Food Bioscience 69 (2025) 106976



Contents lists available at ScienceDirect

Food Bioscience

journal homepage: www.elsevier.com/locate/fbio





Development and characterisation of broccoli by-product-enriched starch-carrageenan films for extending the shelf life of fresh-cut fruits

Oghenetega Lois Orhotohwo [a,b,c,d], Benedetta Fanesi [a], Helen Stephanie Ofei Darko [a], Lama Ismaiel [a], Paolo Lucci [a], Deborah Pacetti [a], Amit K. Jaiswal [b,c,d,e], Swarna Jaiswal [b,c,d,e,*]

[a] Department of Agricultural, Food and Environmental Sciences, Università Politecnica delle Marche, 60131, Ancona, Italy
[b] School of Food Science and Environmental Health, Faculty of Sciences and Health, Technological University Dublin-City Campus, Central Quad, Grangegorman, Dublin D07 ADY7, Ireland
[c] Centre for Sustainable Packaging & Bioproducts (CSPB), Technological University Dublin-City Campus, Central Quad, Grangegorman, Dublin D07 ADY7, Ireland
[d] Sustainability and Health Research Hub, Technological University Dublin-City Campus, Grangegorman, Dublin D07 H6K8, Ireland
[e] Health Engineering & Materials Science Research Hub, Technological University Dublin - City Campus, Grangegorman, Dublin, Ireland

ARTICLE INFO

Keywords:
Edible films
Active packaging
Broccoli by-products
Antimicrobial properties
Food preservation

ABSTRACT

The growing demand for sustainable food packaging necessitates the development of biodegradable films with enhanced functional properties. This study aimed to develop and characterise potato starch (PS) and κ-carrageenan (KCa) composite films enriched with broccoli by-product powder (BBPP) and extract (BBPE) for active food packaging applications. The structural analysis confirmed strong polymer compatibility, with FT-IR spectra revealing intermolecular interactions without significant chemical disruption. The incorporation of BBPP significantly improved tensile strength (43.16 %) and Young's modulus (50.13 %), while BBPE enhanced film flexibility (58.27%). BBPP exhibited superior antioxidant activity (70.29 % DPPH, 93.38 % ABTS), whereas BBPE films demonstrated greater antimicrobial efficacy, reducing *Escherichia coli* and *Staphylococcus aureus* counts to 5.62 and 7.07 log CFU/mL, respectively. When applied as coatings for fresh-cut kiwis, BBPE-based film-forming solutions effectively minimised weight loss, preserved total soluble solids (TSS), and inhibited microbial growth, maintaining total bacterial counts (TBC) below 4 Log CFU/g over 11 days of refrigerated storage. These findings highlight the potential of broccoli by-product-enriched films as sustainable and active packaging solutions.

1. Introduction

Broccoli (*Brassica oleracea* var. *italica*) production generates substantial agricultural waste, with approximately 60–75 % of the total above-ground biomass discarded during harvesting. This waste includes stalks, stems, leaves, outer florets, unmarketable heads, and other field residues (Petkowicz & Williams, 2020). The primary cause of this loss is the limited utilization of the plant's biomass, as only the florets (representing about 15 % of the total biomass) are typically harvested for consumption (Liu et al., 2018). Also, a significant amount of broccoli is discarded at the harvesting stage due to non-compliance with market standards and quality grading practices, contributing significantly to agricultural waste. Broccoli by-products (BBP) are nutrient-rich and contain various bioactive compounds, including glucosinolates and flavonoids, which have demonstrated potential in food formulations (Gudiño et al., 2022; Shinali et al., 2024; Yan et al., 2023). Their bioactive potential has been explored in products such as biscuits (Fanesi et al., 2023), crackers (Lafarga et al., 2019), and bread (Krupa-Kozak et al., 2021), demonstrating their value in sustainable food processing. However, their application in active food packaging remains underexplored, despite the growing demand for eco-friendly packaging solutions. Recent studies have investigated the extraction of cellulose from broccoli stems (Sayanjali et al., 2024) and pectin from stalks (Petkowicz & Williams, 2020) for use in biodegradable films. The valorisation of these by-products in food packaging could mitigate agricultural waste, improve food preservation and extend shelf life (Santhosh et al., 2021).

Conventional plastic food packaging, derived from petroleum sources, poses significant environmental risks due to its non-biodegradability and microplastic pollution (Nešić et al., 2024; Sinha,

* Corresponding author. School of Food Science and Environmental Health, Faculty of Sciences and Health, Technological University Dublin-City Campus, Central Quad, Grangegorman, Dublin D07 ADY7, Ireland.
E-mail addresses: swarna.jaiswal@tudublin.ie, swarna.jaiswal@outlook.com (S. Jaiswal).

https://doi.org/10.1016/j.fbio.2025.106976
Received 7 April 2025; Received in revised form 21 May 2025; Accepted 2 June 2025
Available online 3 June 2025
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2024). This has driven interest in biodegradable alternatives such as starch and carrageenan, valued for their renewability and film-forming properties (Arias et al., 2024; Ramadas et al., 2024).

Starch is a widely available, biodegradable, and cost-effective biopolymer with significant potential as a substitute for conventional plastic films. However, starch-based films often exhibit poor mechanical strength, brittleness, and high sensitivity to moisture, limiting their practical applications in food packaging (Rahmadi Putri et al., 2023). To overcome these drawbacks, starch is frequently blended with other biopolymers, plasticisers, or bioactive additives to enhance its physicochemical properties (Santhosh et al., 2024). Carrageenan, a sulphated polysaccharide derived from red seaweed, is often incorporated into starch-based films due to its gel-forming ability, structural integrity, and capacity to improve mechanical and barrier properties (Kokkuvayil Ramadas et al., 2024; Sabu Mathew et al., 2024). By combining starch with carrageenan, a composite film with improved flexibility, mechanical strength, and water resistance can be developed, making it a promising candidate for food packaging applications.

Broccoli by-products (BBP) are rich in bioactive compounds such as glucosinolates, polyphenols, and flavonoids, which enhance the functionality of biodegradable films. These compounds improve antioxidant capacity by preventing oxidation, similar to polyphenols from grape seed and mango peel extracts (Ivanov & Godjevargova, 2024; Kučuk et al., 2024). Additionally, BBP exhibit antimicrobial properties, inhibiting spoilage microorganisms and reducing reliance on synthetic preservatives (Li et al, 2024; Singaram et al., 2024). Incorporating BBP bioactive extracts into packaging materials could enhance functionality, providing a sustainable and effective approach to active food packaging. Beyond preservation benefits, these polyphenols reinforce the mechanical properties of films, increasing tensile strength and flexibility (Alahmed & Simsek, 2024). Although BBP offers valuable bioactive properties, several limitations may affect its application in packaging materials. The composition of bioactives can vary depending on agricultural conditions, potentially leading to inconsistent performance (Biondi et al., 2021). Moreover, the hydrophilic nature of BBP extracts may pose challenges when blended with certain polymers, potentially affecting film uniformity and barrier properties (Alshehri et al., 2024). Sensory issues like BBP's characteristic smell and colour might also limit consumer acceptance. To address these challenges, cinnamon essential oil was incorporated to improve the sensory characteristics of the films.

Fresh-cut kiwifruits (*Actinidia* spp.) are highly perishable due to the cellular damage caused by minimal processing, such as peeling and slicing, which accelerates enzymatic browning, moisture loss, microbial growth, and textural degradation (Shi et al., 2024; Sortino et al., 2022). Various preservation strategies, including cold storage, antioxidant treatments, edible coatings, chemical dipping, and active atmosphere modification, are employed to extend shelf life and maintain post-cut quality (Iturralde-García et al., 2022; Yousuf et al., 2018). Edible coatings have gained attention as a sustainable alternative for fresh produce preservation by providing a protective barrier that reduces moisture loss, inhibits microbial proliferation, and delays oxidative changes.

This study aims to develop and characterise an active packaging film/coating based on a potato starch (PS) and κ-carrageenan (KCa) biopolymer matrix enriched with broccoli by-product powder (BBPP) and broccoli by-product extract (BBPE). The novelty of this research lies in its approach to incorporating BBP-derived bioactive compounds into biodegradable composite films and evaluating their impact on film structure, physical properties, and functional performance. This is the first systematic study on starch/carrageenan films enriched with BBPP and BBPE, evaluating their physicochemical and functional properties for food packaging. Additionally, the study explores the ability of these films to preserve fresh-cut kiwifruit during refrigerated storage.

Table 1
The formulation blends of composite films.

Samples	Film formulations (F)	BBPP and BBPE (%)
F1	PS	–
F2	PS/KCa	–
F3	PS/KCa/CEO	–
F4	PS/KCa/CEO	BBPP 0.5
F5	PS/KCa/CEO	BBPP 1.0
F6	PS/KCa/CEO	BBPE 0.5
F7	PS/KCa/CEO	BBPE 1.0

PS - Potato starch; KCa - k-Carrageenan; BBPP – Broccoli by-product powder; BBPE – Broccoli by-products extract.

2. Materials and methods

2.1. Materials

Kiwifruits were sourced from a local market in Dublin, Ireland. Potato starch was obtained from Meade Farm (Co. Meath, Ireland), while κ-carrageenan (CAS: 11114-20-8; Mw: 788.6 g/mol), was purchased from Thermo Fisher Scientific (Dublin, Ireland). Both polymers were used as received without further fractionation. Glycerol (FCC, FG) and TWEEN 80 were procured from Sigma Aldrich (Dublin, Ireland), and cinnamon essential oil (CEO) was obtained from a local health store. All other analytical-grade chemicals and standards used in this study were supplied by Thermo Fisher Scientific, Ireland. Frozen broccoli by-products, including outer florets, stems, stalks, and unmarketable whole heads, were collected from O.R.T.O. Verde S. c.a.p.a. (Senigallia, Italy). The samples were freeze-dried (Scanvac CoolSafe, LaboGene, Denmark), vacuum-sealed (Electrolux KBV4X, vacuum drawer), and stored in the dark at room temperature (20 ± 2 °C) until further analysis.

2.2. Preparation of broccoli by-product powder (BBPP) and extract (BBPE)

Freeze-dried broccoli by-products were ground using an automatic mortar mill (RM 200, Retsch GmbH, Germany) and sieved (140-mesh) to obtain BBPP (<105 μm). The extraction procedure was adapted from Chang et al. (2024), with minor modifications. Briefly, 10 g of BBPP was mixed with 100 mL of 70 % ethanol (w/w) and left at room temperature for 10 min. The mixture underwent ultrasonic treatment (Elmasonic xtra ST, Elma Schmidbauer GmbH, Germany) at 55 °C for 30 min, followed by centrifugation at 4610×*g* for 10 min (Sorvall ST 16, ThermoFisher Scientific, Germany). The sediment was re-extracted under the same conditions, and the supernatants were combined. The pooled extracts were filtered through Whatman No. 1 filter paper, and the ethanol was evaporated under reduced pressure at 45 °C using a Rotavapor (Büchi Labortechnik AG, Switzerland). The concentrated extract was subsequently freeze-dried (Scanvac CoolSafe, LaboGene, Denmark) to yield the final broccoli by-product extract (BBPE). The dried BBPE was stored at −4 °C in airtight containers until further analysis.

2.3. Preparation of composite films

Composite films were prepared following the method of Yap et al. (2024) with modifications. Potato starch (PS, 1.5 g) was dissolved in 100 mL of distilled water and heated with continuous stirring at 90 °C for 30 min at 600 rpm to ensure complete solubilization and gelatinization. Subsequently, κ-carrageenan (KCa, 0.5 g) was added and stirred until fully dissolved. Glycerol (45 % w/w, based on the total polymer weight) was then incorporated as a plasticizer. After reducing the temperature to 55 °C, CEO (0.1 %) and Tween 80 were incorporated. BBPP and BBPE were added at 0.5 % and 1.0 % concentrations. Control films (without BBPP/BBPE) were also prepared. The formulation blends are shown in Table 1. The film-forming solutions (40 mL) were poured into Petri dishes (12 × 12 mm) and oven-dried (Memmert UN55) at 35 °C for

24 h. The dried films were peeled off and conditioned at 50 % RH for 48 h before characterisation.

2.4. Characterisation of composite films

2.4.1. Determination of film structure

The chemical structure and molecular interactions of the films were analysed using attenuated total reflection Fourier Transform Infrared (ATR-FTIR) spectroscopy (Nicolet iZ10, ThermoFisher Scientific) with OMNIC software (v7.3, Thermo Electron Corp., USA). Spectra were recorded at room temperature with a resolution of 4 cm^{-1} over 64 scans.

2.4.2. Measurement of film thickness

Film thickness was measured using a digital micrometre (NTK131, Neoteck, China) with 0.001 mm accuracy. Measurements were taken at ten random points, and the average value was recorded.

2.4.3. Mechanical properties

Tensile strength (TS), elongation at break (EAB), and Young's modulus (YM) were measured following ASTM D882 using a texture analyser (TA.XT-plus, Stable Micro Systems, UK) as described by Santhosh and Sarkar (2024) with slight modifications. Film samples (10 × 80 mm) were clamped with a 50 mm initial grip separation and tested at a crosshead speed of 50 mm/min. Measurements were taken from five strips per film, and the average value was recorded.

2.4.4. Moisture content and water solubility

Moisture content was determined using a moisture analyser (DLB, Kern GmbH, Germany) at 105 °C, with results displayed automatically. Water solubility was measured following Goudar et al. (2020) with modifications. Dried film samples (3 × 3 cm) were weighed after 24 h at 70 °C (Memmert UN55 oven). The samples were immersed in 25 mL of distilled water at room temperature for 6 h with periodic stirring. After removal, they were dried at 80 °C for 24 h, and the final weight was recorded. Water solubility (WS) was calculated using the following equation (1).

$$WS\ (\%) = \frac{Wi - Wf}{Wi} \times 100 \quad (1)$$

where, Wi and Wf are the initial and final weight of the sample, respectively.

2.4.5. Water contact angle

The water contact angle (WCA) of the films was measured at room temperature using an OCA Optical Tensiometer (DataPhysics Instruments GmbH, Germany) via the sessile drop technique. A 3 μL distilled water droplet was carefully placed on the film surface, and its hydrophilicity was assessed. Contact angle images were captured using a computer-connected camera and analysed with dpiMAX software. Ten measurements were taken per sample, and the average WCA was recorded.

2.4.6. Water vapour transmission rate

The water vapour transmission rate (WVTR) was measured following ASTM E96/E96M−16 and the method of Gasti et al. (2021). Film samples were secured over the opening of a 20 mm diameter glass bottle containing 10 mL of distilled water using Teflon tape. The initial bottle weight (W_1) was recorded before placing it in an oven at 40 °C for 24 h. The final weight (W_2) was then measured, and WVTR was calculated by equation (2).

$$WVTR = \frac{W_1 - W_2}{A \times T} \quad (2)$$

where A is the area of the mouth of the glass bottle, and T is the time in hours.

2.4.7. Optical properties

2.4.7.1. Colour. Film colour was assessed using a Minolta colorimeter (CR 400, Minolta, Japan) calibrated with a white standard plate (L* = 94.54, a* = −1.11, b* = −0.54). The CIELab parameters—L* (lightness), a* (red-green), and b* (yellow-blue) — were recorded. Colour changes were quantified using the total colour difference (ΔE), calculated according to equation (3):

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

where L*, a*, and b* are standard values, and L, a, and b are the measured values of the films. Each sample was measured six times.

2.4.7.2. Opacity. The Hunter lab method, which relates each sample's opacity on a black standard (Yb) to its opacity on a white standard (Yw), was used to determine the samples' opacity. The same apparatus used for colour measurements automatically performed this calculation (Y=Yb/Yw). Each sample film was taken in six replicates.

2.4.8. Measurement of antioxidant activities

To prepare film extracts for antioxidant activity analysis, 0.1 g of each sample was dissolved in 6 mL of water and stirred at room temperature for 3 h. The solution was then centrifuged (Sorvall ST 16, Thermo Fisher Scientific, Germany) at 5000 rpm for 10 min, and the supernatant was used for further analysis.

2.4.8.1. DPPH radical scavenging activity. The DPPH assay was performed following Zheng et al. (2018) with modifications. A 3.0 mL aliquot of the soaking solution was mixed with 1.0 mL of 1 mM DPPH methanolic solution, shaken, and incubated in the dark at room temperature for 30 min. Absorbance was measured at 517 nm using a Thermo Fisher Scientific Multiskan GO Microplate Reader with SkanIt™ software. The DPPH scavenging activity (%) was calculated according to equation (4).

$$DPPH\ activity\ (\%) = \frac{A_{DPPH} - A_{Sample}}{A_{DPPH}} \times 100 \quad (4)$$

where A_{DPPH} is the absorbance of the DPPH blank solution and A_{SAMPLE} is the absorbance of the sample extracts.

2.4.8.2. ABTS radical scavenging activity. With a few modifications, the ABTS radical scavenging activity assay was carried out as described by Hanani et al. (2019). Two stock solutions were made: a 2.45 mM potassium persulfate ($K_2S_2O_8$) solution and a 7.0 mM ABTS solution. After combining the two stock solutions in a 1:1 ratio, they were allowed to sit at room temperature in the dark for 16 h. Using a spectrophotometer, the initial absorbance reading of the ABTS solution was 0.70 ± 0.02 at 734 rpm after it had been diluted with ethanol. After mixing the extract dilution with the ABTS solution (0.1:3, v/v), the mixture was allowed to sit at room temperature for 6 min in the dark. Using SkanItTM software and a Thermo Fisher Scientific Multiskan GO Microplate Reader, the absorbance was measured at 734 nm. Absolute ethanol was used in place of the extract to create control. The radical scavenging percentage was calculated according to equation (5).

$$ABTS\ Scavenging\ effect\ (\%) = \frac{A_{control} - A_{sample}}{A_{control}} \times 100 \quad (5)$$

where $A_{control}$ is the absorbance of the control, and A_{sample} is the absorbance of the test sample. All tests were performed in triplicate.

2.4.9. Antibacterial activities of composite films

The antibacterial efficacy of the films was assessed following the Japanese Industrial Standard (JIS Z 2801) protocol (Perera et al., 2022). *Staphylococcus aureus* (Gram-positive) and *Escherichia coli*

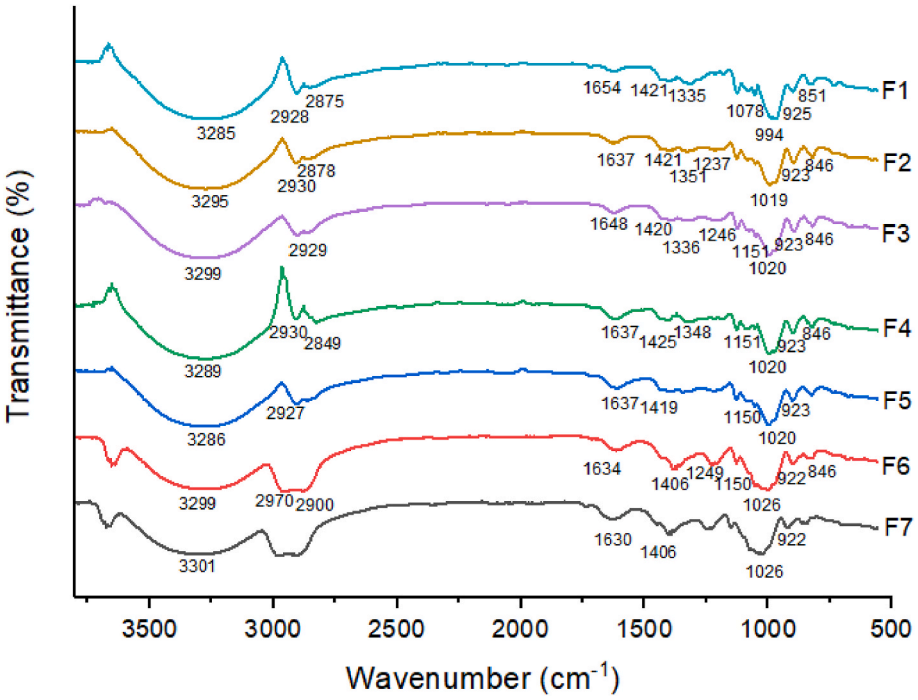


Fig. 1. The Fourier Transform Infrared (FT-IR) spectra of F1 (PS), F2 (PS/KCa), F3 (PS/KCa/CEO), F4 (PS/KCa/CEO/BBPP 0.5 %), F5 (PS/KCa/CEO/BBPP 1.0 %), F6 (PS/KCa/CEO/BBPE 0.5 %), and F7 (PS/KCa/CEO/BBPE 1.0 %) composite films.

(Gram-negative) were used as test organisms. Overnight cultures were prepared by inoculating bacterial strains into tryptic soy broth (TSB) and incubating at 37 °C for 18 ± 2 h. Cultures were standardised to 0.5 McFarland (~1.5 × 10^8 CFU/mL) using a Densimat photometer (Bio-Mérieux, France). A working concentration of 10^6 CFU/mL was achieved by diluting 100 μL of inoculum in 10 mL TSB. A moistened filter paper was placed in a Petri dish, over which a sterile glass slide (75 × 25 mm) was positioned using sterilised swab sticks. The bacterial suspension (400 μL) was added, and composite films (cut to slide size) were carefully placed over the inoculum. Selected film samples (F1, F2, F3, F5, and F7) were incubated at 37 °C for 24 h. Post-incubation, the films were transferred to sterile stomacher bags containing 10 mL of maximum recovery diluent (MRD) and homogenised for 45 s (AGB Scientific-Lab Blender 400). Serial dilutions of the MRD cultures were plated on plate count agar, and viable cell counts were recorded. Antibacterial activity was quantified by determining the total viable counts and calculating logarithmic reduction values relative to the control samples.

2.4.10. *Effect of coatings on the preservation of fresh cut kiwi*

The same film-forming solution described in Section 2.3 was used as a coating on fresh-cut kiwi to assess its preservation effects, as it allows for uniform coverage and better adherence to the fruit surface compared to applying solid films. The efficacy of the coating solution was evaluated on fresh-cut kiwi over an 11-day storage period. Kiwi cubes were immersed in the respective coating solutions (F3, F5, and F7, as defined in Table 1) for 1 min at room temperature, while cubes treated with distilled water served as controls. Samples were air-dried for 15 min before packaging. Approximately 30–40 g of kiwi cubes was placed in polyethylene plates and stored at 4 ± 1 °C. A total of 60 plates were prepared, with 15 allocated to each treatment, including the control. Three trays from each group were randomly selected daily for analysis, except for day 0, where samples were analysed immediately after preparation. An 11-day storage period was chosen based on past studies (Passafiume et al., 2020) and preliminary trials to capture key quality changes in fresh-cut kiwifruit under refrigeration and assess coating efficacy within a realistic shelf-life timeframe.

Samples were assessed for weight loss, total soluble solids (TSS), pH, titratable acidity (TA), and total bacterial count (TBC) on days 0, 2, 4, 6, 8, and 11. Weight loss was calculated relative to the initial weight of the fruit. Kiwi cubes were homogenised using a hand blender, and the blended puree was used to determine TSS, pH, and TA. TSS (°Brix) was measured with a hand-held refractometer (Model N1, Atago, Tokyo, Japan), pH using a calibrated digital pH meter (Eutech pH 700, Lennox, Dublin, Ireland), and TA was determined by titration with 0.1 mol/L NaOH using phenolphthalein as an indicator with a few changes to the methodology by Sortino et al. (2022).

TBC was determined using the spread plate method as described by Perera et al. (2022). Kiwi samples were placed in a stomacher bag with 10 mL of Maximum Recovery Diluent (MRD) and homogenised for 2 min. The homogenate was serially diluted, and 0.1 mL of sample was inoculated onto the plate count agar. The plates were incubated at 37 °C for 24 h and the colonies were counted. Results were analysed by calculating logarithmic values and assessing log reduction relative to the bacterial count at 0 h.

2.4.11. *Statistical analysis*

Statistical analysis was performed using SPSS IBM Statistics 23 (SPSS Inc., Chicago, IL, USA). Data were expressed as mean ± standard deviation (SD), and differences between sample means were evaluated using Tukey's Honest Significant Difference (HSD) test. The significance level of $p < 0.05$ was considered statistically significant.

3. Results and discussions

3.1. *Fourier Transform Infrared (FT-IR) spectroscopy*

FT-IR spectroscopy was used to investigate the structural changes and intermolecular interactions in the composite films upon incorporating BBPP and BBPE, as shown in Fig. 1. The FT-IR spectrum of the F3 film exhibited key absorption bands at 3299 cm^{-1}, 2929 cm^{-1}, 2878 cm^{-1}, 1648 cm^{-1}, 1420 cm^{-1}, 1366 cm^{-1}, 1244 cm^{-1}, 1151 cm^{-1}, 1020 cm^{-1}, 923 cm^{-1}, and 846 cm^{-1}, corresponding to functional groups characteristic of the film components. The broad band at 3299 cm^{-1}

Table 2
Thickness and mechanical properties of composite films.

Samples	Thickness (mm)	TS (MPa)	EAB (%)	YM (MPa)
F1*	0.047 ± 0.004^{f}	4.02 ± 0.89^{c}	52.84 ± 14.69^{a}	44.52 ± 12.07^{d}
F2	0.086 ± 0.002^{de}	11.8 ± 3.36^{b}	12.14 ± 9.03^{c}	226.12 ± 91.18^{bc}
F3	0.082 ± 0.001^{e}	10.72 ± 1.76^{b}	10.72 ± 2.73^{c}	155.01 ± 17.61^{cd}
F4	0.112 ± 0.004^{b}	18.86 ± 3.67^{a}	11.27 ± 3.12^{bc}	310.85 ± 86.06^{ab}
F5	0.120 ± 0.005^{a}	16.47 ± 3.30^{a}	7.54 ± 2.66^{c}	422.66 ± 88.71^{a}
F6	0.089 ± 0.007^{cd}	11.76 ± 0.96^{b}	18.94 ± 1.44^{bc}	162.81 ± 18.9^{cd}
F7	0.095 ± 0.003^{c}	11.33 ± 1.39^{b}	27.01 ± 5.83^{b}	118.32 ± 16.13^{cd}

*F1 – PS; F2 - PS/KCa; F3 - PS/KCa/CEO; F4 - PS/KCa/CEO/BBPP 0.5 %; F5 - PS/KCa/CEO/BBPP 1.0 %; F6 - PS/KCa/CEO/BBPE 0.5 %; and F7 - PS/KCa/CEO/BBPE 1.0 % composite films. Different letters in the same column indicate a significant difference ($p < 0.05$). TS: tensile strength; EAB: elongation at break; YM: young modulus.

corresponds to O–H stretching vibrations, indicating hydroxyl groups from potato starch (PS) and κ-carrageenan (KCa) and extensive hydrogen bonding interactions (Nithyadevi & Pandiyan, 2022; Wang et al., 2022). The bands at 2929 cm^{-1} and 2878 cm^{-1} are assigned to aliphatic C–H stretching from CH_2 and CH_3 groups, originating from starch and essential oil components (Sirbu et al., 2024). A peak at 1648 cm^{-1} corresponds to C=O stretching, likely from carbonyl groups in the polysaccharides and ester groups in the essential oil.

Further structural contributions were observed at 1420 cm^{-1} and 1366 cm^{-1}, attributed to bending vibrations of CH_2 and CH_3 groups, which reflect contributions from the polymer backbone and essential oils (Arockia Mary et al., 2019; Sirbu et al., 2024). The 1244 cm^{-1} band is assigned to S=O stretching in the sulfate groups of κ-carrageenan, confirming its polysaccharide structure (Arockia Mary et al., 2019). Peaks at 1151 cm^{-1} and 1020 cm^{-1} correspond to C–O–C and C–O stretching, which are characteristic of ether and glycosidic linkages in starch and carrageenan. Additionally, bands at 923 cm^{-1} and 846 cm^{-1} represent C–O–C stretching of 3,6-anhydro galactose and galactose 4-sulfuric acid, confirming the presence of κ-carrageenan (Arockia Mary et al., 2019; Wang et al., 2022).

The spectra of F4 to F7 showed no major structural changes, suggesting that BBPP and BBPE were well integrated into the polymer matrix without disrupting its chemical structure. However, subtle shifts in specific absorption bands indicated interactions between the film components and bioactive compounds in BBPP and BBPE. The O–H stretching peak shifted to 3286 cm^{-1} for BBPP at 1.0 % and to 3301 cm^{-1} for BBPE at 1.0 %, suggesting modifications in hydrogen bonding interactions due to hydroxyl groups in phenolic compounds from BBPP and BBPE interacting with the starch-carrageenan matrix. Similar O–H band shifts were reported by Song et al. (2023) when incorporating broccoli leaf polyphenols into tapioca starch/pectin composite films.

In addition, an increasing concentration of BBPP or BBPE led to a downshift of the C=O stretching band at 1648 cm^{-1}, which moved to 1637 cm^{-1} for BBPP and 1630 cm^{-1} for BBPE. This suggests interactions between carbonyl groups in flavonoids, aldehydes, and ketones from BBPP/BBPE and the film matrix, likely forming new hydrogen bonds or dipole-dipole interactions. These findings confirm that BBPP and BBPE are chemically compatible with the starch-carrageenan matrix, and their incorporation does not compromise film integrity. Instead, the observed band shifts indicate specific molecular interactions, which could contribute to enhanced mechanical, barrier, and functional properties of the composite films.

3.2. Film thickness

The effects of BBP concentration on the thickness of the composite films are presented in Table 2. Film thickness increased with higher BBP concentrations, with BBPP contributing to a more pronounced increase. This change is attributed to the additional solid content and enhanced interactions between the biopolymer matrix and the incorporated materials, leading to increased structural density (Kola & Carvalho, 2023; Said & Sarbon, 2022). Despite the increase in thickness, all films remained within the standard limit outlined in ASTM D6988-21, which specifies a maximum thickness of 0.25 mm for plastic films (ASTM International, 2021).

Similar trends have been observed in other studies incorporating by-product powders or extracts into edible films. For example, the addition of olive pomace flour to chitosan films (de Moraes Crizel et al., 2018), potato and quince peel flours to starch films (Coimbra et al., 2023), pomegranate peel extract to jackfruit seed starch-based films (Bodana

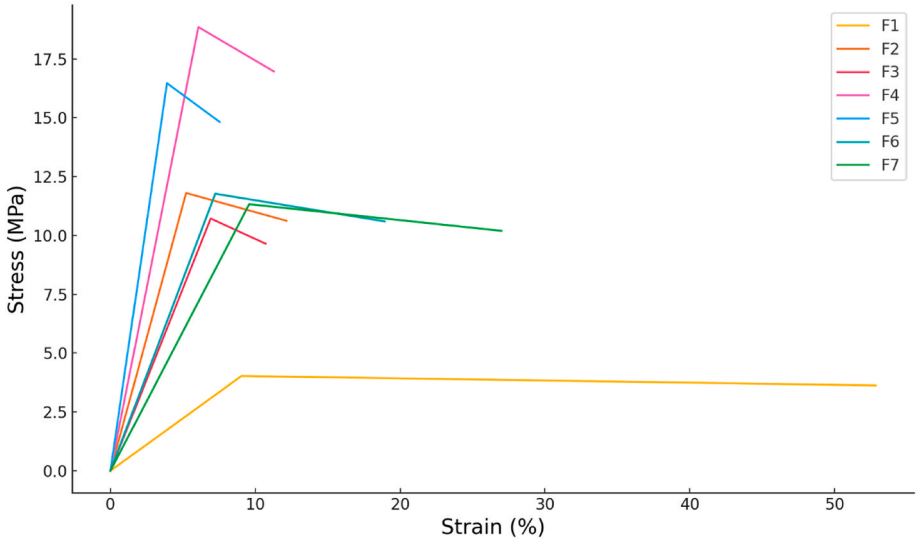


Fig. 2. Stress–strain curves of composite films.

Table 3
Physical properties of composite films incorporated with BBPP and/or BBPE.

Samples	Moisture content (%)	Water solubility (%)	WCA (°)	WVTR (g/m^{2}h)
F1 *	8.58 ± 0.63^{ab}	25.50 ± 2.80^{c}	62.27 ± 3.17^{b}	4.00 ± 0.72^{c}
F2	11.29 + 2.26^{a}	42.24 ± 0.74^{b}	65.07 ± 2.32^{b}	12.26 ± 0.34^{b}
F3	8.36 + 0.85^{ab}	54.11 ± 0.74^{a}	45.22 ± 4.07^{cd}	13.38 ± 1.63^{ab}
F4	8.94 + 1.47^{ab}	57.36 ± 1.69^{a}	76.54 ± 2.04^{a}	16.09 ± 1.34^{a}
F5	7.42 + 0.70^{b}	44.33 ± 3.94^{b}	77.41 ± 2.66^{a}	13.55 ± 1.52^{ab}
F6	9.56 + 0.55^{ab}	55.83 ± 3.40^{a}	47.87 ± 3.61^{c}	13.98 ± 0.62^{ab}
F7	7.18 + 1.54^{b}	43.13 ± 0.24^{b}	42.92 ± 2.22^{d}	13.59 ± 0.18^{ab}

*F1 – PS; F2 - PS/KCa; F3 - PS/KCa/CEO; F4 - PS/KCa/CEO/BBPP 0.5 %; F5 - PS/KCa/CEO/BBPP 1.0 %; F6 - PS/KCa/CEO/BBPE 0.5 %; and F7 - PS/KCa/CEO/BBPE 1.0 % composite films. Different letters in the same column indicate a significant difference ($p < 0.05$). WCA: water contact angle; WVTR: water vapour permeability rate.

et al., 2024), avocado peel extract to gelatin/carboxymethylcellulose active films (Vargas-Torrico et al., 2022), and banana peel extract to chitosan films (Zhang et al., 2020) have all resulted in significant increases in film thickness. These findings confirm that BBPP and BBPE incorporation follows a similar trend, contributing to structural reinforcement without exceeding standard thickness requirements.

3.3. Mechanical properties

The mechanical properties of the films, including tensile strength (TS), elongation at break (EAB), and Young's modulus (YM), are summarized in Table 2. The incorporation of 0.5 % BBPP significantly ($p < 0.05$) enhanced all three parameters compared to the F3 control film. Specifically, TS increased by approximately 43.16 %, EAB by 4.88 %, and YM by 50.13 %. However, further increasing the BBPP concentration to 1.0 % resulted in a slight reduction in TS compared to the 0.5 % BBPP film (F4), though it remained significantly higher (34.91 %) than the control. YM increased by 63.33 % at this concentration, while EAB exhibited a non-significant decrease of 29.66 %. Fig. 2 illustrates the characteristic stress-strain profiles of each film sample, providing a visual representation of their mechanical performance under tensile loading.

In contrast, the addition of BBPE primarily affected EAB, which showed a significant increase, while TS and YM experienced minor, statistically insignificant reductions. Across all BBPE-containing samples, this trend remained consistent, highlighting the potential of BBPE to enhance flexibility without markedly altering strength or stiffness.

The improvements in TS and YM with BBPP addition at lower concentrations may be attributed to enhanced interactions between the powder particles and the polymer matrix, likely through hydrogen bonding or other intermolecular forces that improve matrix cohesion. However, at higher concentrations, BBPP may disrupt matrix homogeneity, leading to phase separation, increased porosity, or weakened internal bonding, compromising mechanical integrity (Bodana et al., 2024; Rojas-Bravo et al., 2019).

These results are consistent with earlier studies. For instance, Song et al. (2023) reported a similar trend when incorporating broccoli leaf polyphenols into tapioca starch/pectin composite films, where TS peaked at 3 % and decreased at 5 % inclusion. Similarly, Alshehri et al. (2024) found that incorporating broccoli sprout seed extract (BSSE) at 0.7 % and 1.4 % concentrations into carboxymethyl cellulose/polyvinyl alcohol films progressively enhanced TS. However, a further increase to 2.1 % led to a significant decline. Comparable outcomes were observed by Li et al. (2022), who noted an increase in TS with 0.25 % soluble green tea powder in konjac glucomannan films, followed by a decrease of 0.5 %. Rizal et al. (2023) also reported a similar concentration-dependent behavior.

3.4. Moisture content and water solubility

The incorporation of BBPP and BBPE into the composite films, particularly at 1.0 % concentration, significantly reduced moisture content (Table 3). This reduction can be attributed to the hydrophobic nature of certain bioactive compounds in broccoli, which lower the overall water affinity of the film matrix. Additionally, BBP incorporation may disrupt the polymer network, limiting water absorption and retention. These findings align with Alshehri et al. (2024), who observed a similar moisture reduction when adding broccoli sprout seed extract to carboxymethyl cellulose/polyvinyl alcohol biocomposite films.

Water solubility trends varied across the formulations. The control films (F1–F3) exhibited a significant increase in solubility, while the addition of 0.5 % BBPP/BBPE resulted in a slight but statistically insignificant increase compared to F3. However, at 1.0 % BBPP/BBPE, solubility significantly decreased. This reduction is likely due to the formation of stronger intermolecular interactions within the polymer matrix at higher BBP concentrations. Bioactive compounds, such as phenolic compounds, may establish additional hydrogen bonds or hydrophobic interactions with the film-forming polymers, leading to a denser, less hydrophilic network and reduced solubility (Moghadam et al., 2020; Vargas-Torrico et al., 2022).

A similar pattern was reported by Song et al. (2023), who found that incorporating 1–3 % broccoli leaf polyphenols into tapioca starch/pectin composite films reduced water solubility, although an increase was observed at 5 % extract concentration. This suggests that while moderate BBP levels enhance polymer cohesion and reduce solubility, excessive amounts may alter the film structure, potentially increasing solubility due to phase separation or incomplete polymer interactions.

3.5. Water contact angle

The surface wettability of the biopolymer films was assessed using water contact angle (WCA) analysis (Table 3). The F1 control film exhibited a WCA of 62.27°, which slightly increased to 65.07° with the incorporation of carrageenan, suggesting a minor reduction in hydrophilicity. However, the addition of cinnamon essential oil (CEO) led to a significant decrease in WCA, likely due to the hydrophobic nature of CEO components, which may alter surface energy and film homogeneity. In contrast, the incorporation of BBPP resulted in a significant increase in WCA compared to all control films, with values exceeding those observed in BBPE-containing films. The visually observed surface roughness in BBPP films may have contributed to the increased water contact angle, as a rougher surface can trap air pockets, reducing direct water contact and enhancing hydrophobicity (Ngo et al., 2020). This suggests that BBPP enhances the film's water resistance more effectively than BBPE, potentially improving its barrier properties for food packaging applications.

3.6. Water vapour transmission rate

The water vapour transmission rate (WVTR) of the films is shown in Table 3. A significant increase in WVTR was observed in the control films (F1–F3) following the addition of carrageenan and CEO, indicating an increase in moisture permeability. Incorporating BBPP and BBPE further elevated WVTR; however, at higher concentrations (1.0 %), WVTR levels decreased, with the reduction being statistically significant for BBPP but not for BBPE. These findings are consistent with previous research indicating that phenolic compounds from by-product powders or extracts interact with polymer molecules, potentially hindering the formation of intermolecular bonds between the biopolymer matrix and water molecules. This effect leads to a denser film structure, reducing moisture permeability and lowering WVTR at higher BBPP concentrations (Alshehri et al., 2024; Song et al., 2023; Vargas-Torrico et al., 2022). These results suggest that BBPP incorporation may improve the film's barrier properties, making it more suitable for food packaging

Table 4
Optical properties of composite films.

Samples	L	a	b	ΔE	Opacity
F1 *	91.46 ± 0.07^{a}	−1.25 ± 0.01^{a}	−0.56 ± 0.02^{e}	3.09 ± 0.07^{e}	0.42 ± 0.09^{e}
F2	91.59 ± 0.06^{a}	−1.27 ± 0.01^{a}	−0.07 ± 0.31^{e}	3.01 ± 0.06^{e}	0.68 ± 0.12^{e}
F3	91.41 ± 0.10^{a}	−1.43 ± 0.09^{a}	0.61 ± 0.20^{e}	3.35 ± 0.14^{e}	1.56 ± 0.24^{d}
F4	84.86 ± 0.78$_{b}$	−5.51 ± 0.48^{b}	21.98 ± 1.97^{d}	24.92 ± 1.96^{d}	5.27 ± 0.49^{b}
F5	78.92 ± 0.34^{c}	−6.09 ± 0.57^{c}	37.91 ± 2.25^{c}	41.81 ± 2.18^{b}	8.71 ± 0.74^{a}
F6	84.56 ± 0.45^{b}	−6.97 ± 0.07^{d}	32.22 ± 1.92^{b}	34.75 ± 1.95^{c}	2.21 ± 0.20^{d}
F7	78.34 ± 1.25^{c}	−6.35 ± 0.64^{c}	52.89 ± 3.06^{a}	56.08 ± 3.21^{a}	3.14 ± 0.84^{c}

F1 – PS; F2 - PS/KCa; F3 - PS/KCa/CEO; F4 - PS/KCa/CEO/BBPP 0.5 %; F5 - PS/KCa/CEO/BBPP 1.0 %; F6 - PS/KCa/CEO/BBPE 0.5 %; and F7 - PS/KCa/CEO/BBPE 1.0 % composite films. Different letters in the same column indicate a significant difference ($p < 0.05$). L: lightness; a*: red–green; b*: yellow–blue; ΔE: colour difference.

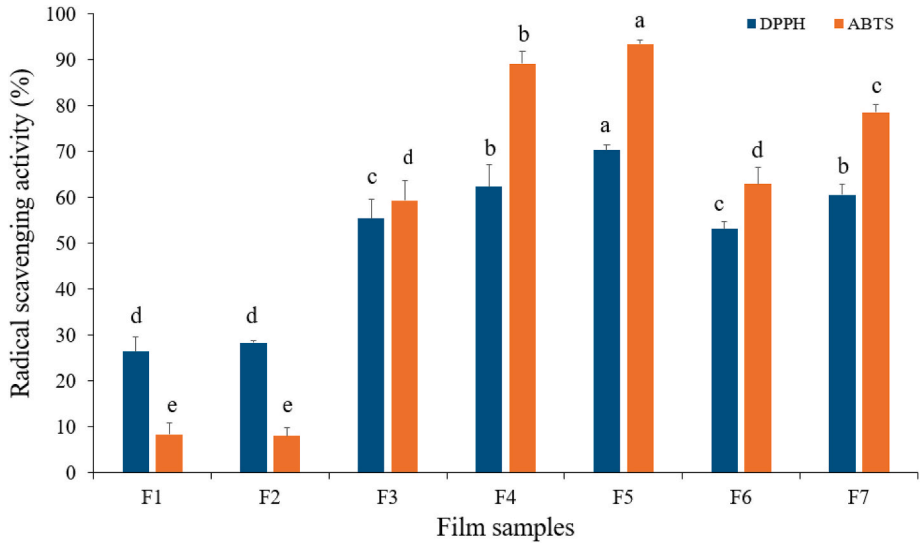


Fig. 3. Antioxidant activities (%) of composite films containing BBPP/BBPE. Different letters in the error bar indicate statistically significant differences ($p < 0.05$) in the antioxidant activity of the different compositions in the films. (F1 – PS; F2 - PS/KCa; F3 - PS/KCa/CEO; F4 - PS/KCa/CEO/BBPP 0.5 %; F5 - PS/KCa/CEO/BBPP 1.0 %; F6 - PS/KCa/CEO/BBPE 0.5 %; and F7 - PS/KCa/CEO/BBPE 1.0 %).

applications requiring moisture resistance.

3.7. Optical properties

Colour plays a crucial role in edible film development, as it directly influences visual appeal and consumer acceptance. The colorimetric parameters (*L, a*, b*, and total colour difference (ΔE)) of the composite films were evaluated (Table 4). The control films (F1–F3) appeared clear and transparent, whereas the incorporation of BBPP and BBPE significantly altered film colour due to the natural greenish pigments in broccoli by-products. A notable *decrease in L values** indicated increased opacity, while *a and b* values increased, reflecting changes in red-green and yellow-blue balance. These modifications are attributed to polyphenols and other bioactive compounds interacting with the biopolymer matrix, influencing light absorption and scattering (Mir et al., 2018). The higher the BBPP/BBPE concentration, the greater the colour intensity, consistent with previous findings on broccoli leaf polyphenols in starch/pectin-based films (Song et al., 2023). Similar trends have been reported for avocado peel extract in gelatin/carboxymethylcellulose films (Vargas-Torrico et al., 2022) and pomegranate peel powder in starch films (Esfahani et al., 2022), both rich in polyphenolic compounds, which reduced *lightness (L)** and enhanced colour intensity.

Film opacity, representing the inverse of transparency, ranged from 0.42 to 8.71 (Table 4), with significantly higher values in films containing higher BBPP concentrations. This increase is attributed to light scattering effects from pigments and phenolic compounds incorporated into the film matrix, as well as the increase in film thickness. These findings align with Rahma et al. (2023) and Vargas-Torrico et al. (2022), who observed that increasing by-product powder/extract concentrations in films increased opacity. It is well documented that by-product-derived powders and extracts contribute to higher opacity in edible films (Kola & Carvalho, 2023), which was also evident in this study. Although transparent and colourless packaging materials are typically preferred, coloured films can be advantageous for light-sensitive food products. These films may help prevent lipid oxidation and delay off-flavour development, enhancing food quality and shelf-life.

3.8. Antioxidant activity of composite films

The DPPH and ABTS radical scavenging assays are widely used to evaluate the antioxidant capacity of edible packaging films. Fig. 3 presents the radical-scavenging activity of control films and those formulated with BBPP and BBPE. All films exhibited antioxidant activity, with notable variations depending on their composition. The F1 and F2 control films displayed less than 30 % inhibition in both assays, while incorporating CEO (F3) significantly enhanced antioxidant activity to 53.10 % (DPPH) and 59.34 % (ABTS).

The addition of BBPP further improved radical-scavenging capacity, with 70.29 % (DPPH) and 93.38 % (ABTS) inhibition, which was higher than BBPE-containing films (60.62 % and 78.48 %, respectively). Increasing the concentration of BBPP or BBPE significantly enhanced antioxidant activity, attributed to the strong radical-scavenging properties of BBP. Similar trends were reported by Alshehri et al. (2024) and

Table 5
Antibacterial activity of composite film after 24 h against Gram-negative *Escherichia coli* and Gram-positive *Staphylococcus aureus*.

Samples	Log CFU/mL	
	E. coli	*S. aureus*
F1	8.77 ± 0.04^{a}	8.32 ± 0.07^{a}
F2	8.57 ± 0.24^{ab}	8.30 ± 0.01^{a}
F3	7.70 ± 0.14^{b}	8.13 ± 0.05^{a}
F5	6.14 ± 0.39^{c}	8.03 ± 0.05^{a}
F7	5.62 ± 0.42^{c}	7.07 ± 0.05^{b}

Different letters in the same column indicate a significant difference ($p < 0.05$).

Song et al. (2023), where the antioxidant capacity of biopolymer films increased with higher concentrations of broccoli sprout seed extract and broccoli leaf polyphenols, respectively.

The superior antioxidant potential of BBPP compared to BBPE suggests that the whole by-product powder retains a broader range of bioactive compounds, contributing to its stronger radical-scavenging effect (Villaño et al., 2023). In contrast, the extraction process used to obtain BBPE may selectively isolate certain phenolic compounds while excluding other essential antioxidants, thereby reducing its overall antioxidant efficacy (Uvaraj et al., 2024). Additionally, BBPP in its intact powder form may facilitate a sustained release of antioxidants, ensuring prolonged radical-scavenging activity, whereas the bioactive compounds in BBPE may be depleted more rapidly.

The incorporation of BBPP/BBPE into edible films offers a promising strategy to extend the shelf life of food products by providing enhanced oxidative protection. The interactions between BBP bioactives and the polymer matrix may further stabilise these compounds, improving their functional performance and enhancing film durability against oxidative degradation (Li et al, 2024). These findings highlight the importance of using whole by-product powders in edible film formulations, as the synergistic interactions within the matrix are critical in determining overall antioxidant potential.

3.9. Antibacterial activities of composite films

The antimicrobial efficacy of the composite films against *Escherichia coli* and *Staphylococcus aureus* after 24 h is presented in Table 5. The results, expressed as log CFU/mL, indicate varying degrees of microbial reduction across the different formulations. F1, F2, and F3 served as control samples, while F5 and F7 represented BBPP- and BBPE-based

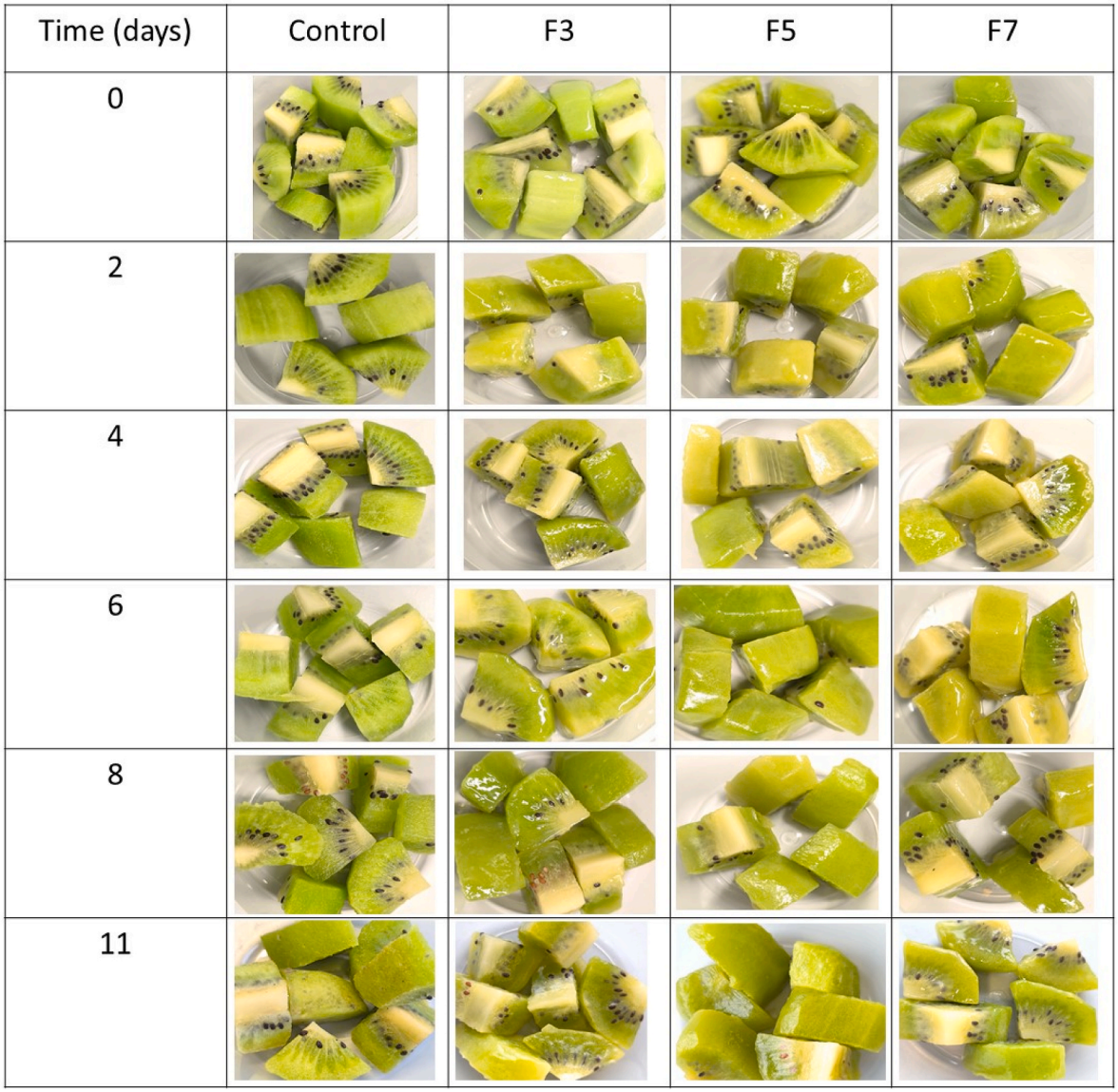


Fig. 4. Appearance of fresh-cut kiwi during cold storage (4 °C).

Table 6
Change in weight loss, total soluble solids (TSS), pH, and titratable acidity (TA) of kiwifruit cubes during cold storage at 4 ± 1 °C.

Storage time (Days)	Control	F3	F5	F7
Weight loss (%)				
0	0^{f}	0^{f}	0^{f}	0^{f}
2	0.0347 ± 0.001^{e}	0.0281 ± 0.001^{e}	0.0274 ± 0.002^{e}	0.0199 ± 0.005^{e}
4	0.0745 ± 0.001^{d}	0.0704 ± 0.002^{d}	0.0659 ± 0.003^{d}	0.0602 ± 0.004^{d}
6	0.1185 ± 0.005^{c}	0.1075 ± 0.001^{c}	0.1093 ± 0.005^{c}	0.0963 ± 0.005^{c}
8	0.1555 ± 0.003^{b}	0.1460 ± 0.006^{b}	0.1464 ± 0.003^{b}	0.1243 ± 0.009^{b}
11	0.2169 ± 0.007^{a}	0.2001 ± 0.011^{a}	0.2038 ± 0.006^{a}	0.1803 ± 0.012^{a}
TSS (°Brix)				
0	13.93 ± 0.25^{Aa}	11.73 ± 0.90^{B}	9.50 ± 0.41^{Cb}	9.17 ± 0.24^{Cb}
2	13.23 ± 0.21^{Aab}	10.77 ± 0.71^{B}	10.40 ± 0.85^{Bab}	10.27 ± 0.52^{Bab}
4	12.67 ± 0.24^{Ab}	10.97 ± 0.33^{B}	10.57 ± 0.33^{Bab}	10.67 ± 0.47^{Bab}
6	13.50 ± 0.30^{Aab}	11.10 ± 0.10^{BC}	11.35 ± 0.15^{Ba}	10.15 ± 0.65^{Cab}
8	13.40 ± 0.40^{Aab}	11.25 ± 0.25^{B}	11.70 ± 0.10^{Ba}	11.00 ± 0.50^{Ba}
11	14.10 ± 0.29^{Aa}	11.57 ± 0.33^{B}	11.57 ± 0.33^{Ba}	11.33 ± 0.81^{Ba}
pH				
0	3.41 ± 0.02^{Abc}	3.41 ± 0.02^{Ab}	3.38 ± 0.04^{Aa}	3.37 ± 0.04^{Ac}
2	3.39 ± 0.03^{Ac}	$3.47 \pm 0.04A^{ab}$	3.49 ± 0.04^{Aa}	3.46 ± 0.04^{Abc}
4	3.42 ± 0.05^{ABbc}	3.34 ± 0.03^{Bc}	3.48 ± 0.06^{Aa}	3.44 ± 0.02^{ABbc}
6	3.50 ± 0.01^{Aab}	3.48 ± 0.01^{Aab}	3.48 ± 0.04^{Aa}	3.45 ± 0.01^{Abc}
8	3.56 ± 0.05^{Aa}	3.54 ± 0.03^{Aa}	3.50 ± 0.02^{Aa}	3.47 ± 0.02^{Ab}
11	3.46 ± 0.02^{Babc}	3.52 ± 0.02^{Ba}	3.44 ± 0.03^{Ba}	3.61 ± 0.03^{Aa}
TA (%)				
0	1.41 ± 0.11^{Aa}	1.05 ± 0.06^{Ba}	1.03 ± 0.04^{Ba}	0.95 ± 0.04^{Ba}
2	1.22 ± 0.03^{Aab}	1.04 ± 0.04^{Ba}	0.98 ± 0.02^{Ba}	0.97 ± 0.06^{Ba}
4	1.31 ± 0.14^{Aab}	1.01 ± 0.09^{Bab}	1.05 ± 0.05^{ABa}	0.96 ± 0.01^{Ba}
6	1.07 ± 0.02^{Ab}	0.81 ± 0.06^{Cc}	0.97 ± 0.04^{B}	0.92 ± 0.01^{Ba}
8	1.11 ± 0.07^{Ab}	0.90 ± 0.03^{Bab}	1.00 ± 0.04^{ABa}	0.92 ± 0.05^{Ba}
11	1.27 ± 0.07^{Aab}	0.96 ± 0.09^{Bab}	0.99 ± 0.08^{Ba}	0.88 ± 0.07^{Ba}

*Control – Not coated; F3 - PS/KCa/CEO; F5 - PS/KCa/CEO/BBPP 1.0 %; and F7 - PS/KCa/CEO/BBPE 1.0 % treatments. Different upper-case letters indicate statistical differences between the treatments (horizontal rows) ($p > 0.05$). Different lower-case letters indicate statistical differences between the storage time (vertical columns) ($p > 0.05$).

films, respectively.

Significant antibacterial activity was observed in F5 and F7, with the highest reduction recorded for F7 (BBPE-based film). Against *E. coli*, F7 exhibited the most pronounced antimicrobial effect, with a 5.62 log CFU/mL reduction, indicating strong inhibition of this Gram-negative bacterium. Similarly, for *S. aureus*, F7 showed the lowest bacterial count (7.07 log CFU/mL), demonstrating substantial activity against this Gram-positive pathogen. Among all tested samples, F7 exhibited the strongest antimicrobial properties against both bacterial species.

The enhanced efficacy of F7 may be attributed to the higher concentration of bioactive compounds in BBPE, particularly polyphenols, which are well-documented for their antimicrobial properties (Gudiño et al., 2022). The use of ethanol as a solvent in the BBPE extraction process may have further enhanced its bioactivity by improving bioavailability, promoting synergistic effects, and increasing interaction with bacterial cell membranes (Gil-Martín et al., 2022). In contrast, BBPP (whole powder) lacks this selective enrichment, as its bioactive compounds remain diluted by other inert plant components, potentially reducing its antibacterial effectiveness.

Interestingly, *E. coli* was more susceptible to the composite films than *S. aureus*. This difference is likely due to structural variations in bacterial cell walls, as Gram-negative bacteria have an outer membrane that, while providing protection, may also contain porins, facilitating bioactive compound penetration. These findings are consistent with Alshehri et al. (2024), who reported that bio-composite films containing broccoli sprout seed extract exhibited stronger inhibition against Gram-negative (*Salmonella typhimurium*) than Gram-positive bacteria (*Clostridium botulinum*).

The antibacterial properties of broccoli by-products are primarily attributed to glucoraphanin, polyphenols, and flavonoids, which possess strong antimicrobial activity by disrupting bacterial membranes, inhibiting enzymatic activity, and interfering with microbial metabolism (Yan et al., 2023). These findings reinforce the potential of BBPE-enriched films as effective antimicrobial packaging materials for enhancing food safety and shelf-life.

3.10. Effect of film-forming solutions on fresh-cut kiwi quality during storage

The impact of film-forming solutions on the preservation of fresh-cut kiwis during cold storage (4 ± 1 °C) over 11 days was evaluated. Fig. 4 illustrates the visual changes in stored kiwis, while Table 6 presents data on weight loss, chemical parameters, and microbiological stability. Weight loss progressively increased across all samples during storage; however, no significant differences ($p > 0.05$) were observed among treatments. Notably, Sample F7 consistently exhibited the lowest weight loss, whereas the uncoated control sample experienced the highest loss at all time points. This suggests that F7 provided superior water retention, minimising moisture loss and preserving fruit weight more effectively than the other treatments.

The chemical parameters of coated fruits during storage (Table 6) revealed that total soluble solids (TSS) initially decreased slightly in all samples before increasing over time. On day 11, the control sample had the highest TSS value (14.10 °Brix), while treated samples exhibited slightly lower but statistically similar values ($p > 0.05$). This trend may be attributed to metabolic changes and moisture retention, influencing sugar concentration in the fruit. The steadier TSS values in Sample F7 suggest its enhanced ability to preserve fruit quality, aligning with findings by Vivek and Subbarao (2018) on coated fresh-cut kiwis.

pH levels remained generally stable throughout storage, with Sample F7 showing a slight but significant difference on day 11. Variations in pH can be linked to natural differences in fruit composition and metabolic activity. Similarly, titratable acidity (TA) showed a gradual decline, reflecting the natural ripening process, followed by a minor increase by day 11. The lower TA values in Sample F7 suggest reduced biochemical activity, likely due to its effective preservation properties, which align with results reported by Benítez et al. (2013) in minimally processed kiwifruit coated with aloe vera-based films.

Microbial analysis, measured by total bacterial count (TBC) (Fig. 5), revealed that bacterial growth began on day 6. The control and Sample F3 exhibited the highest bacterial counts (3.74 and 2.54 Log CFU/mL, respectively), while Samples F5 and F7 showed no bacterial growth at this stage. By day 11, TBC levels in the control and F3 reached 5.30 and 4.54 Log CFU/mL, respectively, significantly exceeding F5 and F7, which recorded 4.05 and 3.72 Log CFU/mL, demonstrating that BBPP and BBPE effectively inhibited microbial proliferation and extended the fruit's shelf life.

These findings align with Song et al. (2023), who reported that

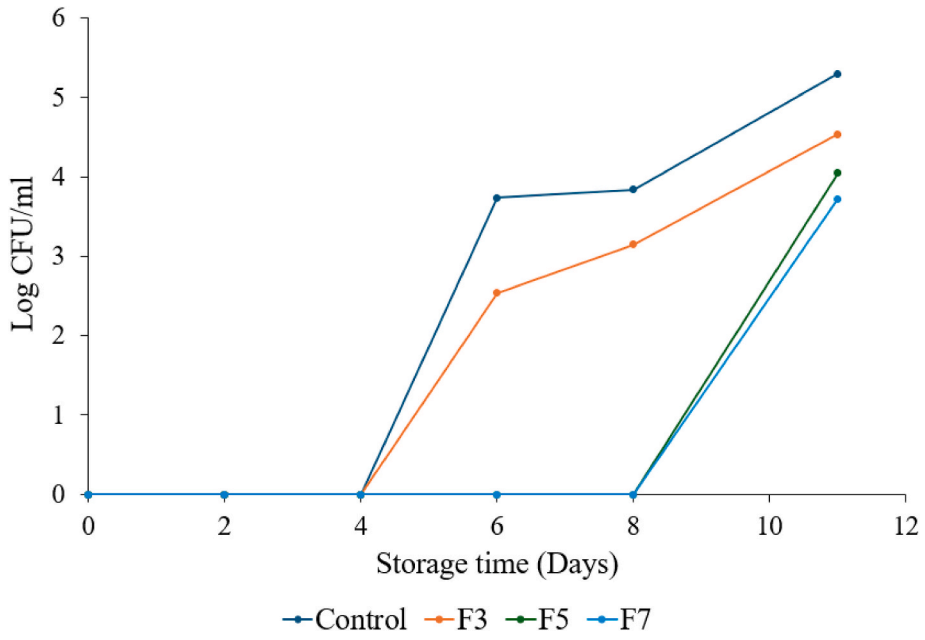


Fig. 5. Effect of different treatments on the total bacterial count of fresh-cut kiwis stored for 11 days at 4 °C, for control – uncoated samples, F3 - PS/KCa/CEO, F5 - PS/KCa/CEO/BBPP 1.0 % and F7 - PS/KCa/CEO/BBPE 1.0 %.

broccoli leaf polyphenols in composite films significantly inhibited microbial growth, extending the shelf life of packaged mutton to 12 days. Similarly, studies by Al Talebi et al. (2023) and Radünz et al. (2024) demonstrated the in vitro antibacterial efficacy of broccoli extracts against spoilage bacteria, reinforcing the potential of broccoli-based additives in improving the antimicrobial and preservative properties of edible coatings for fresh-cut products.

According to HACCP guidelines, foods with microbial counts below 4 Log CFU/g are classified as 'good', while counts exceeding 7 Log CFU/g in fresh-cut fruits are perceptible to consumers and indicate spoilage (Elabd & Gomma, 2018; Passafiume et al., 2020). In this study, TBC levels remained below the spoilage threshold (7 Log CFU/g) throughout the 11-day storage period. Notably, BBPE-treated samples consistently maintained TBC levels below 4 Log CFU/g, confirming their effective microbial inhibition and preservation of microbial quality within acceptable limits.

4. Conclusion

This study highlights the potential of potato starch and κ-carrageenan-based films, enriched with broccoli by-products, as sustainable and functional edible packaging materials. Incorporating both BBPP and BBPE improved the films' mechanical strength, barrier properties, and bioactivity. Enhanced antioxidant and antimicrobial activities were observed, contributing to the films' effectiveness in extending the shelf life of perishable products such as fresh-cut kiwis. BBPE-enriched films demonstrated particularly strong antimicrobial performance among the formulations, while BBPP-enhanced films showed favorable mechanical and antioxidant properties. These findings support the valorisation of agricultural by-products for food packaging applications, offering a promising strategy for reducing food and packaging waste. Future work should focus on scalability, regulatory compliance, and consumer acceptance to facilitate broader industrial implementation.

CRediT authorship contribution statement

Oghenetega Lois Orhotohwo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Benedetta Fanesi:** Writing – review & editing. **Helen Stephanie Ofei Darko:** Writing – review & editing. **Lama Ismaiel:** Writing – review & editing. **Paolo Lucci:** Writing – review & editing, Validation. **Deborah Pacetti:** Writing – review & editing, Validation, Project administration, Conceptualization. **Amit K. Jaiswal:** Writing – review & editing, Validation, Supervision, Resources, Methodology. **Swarna Jaiswal:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the European project Vitality (Next Generation EU, Project Code ECS00000041, CUP I33C22001330007) funded under the National Recovery and Resilience Plan (NRRP) and by the project WINfood (PSR Marche 2014/2020, ID 59459, Sottoprodotti della lavorazione industriale dei vegetali: da scarti ad ingredienti funzionali per la formulazione di alimenti innovativi).

The authors would like to thank the company O.R.T.O Verde Scapa for the provision of broccoli by-products.

Data availability

Data will be made available on request.

References

Al Talebi, Z., Karhib, M. M., Taki, M. M., Salaam Abood, E., Mubarak, H. A., & Ibrahim, S. A. C. (2023). Chemical analysis, antioxidant, and antibacterial potential of aqueous extract of broccoli (*Brassica oleracea*) using GC-MS. *Archives of Razi Institute, 78*(2), 593. https://doi.org/10.22092/ari.2022.359860.2488

Alahmed, A., & Simsek, S. (2024). Enhancing mechanical properties of corn bran arabinoxylan films for sustainable food packaging. *Foods, 13*. https://doi.org/10.3390/foods13091314

Alshehri, A. A., Hamed, Y. S., Kamel, R. M., Shawir, S. M. S., Sakr, H., Ali, M., Ammar, A., Saleh, M. N., El Fadly, E., Salama, M. A., & Abdin, M. (2024). Enhanced physical properties, antioxidant and antibacterial activity of bio-composite films composed from carboxymethyl cellulose and polyvinyl alcohol incorporated with broccoli

sprout seed extract for butter packaging. *International Journal of Biological Macromolecules, 255*. https://doi.org/10.1016/j.ijbiomac.2023.128346
Arias, L., De Souza Silva, V., Vieira, J., Fakhouri, F., & De Oliveira, R. (2024). Plant-based films for food packaging as a plastic waste management alternative: Potato and cassava starch case. *Polymers (Basel), 16*. https://doi.org/10.3390/polym16172390
Arockia Mary, I., Selvanayagam, S., Selvasekarapandian, S., Srikumar, S. R., Ponraj, T., & Moniha, V. (2019). Lithium ion conducting membrane based on K-carrageenan complexed with lithium bromide and its electrochemical applications. *Ionics (Kiel), 25*(12), 5839–5855. https://doi.org/10.1007/s11581-019-03150-x
ASTM International. (2021). ASTM D6988-21. Standard guide for determination of thickness of plastic film test specimens. https://doi.org/10.1520/d6988-21.
Benítez, S., Achaerandio, I., Sepulcre, F., & Pujolà, M. (2013). Aloe vera based edible coatings improve the quality of minimally processed "Hayward" kiwifruit. *Postharvest Biology and Technology, 81*. https://doi.org/10.1016/j.postharvbio.2013.02.009
Biondi, F., Balducci, F., Capocasa, F., Visciglio, M., Mei, E., Vagnoni, M., Mezzetti, B., & Mazzoni, L. (2021). Environmental conditions and agronomical factors influencing the levels of phytochemicals in Brassica vegetables responsible for nutritional and sensorial properties. *Applied Sciences, 11*(4), 1927. https://doi.org/10.3390/app11041927
Bodana, V., Swer, T. L., Kumar, N., Singh, A., Samtiya, M., Sari, T. P., & Babar, O. A. (2024). Development and characterization of pomegranate peel extract-functionalized jackfruit seed starch-based edible films and coatings for prolonging the shelf life of white grapes. *International Journal of Biological Macromolecules, 254*, Article 127234. https://doi.org/10.1016/j.ijbiomac.2023.127234
Chang, Y. W., Chen, Y. L., Park, S. H., Yap, E. E. S., & Sung, W. C. (2024). Characterization of functional ingredients extracted with ethanol solvents from Ponkan (*Citrus reticulata*) by-products using the microwave vacuum drying method combined with ultrasound-assisted extraction. *Foods, 13*(13), 2129. https://doi.org/10.3390/foods13132129
Coimbra, P., Marona, B., Henriques, M. H. F., Campos, L., Gomes, D. M. G. S., Vitorino, C., Sousa, J. J. S., Braga, M. E. M., & Gaspar, M. C. (2023). Edible films based on potato and quince peels with potential for the preservation of cured cheese. *Food Packaging and Shelf Life, 40*, Article 101176. https://doi.org/10.1016/j.fpsl.2023.101176
de Moraes Crizel, T., de Oliveira Rios, A., D Alves, V., Bandarra, N., Moldão-Martins, M., & Hickmann Flôres, S. (2018). Active food packaging prepared with chitosan and olive pomace. *Food Hydrocolloids, 74*, 139–150. https://doi.org/10.1016/j.foodhyd.2017.08.007
Elabd, M. A., & Gomma, M. M. (2018). The use of edible coatings to preserve quality of fresh cut kiwi fruits (ready to eat). *Egyptian Journal of Food Science, 46*.
Esfahani, A., Mohammadi Nafchi, A., Baghaei, H., & Nouri, L. (2022). Fabrication and characterization of a smart film based on cassava starch and pomegranate peel powder for monitoring lamb meat freshness. *Food Science and Nutrition, 10*(10), 3293–3301. https://doi.org/10.1002/fsn3.2918
Fanesi, B., Ismaiel, L., Nartea, A., Orhotohwo, O. L., Kuhalskaya, A., Pacetti, D., Lucci, P., & Falcone, P. M. (2023). Bioactives and technological quality of functional biscuits containing flour and liquid extracts from broccoli by-products. *Antioxidants, 12*(12), 2115. https://doi.org/10.3390/antiox12122115
Gasti, T., Dixit, S., D'souza, O. J., Hiremani, V. D., Vootla, S. K., Masti, S. P., Chougale, R. B., & Malabadi, R. B. (2021). Smart biodegradable films based on chitosan/methylcellulose containing Phyllanthus reticulatus anthocyanin for monitoring the freshness of fish fillet. *International Journal of Biological Macromolecules, 187*, 451–461. https://doi.org/10.1016/j.ijbiomac.2021.07.128
Gil-Martín, E., Forbes-Hernández, T., Romero, A., Cianciosi, D., Giampieri, F., & Battino, M. (2022). Influence of the extraction method on the recovery of bioactive phenolic compounds from food industry by-products. *Food Chemistry, 378*, Article 131918. https://doi.org/10.1016/j.foodchem.2021.131918
Goudar, N., Vanjeri, V. N., Dixit, S., Hiremani, V., Sataraddi, S., Gasti, T., Vootla, S. K., Masti, S. P., & Chougale, R. B. (2020). Evaluation of multifunctional properties of gallic acid crosslinked Poly (vinyl alcohol)/Tragacanth Gum blend films for food packaging applications. *International Journal of Biological Macromolecules, 158*, 139–149. https://doi.org/10.1016/j.ijbiomac.2020.04.223
Gudiño, I., Martín, A., Casquete, R., Prieto, M. H., Ayuso, M. C., & Córdoba, M. G. (2022). Evaluation of broccoli (*Brassica oleracea* var. *italica*) crop by-products as sources of bioactive compounds. *Scientia Horticulturae, 304*. https://doi.org/10.1016/j.scienta.2022.111284
Hanani, Z. A. N., Yee, F. C., & Nor-Khaizura, M. A. R. (2019). Effect of pomegranate (*Punica granatum* L.) peel powder on the antioxidant and antimicrobial properties of fish gelatin films as active packaging. *Food Hydrocolloids, 89*, 253–259. https://doi.org/10.1016/j.foodhyd.2018.10.007
Iturralde-García, R. D., Cinco-Moroyoqui, F. J., Martínez-Cruz, O., Ruiz-Cruz, S., Wong-Corral, F. J., Borboa-Flores, J., Cornejo-Ramírez, Y. I., Bernal-Mercado, A. T., & Del-Toro-Sánchez, C. L. (2022). Emerging technologies for prolonging fresh-cut fruits' quality and safety during storage. *Horticulturae, 8*(8), 731. https://doi.org/10.3390/horticulturae8080731
Ivanov, Y., & Godjevargova, T. (2024). Antimicrobial polymer films with grape seed and skin extracts for food packaging. *Microorganisms, 12*. https://doi.org/10.3390/microorganisms12071378
Kokkuvayil Ramadas, B., Rhim, J. W., & Roy, S. (2024). Recent progress of carrageenan-based composite films in active and intelligent food packaging applications. *Polymers (Basel), 16*(7), 1001. https://doi.org/10.3390/polym16071001
Kola, V., & Carvalho, I. S. (2023). Plant extracts as additives in biodegradable films and coatings in active food packaging. *Food Bioscience, 54*, Article 102860. https://doi.org/10.1016/j.fbio.2023.102860
Krupa-Kozak, U., Drabińska, N., Baczek, N., Šimková, K., Starowicz, M., & Jeliński, T. (2021). Application of broccoli leaf powder in gluten-free bread: An innovative approach to improve its bioactive potential and technological quality. *Foods, 10*(4). https://doi.org/10.3390/foods10040819
Kučuk, N., Primožič, M., Kotnik, P., Knez, Ž., & Leitgeb, M. (2024). Mango peels as an industrial by-product: A sustainable source of compounds with antioxidant, enzymatic, and antimicrobial activity. *Foods, 13*. https://doi.org/10.3390/foods13040553
Lafarga, T., Gallagher, E., Bademunt, A., Bobo, G., Echeverria, G., Viñas, I., & Aguiló-Aguayo, I. (2019). Physiochemical and nutritional characteristics, bioaccessibility and sensory acceptance of baked crackers containing broccoli co-products. *International Journal of Food Science and Technology, 54*(3), 634–640. https://doi.org/10.1111/ijfs.13908
Li, X., Li, F., Zhang, X., Tang, W., Huang, M., Huang, Q., & Tu, Z. (2024a). Interaction mechanisms of edible film ingredients and their effects on food quality. *Current Research in Food Science, 8*, Article 100696. https://doi.org/10.1016/j.crfs.2024.100696
Li, J., Sun, H., & Weng, Y. (2024b). Natural extracts and their applications in polymer-based active packaging: A review. *Polymers (Basel), 16*. https://doi.org/10.3390/polym16050625
Li, Z., Zheng, S., Sun, H., Xi, R., Sun, Y., Luo, D., Xu, W., Jin, W., & Shah, B. R. (2022). Structural characterization and antibacterial properties of konjac glucomannan/soluble green tea powder blend films for food packaging. *Journal of Food Science and Technology, 59*(2), 562–571. https://doi.org/10.1007/s13197-021-05041-4
Liu, M., Zhang, L., Ser, S. L., Cumming, J. R., & Ku, K. M. (2018). Comparative phytonutrient analysis of broccoli by-products: The potentials for broccoli by-product utilization. *Molecules (Basel), 23*(4), 900. https://doi.org/10.3390/molecules23040900
Mir, S. A., Dar, B. N., Wani, A. A., & Shah, M. A. (2018). Effect of plant extracts on the techno-functional properties of biodegradable packaging films. *Trends in Food Science & Technology, 80*, 141–154. https://doi.org/10.1016/j.tifs.2018.08.004
Moghadam, M., Salami, M., Mohammadian, M., Khodadadi, M., & Emam-Djomeh, Z. (2020). Development of antioxidant edible films based on mung bean protein enriched with pomegranate peel. *Food Hydrocolloids, 104*, Article 105735. https://doi.org/10.1016/j.foodhyd.2020.105735
Nešić, A., Meseldzija, S., Benavides, S., Figueroa, F., & Cabrera-Barjas, G. (2024). Seaweed as a valuable and sustainable resource for food packaging materials. *Foods, 13*. https://doi.org/10.3390/foods13193212
Ngo, T. M. P., Nguyen, T. H., Dang, T. M. Q., Tran, T. X., & Rachtanapun, P. (2020). Characteristics and antimicrobial properties of active edible films based on pectin and nanochitosan. *International Journal of Molecular Sciences, 21*(6), 2224. https://doi.org/10.3390/ijms21062224
Nithyadevi, K., & Pandiyan, V. (2022). Analyze infrared heating characteristics of potato starch and measure its functional film properties. *Indian Journal of Science and Technology, 15*(30), 1495–1503. https://doi.org/10.17485/ijst/v15I30.1231
Passafiume, R., Gaglio, R., Sortino, G., & Farina, V. (2020). Effect of three different aloe vera gel-based edible coatings on the quality of fresh-cut "hayward" kiwifruits. *Foods, 9*(7), 939. https://doi.org/10.3390/foods9070939
Perera, K. Y., Sharma, S., Duffy, B., Pathania, S., Jaiswal, A. K., & Jaiswal, S. (2022). An active biodegradable layer-by-layer film based on chitosan-alginate-TiO_2 for the enhanced shelf life of tomatoes. *Food Packaging and Shelf Life, 34*, Article 100971. https://doi.org/10.1016/j.fpsl.2022.100971
Petkowicz, C. L. O., & Williams, P. A. (2020). Pectins from food waste: Characterization and functional properties of a pectin extracted from broccoli stalk. *Food Hydrocolloids, 107*, Article 105930. https://doi.org/10.1016/j.foodhyd.2020.105930
Radünz, M., Camargo, T. M., Raphaelli, C. de O., Radünz, A. L., Gandra, E.Á., & Zavareze, E. da R. (2024). Chemical composition, antimicrobial and antioxidant activities of broccoli, kale, and cauliflower extracts. *Plant Foods for Human Nutrition, 79*(3), 700–706. https://doi.org/10.1007/s11130-024-01212-8
Rahma, R. A., Putri, W. D. R., Megatri, A. A., Nur, M., Mubarok, A. Z., & Wardana, A. A. (2023). Optimisation of fish gelatin and red pitaya peel powder edible film production. *International Journal of Food Science and Technology, 58*(10), 5578–5590. https://doi.org/10.1111/ijfs.16548
Rahmadi Putri, T., Adhitasari, A., Paramita, V., Endy Yulianto, M., & Dwi Ariyanto, H. (2023). Effect of different starch on the characteristics of edible film as functional packaging in fresh meat or meat products: A review. *Materials Today: Proceedings, 87*. https://doi.org/10.1016/j.matpr.2023.02.396
Ramadas, B., Rhim, J., & Roy, S. (2024). Recent progress of carrageenan-based composite films in active and intelligent food packaging applications. *Polymers (Basel), 16*. https://doi.org/10.3390/polym16071001
Rizal, S., Abdul Khalil, H. P. S., Hamid, S. A., Ikramullah, I., Kurniawan, R., Hazwan, C. M., Muksin, U., Aprilia, S., & Alfatah, T. (2023). Coffee waste macro-particle enhancement in biopolymer materials for edible packaging. *Polymers (Basel), 15*(2). https://doi.org/10.3390/polym15020365
Rojas-Bravo, M., Rojas-Zenteno, E. G., Hernández-Carranza, P., Ávila-Sosa, R., Aguilar-Sánchez, R., Ruiz-López, I. I., & Ochoa-Velasco, C. E. (2019). A potential application of mango (*Mangifera indica* L. Cv Manila) peel powder to increase the total phenolic compounds and antioxidant capacity of edible films and coatings. *Food and Bioprocess Technology, 12*(9), 1584–1592. https://doi.org/10.1007/s11947-019-02317-8
Sabu Mathew, S., Jaiswal, A. K., & Jaiswal, S. (2024). Carrageenan-based sustainable biomaterials for intelligent food packaging: A review. *Carbohydrate Polymers, 342*, Article 122267. https://doi.org/10.1016/j.carbpol.2024.122267

Said, N. S., & Sarbon, N. M. (2022). Physical and mechanical characteristics of gelatin-based films as a potential food packaging material: A review. *Membranes, 12*(5), 442. https://doi.org/10.3390/membranes12050442

Santhosh, R., Ahmed, J., Thakur, R., & Sarkar, P. (2024). Starch-based edible packaging: Rheological, thermal, mechanical, microstructural, and barrier properties - a review. *Sustainable Food Technology, 2*(2). https://doi.org/10.1039/d3fb00211j

Santhosh, R., Nath, D., & Sarkar, P. (2021). Novel food packaging materials including plant-based byproducts: A review. *Trends in Food Science & Technology, 118*, 471–489. https://doi.org/10.1016/j.tifs.2021.10.013

Santhosh, R., & Sarkar, P. (2024). Fabrication of jamun seed starch/tamarind kernel xyloglucan bio-nanocomposite films incorporated with chitosan nanoparticles and their application on sapota (*Manilkara zapota*) fruits. *International Journal of Biological Macromolecules, 260*, Article 129625. https://doi.org/10.1016/j.ijbiomac.2024.129625

Sayanjali, S., Lu, Y., & Howell, K. (2024). Extraction and characterization of cellulose from broccoli stems as a new biopolymer source for producing carboxymethyl cellulose films. *International Journal of Food Science, 2024*(1), Article 7661288. https://doi.org/10.1155/2024/7661288

Shi, C., Shen, S. wan, Sun, Y., Liu, E. qi, Gong, H., Ni, Z. zhong, & He, Y. (2024). Effect of cutting styles on physicochemical properties and antioxidant capacity of fresh-cut kiwifruits (*Actinidia* spp.). *Journal of Food Measurement and Characterization, 18*(1). https://doi.org/10.1007/s11694-023-02203-0

Shinali, T. S., Zhang, Y., Altaf, M., Nsabiyeze, A., Han, Z., Shi, S., & Shang, N. (2024). The valorization of wastes and byproducts from cruciferous vegetables: A review on the potential utilization of cabbage, cauliflower, and broccoli byproducts. *Foods, 13*(8), 1163. https://doi.org/10.3390/foods13081163

Singaram, A., Guruchandran, S., & Ganesan, N. (2024). Review on functionalized pectin films for active food packaging. *Packaging Technology and Science, 37*, 237–262. https://doi.org/10.1002/pts.2793

Sinha, S. (2024). An overview of biopolymer-derived packaging material. *Polymers from Renewable Resources, 15*, 193–209. https://doi.org/10.1177/20412479241226884

Sîrbu, E. E., Dinita, A., Tănase, M., Portoacă, A. I., Bondarev, A., Enascuta, C. E., & Calin, C. (2024). Influence of plasticizers concentration on thermal, mechanical, and physicochemical properties on starch films. *Processes, 12*(9), 2021. https://doi.org/10.3390/pr12092021

Song, Z., Wei, J., Cao, Y., Yu, Q., & Han, L. (2023). Development and characterization of tapioca starch/pectin composite films incorporated with broccoli leaf polyphenols and the improvement of quality during the chilled mutton storage. *Food Chemistry, 418*. https://doi.org/10.1016/j.foodchem.2023.135958

Sortino, G., Inglese, P., Farina, V., Passafiume, R., & Allegra, A. (2022). The use of opuntia ficus-indica mucilage and aloe arborescens as edible coatings to improve the physical, chemical, and microbiological properties of 'Hayward' kiwifruit slices. *Horticulturae, 8*(3). https://doi.org/10.3390/horticulturae8030219

Uvaraj, D., Alharbi, N. S., Kadaikunnan, S., Thiruvengadam, M., & Venkidasamy, B. (2024). Comprehensive study on the differential extraction and comparison of bioactive health potential of the Broccoli (*Brassica oleracea*). *International Journal of Medical Sciences, 21*(4), 593. https://doi.org/10.7150/ijms.92456

Vargas-Torrico, M. F., von Borries-Medrano, E., & Aguilar-Méndez, M. A. (2022). Development of gelatin/carboxymethylcellulose active films containing Hass avocado peel extract and their application as a packaging for the preservation of berries. *International Journal of Biological Macromolecules, 206*, 1012–1025. https://doi.org/10.1016/j.ijbiomac.2022.03.101

Villaño, D., Fernández-Pan, I., Arozarena, Í., Ibañez, F. C., Vírseda, P., & Beriain, M. J. (2023). Revalorisation of broccoli crop surpluses and field residues: Novel ingredients for food industry uses. *European Food Research and Technology, 249*(12), 3227–3237. https://doi.org/10.1007/s00217-023-04362-2

Vivek, K., & Subbarao, K. V. (2018). Effect of edible chitosan coating on combined ultrasound and NaOCl treated kiwi fruits during refrigerated storage. *International Food Research Journal, 25*(1), 101–108.

Wang, C., Lu, Y., Li, Z., An, X., Gao, Z., & Tian, S. (2022). Preparation and performance characterization of a composite film based on corn starch, κ-carrageenan, and ethanol extract of onion skin. *Polymers (Basel), 14*(15), 2986. https://doi.org/10.3390/polym14152986

Yan, L., Zhou, G., Shahzad, K., Zhang, H., Yu, X., Wang, Y., Yang, N., Wang, M., & Zhang, X. (2023). Research progress on the utilization technology of broccoli stalk, leaf resources, and the mechanism of action of its bioactive substances. *Frontiers in Plant Science, 14*, Article 1138700. https://doi.org/10.3389/fpls.2023.1138700

Yap, X. Y., Khalid, M., Raju, G., Gew, L. T., & Yow, Y. Y. (2024). Synergistic effects of starch and carrageenan from *Kappaphycus alvarezii* in composite film formation: Physicochemical and degradable properties. *International Journal of Biological Macromolecules, 278*, Article 135205. https://doi.org/10.1016/j.ijbiomac.2024.135205

Yousuf, B., Qadri, O. S., & Srivastava, A. K. (2018). Recent developments in shelf-life extension of fresh-cut fruits and vegetables by application of different edible coatings: A review. *Lebensmittel-Wissenschaft & Technologie, 89*, 198–209. https://doi.org/10.1016/j.lwt.2017.10.051

Zhang, W., Li, X., & Jiang, W. (2020). Development of antioxidant chitosan film with banana peels extract and its application as coating in maintaining the storage quality of apple. *International Journal of Biological Macromolecules, 154*, 1205–1214. https://doi.org/10.1016/j.ijbiomac.2019.10.275

Zheng, K., Li, W., Fu, B., Fu, M., Ren, Q., Yang, F., & Qin, C. (2018). Physical, antibacterial and antioxidant properties of chitosan films containing hardleaf oatchestnut starch and *Litsea cubeba* oil. *International Journal of Biological Macromolecules, 118*, 707–715. https://doi.org/10.1016/j.ijbiomac.2018.06.126