflicts to declare.

Data availability

The authors have provided all data in the manuscript.

Supplementary information is available: the rambutan peel extract and corn starch-soy protein isolate blend film were prepared according to the procedures in the real-time images. See DOI: https://doi.org/10.1039/d5fb00343a.

Acknowledgements

The authors would like to thank Universiti Putra Malaysia (UPM) for the facilities provided.

References

1 K. Łupina, D. Kowalczyk, M. Lis and M. Basiura-Cembala, Antioxidant polysaccharide/gelatin blend films loaded with curcumin - A comparative study, *Int. J. Biol. Macromol.*, 2023, **236**, DOI: 10.1016/j.ijbiomac.2023.123945.

2 Z. Xu, J. Chen, Y. Lv, J. Du, O. J. Rojas and H. Wang, Controlled release of active food packaging by nanocarriers: Design, mechanism, models and applications, *Food Packag. Shelf Life*, 2025, **49**, 101524, DOI: 10.1016/j.fpsl.2025.101524.

3 R. Chollakup, S. Pongburoos, W. Boonsong, N. Khanoonkon, K. Kongsin, R. Sothornvit, P. Sukyai, U. Sukatta and N. Harnkarnsujarit, Antioxidant and antibacterial activities of cassava starch and whey protein blend films containing rambutan peel extract and cinnamon oil for active packaging, *LWT-Food Sci. Technol.*, 2020, **130**, DOI: 10.1016/j.lwt.2020.109573.

4 A. S. Nandane and R. Jain, Study of mechanical properties of soy protein based edible film as affected by its composition and process parameters by using RSM, *J. Food Sci. Technol.*, 2015, **52**, 3645–3650, DOI: 10.1007/s13197-014-1417-4.

5 Y. A. Shah, S. Bhatia, A. Al-Harrasi, M. Afzaal, F. Saeed, M. K. Anwer, M. R. Khan, M. Jawad, N. Akram and Z. Faisal, Mechanical Properties of Protein-Based Food Packaging Materials, *Polymers*, 2023, **15**, 1–13, DOI: 10.3390/polym15071724.

6 L. F. Ferreira, A. C. S. de Oliveira, D. de O. Begali, A. R. de S. Neto, M. A. Martins, J. E. de Oliveira, S. V. Borges, M. I. Yoshida, G. H. D. Tonoli and M. V. Dias, Characterization of cassava starch/soy protein isolate blends obtained by extrusion and thermocompression, *Ind. Crops Prod.*, 2021, **160**, DOI: 10.1016/j.indcrop.2020.113092.

7 K. Mahmood, H. Kamilah, A. Karim Alias and F. Ariffin, Nutritional and therapeutic potentials of rambutan fruit (Nephelium lappaceum L.) and the by-products: a review, *Journal of Food Measurement and Characterization*, 2018, **12**, 1556–1571, DOI: 10.1007/s11694-018-9771-y.

8 K. Rakariyatham, D. Zhou, N. Rakariyatham and F. Shahidi, Sapindaceae (*Dimocarpus longan* and *Nephelium lappaceum*) seed and peel by-products: Potential sources for phenolic compounds and use as functional ingredients in food and health applications, *J. Funct. Foods*, 2020, **67**, 103846, DOI: 10.1016/j.jff.2020.103846.

9 Z. Tingting, Z. Xiuli, W. Kun, S. Liping and Z. Yongliang, A review: extraction, phytochemicals, and biological activities of rambutan (*Nephelium lappaceum* L) peel, *Heliyon*, 2022, **8**, e11314, DOI: 10.1016/j.heliyon.2022.e11314.

10 B. R. Albuquerque, J. Pinela, M. I. Dias, C. Pereira, J. Petrović, M. Soković, R. C. Calhelha, M. B. P. P. Oliveira, I. C. F. R. Ferreira and L. Barros, Valorization of rambutan (*Nephelium lappaceum* L.) peel: Chemical composition, biological activity, and optimized recovery of anthocyanins, *Food Res. Int.*, 2023, **165**, DOI: 10.1016/j.foodres.2023.112574.

11 N. N. M. Phuong, T. T. Le, M. Q. Dang, J. Van Camp and K. Raes, Selection of extraction conditions of phenolic compounds from rambutan (*Nephelium lappaceum* L.) peel, *Food Bioprod. Process.*, 2020, **122**, 222–229.

12 C. Hernández-Hernández, C. Aguilar, R. Rodríguez-Herrera, A. Flores-Gallegosa, J. Morlett-chávez, M. Govea-salas and J. Ascacio-valdés, Rambutan (*Nephelium lappaceum* L.): Nutritional and functional properties, *Trends Food Sci. Technol.*, 2019, **85**, 201–210.

13 S. Torgbo, U. Sukatta, P. Kamonpatana and P. Sukyai, Ohmic heating extraction and characterization of rambutan (*Nephelium lappaceum* L.) peel extract with enhanced antioxidant and antifungal activity as a bioactive and functional ingredient in white bread preparation, *Food Chem.*, 2022, **382**, 132332, DOI: 10.1016/j.foodchem.2022.132332.

14 D. Yun, Y. Qin, J. Zhang, M. Zhang, C. Qian and J. Liu, Development of chitosan films incorporated with rambutan (*Nephelium lappaceum* L.) peel extract and their application in pork preservation, *Int. J. Biol. Macromol.*, 2021, **189**, 900–909, DOI: 10.1016/j.ijbiomac.2021.08.171.

15 E. J. Go and K. Bin Song, Development and characterization of Citrus Junos Pomace pectin films incorporated with Rambutan (*Nephelium Lappaceum*) peel extract, *Coatings*, 2020, **10**, 1–15, DOI: 10.3390/COATINGS10080714.

16 Z. A. Maryam Adilah, F. Han Lyn, B. Nabilah, B. Jamilah, C. Gun Hean and Z. A. Nur Hanani, Enhancing the physicochemical and functional properties of gelatin/graphene oxide/cinnamon bark oil nanocomposite packaging films using ferulic acid, *Food Packag. Shelf Life*, 2022, **34**, DOI: 10.1016/j.fpsl.2022.100960.

17 S. R. Mistriyani and A. Rohman, Antioxidant activities of Rambutan (*Nephelium lappaceum* L) peel in vitro, *Food Res.*, 2018, **1**, 119–123.

18 J. F. Mendes, J. T. Martins, A. Manrich, A. R. Sena Neto, A. C. M. Pinheiro, L. H. C. Mattoso and M. A. Martins, Development and physical-chemical properties of pectin film reinforced with spent coffee grounds by continuous casting, *Carbohydr. Polym.*, 2019, **210**, 92–99, DOI: **10.1016/j.carbpol.2019.01.058**.

19 Y. Zhuang, S. Ruan, H. Yao and Y. Sun, Physical properties of composite films from tilapia skin collagen with Pachyrhizus starch and rambutan peel phenolics, *Mar. Drugs*, 2019, **17**, DOI: **10.3390/md17120662**.

20 A. Valdés, E. Garcia-Serna, A. Martínez-Abad, F. Vilaplana, A. Jimenez and M. C. Garrigós, Gelatin-Based Antimicrobial Films Incorporating Pomegranate (*Punica granatum* L.) Seed Juice by-Product, *Molecules*, 2020, **25**, DOI: **10.3390/molecules25010166**.

21 L. Zhang, Z. Liu, Y. Sun, X. Wang and L. Li, Effect of α-tocopherol antioxidant on rheological and physicochemical properties of chitosan/zein edible films, *LWT – Food Science and Technology*, 2020, **118**, DOI: **10.1016/j.lwt.2019.108799**.

22 Z. A. Maryam Adilah and Z. A. Nur Hanani, Active packaging of fish gelatin films with *Morinda citrifolia* oil, *Food Biosci.*, 2016, **16**, 66–71.

23 T. T. Dang, L. A. T. Nguyen, D. T. Dau, Q. S. Nguyen, T. N. Le and T. Q. N. Nguyen, Improving properties of chitosan/polyvinyl alcohol films using cashew nut testa extract: potential applications in food packaging, *R. Soc. Open Sci.*, 2024, DOI: **10.1098/rsos.241236**.