

Article

Development of Quince-Based Active Films Functionalized with Broccoli By-Product Extracts and Clove Hydrosol

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Abstract

The increasing demand for sustainable active packaging necessitates the development of bio-based films with enhanced functional properties. This study aimed to functionalize a quince (*Cydonia oblonga*) by-product film, formulated in clove (*Syzygium aromaticum*) hydrosol by casting, incorporating varying concentrations (0–10% *w/v*) of broccoli (*Brassica oleracea* var. *italica*) by-product extract. Increasing the extract concentration led to increments in film thickness (102.2 to 120.2 μm), elongation at break (112.5 to 117.3%), tensile strength (1.5 to 4.2 MPa), opacity (20.2 to 24.0%), and water vapor permeability (2.0 to $2.3 \times 10^{-8} \text{ g s}^{-1} \text{ m}^{-1} \text{ Pa}^{-1}$). The total phenolic content also increased from 17.6 to 24.3 mg GAE/g film, correlating with a decrease in transmittance. While Fourier-Transform Infrared spectra profiling revealed stable intermolecular interactions across all samples without chemical disruption; scanning electron microscopy analysis confirmed distinct morphological differences resulting from broccoli extract incorporation. Notably, while 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity remained stable across treatments, the 2.5% *w/v* extract concentration provided the highest antifungal efficacy against *Aspergillus puulaauensis* (15.7%), *A. jensenii* (8.2%) and *Penicillium nordicum* (5.8%) by the agar diffusion method. These results were comparable with a commercial natamycin-containing coating used as a positive control. The synergy of clove hydrosol and broccoli extract resulted in a quince-based film with superior mechanical and bioactive properties.

Keywords: bio-based active film; bioactivity; antifungal activity; FTIR; quince (*Cydonia oblonga*); clove (*Syzygium aromaticum*); broccoli (*Brassica oleracea* var. *italica*)



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1. Introduction

Active packaging derived from agri-food by-product polymers is emerging as a sustainable, biodegradable alternative to conventional plastics [1]. This valorization of waste into renewable materials addresses the growing demand for eco-friendly industrial solutions [2]. A key strategy in this field is polymer blending, which yields composite films that synergize the advantageous properties of their individual components [3]. For example, while pectin is extensively used as a film-forming material for edible packaging, its inherent physicochemical and mechanical limitations necessitate the incorporation of reinforcing compounds [4]. Recent studies have demonstrated that blending pectin with

starch extracted from potato or tapioca produces edible, biodegradable films characterized by robust mechanical strength and superior oxygen barrier properties [5,6].

Quince (*Cydonia oblonga* Miller), a shrub native to Turkey and Iran, holds significant industrial value due to its high content of pectin, a gelling agent widely used in the production of marmalades, jellies, juices, and beverages [7]. Recently, the abundance of natural polymers in quince by-products (QBs) has spurred extensive research into their multi-sectoral applications [8,9]. Much of this research has focused on (4-O-methyl-D-glucurono)-D-xylan (MGX), a unique hemicellulose-type heteropolysaccharide found in quince seeds, capable of forming robust hydrogels and films [10,11]. While its primary use has been in edible food preservation, its potential in biomedical fields—including drug delivery, wound healing, and cancer detection—is increasingly being explored [12]. Despite these advancements, the integration of MGX with other quince components remains largely unexplored. Indeed, only one study has characterized films composed of a mixture of various QBs [13]. The authors found that films derived from total by-products generated during fruit processing exhibited superior properties to those made from isolated seeds. This enhancement was attributed to the synergistic combination lignin, cellulose, and hemicellulose, identified within the composite matrix [13].

The optimization of green, active packaging extends beyond the study of material compatibility and composite development. Enhancing film functionality through the incorporation of plant extracts is a well-established strategy, largely due to the high concentrations of phenolic compounds that impart potent antioxidant activity [3]. Integrating these natural extracts imbues food coating with bioactive functionality, providing a robust defense against oxidative and microbial degradation [14]. Consequently, a primary objective in the valorization of agri-food by-products is the identification of bioactive compounds capable of serving as natural preservatives.

Broccoli (*Brassica oleracea* var. *italica*) production generates substantial agricultural waste, with approximately 60–75% of the total above-ground biomass discarded during harvest [15]. This residue, comprising stalks, stems, leaves, outer florets, and unmarketable heads, is a rich source of nutrients and bioactive compounds such as glucosinolates and flavonoids. These constituents enhance antioxidant capacity by scavenging free radicals and exhibit antimicrobial properties that inhibit spoilage microorganisms [2]. While their bioactive potential has been validated in processed food such as biscuits or bread [16,17], their integration into polymeric matrices represents a promising, sustainable strategy for developing high-functionality active packaging.

Hydrosols (or hydrolates) are the aqueous by-products generated during the hydro- or steam-distillation of plant material for essential oil extraction [18]. Although frequently discarded as waste [19], hydrosols possess significant industrial potential due to their high concentration of dissolved active constituents, particularly phenolic compounds with demonstrated robust antimicrobial efficacy against a wide range of microorganisms [19]. Notably, hydrosols derived from clove (*Syzygium aromaticum* L. Myrtaceae) are enriched with phenolic and antioxidant compounds [20], chief among which is eugenol. Due to its inherent volatility and free radical-neutralizing capacity, eugenol serves as a potent antioxidant agent [21,22]. Consequently, akin to plant extracts, these aqueous by-products represent a sustainable, low-cost source for the synthesis of natural additives tailored for food preservation applications.

This research proposes the functionalization of a film based on QBs through the dual application of an active solvent (clove hydrosol) and a valorized plant extract (BDe). The incorporation of broccoli by-product extract (BDe), rich in phenolic compounds [2], combined with the bioactive constituents of clove hydrosol is expected to yield a functional coating with enhanced protective capacity against oxidative and microbial degradation [22,23].

Furthermore, introducing the extract via an ethanol carrier may influence the microstructure of the film, potentially modulating its mechanical integrity and water vapor barrier properties [24].

The main objectives of the present study were: (1) to assess the compatibility and potential chemical interactions between the BDe and the matrix; (2) to analyze the effect of the direct incorporation of the extract into the film through their characterization and bioactivity studies; and (3) to optimize the film by incorporating various concentrations of BDe. Comprehensive characterization of the resulting QB-BDe film enabled a systematic evaluation of the impact of the extract on the structure, physical and bioactive properties of the film. Therefore, this approach introduces several noteworthy innovations on bio-based active packaging. While quince by-products have been previously investigated for their film-forming capacity [13,25], no prior studies have combined it with a hydrosol and an ethanolic extract. Secondly, most studies use essential oils as functionalizing agent [5,26–29]; in contrast, hydrosols are rarely explored despite their bioactive content and their potential advantages in terms of safety, miscibility, and regulatory acceptance. Finally, although biopolymer films enriched with ethanolic plant extracts have been studied, the application of ethanolic extracts derived from by-products broccoli in a film matrix has not been previously reported. Given that the solvent strongly influences the phenolic profile, the use of an ethanolic broccoli fraction provides new insights into the behavior of hydrophobic and semi-polar bioactive compounds within bio-based films. This research represents technological advancement, and its importance lies fact that these findings may be applied to any water-based films, using different hydrosols and incorporating ethanolic extracts from diverse plant sources.

2. Materials and Methods

2.1. Materials

Quince by-products were provided by Membrillo Emily S.L. (Murcia, Spain) after processing the fruit to produce paste from the flesh. The QBs consisted of the peel, seeds, and the pulp of the endocarp, which were removed using a combination of water peeling at 50 °C and rotatory sieving. The materials were immediately transported to the laboratory and frozen at −20 °C for 24 h. Subsequently, the QBs were lyophilized using a freezer dryer (Sublimator 30 EKS, Tiel, The Netherlands) at −40 °C for 48 h under vacuum (0.2 mbar). Lyophilized samples were stored under vacuum in polyethylene bags (22 × 30 cm, 90 µm) at room temperature until analysis. Clove hydrosol was supplied by El Jarpil S.R.L (Almería, Spain) and broccoli discards (BD) by Ultracongelados Campoverde S.L. (Albacete, Spain). Glycerol (food grade) was purchased from Guinama (Barcelona, Spain), and polysorbate 20 (1227.5 g/mol) from Sigma-Aldrich (Saint-Louis, MO, USA).

2.2. Polymer Obtainment

The polymer was extracted from lyophilized QB using a ratio of 2.4:30 (by-product: water), according to Codina et al. [13]. For extraction, the corresponding sample was dissolved in distilled water and stirred constantly at 1000 rpm for 30 min at 45 ± 2 °C using an RCT basic magnetic stirrer (IKA-Werke, Staufen, Germany). The resulting solution was then centrifuged (Eppendorf Ultracentrifuge, 5910 Ri; Eppendorf, Hamburg, Germany) at 6500 rpm for 15 min at 20 °C. The supernatant was filtered through a cotton gauze, spread on a tray, and dried overnight in an oven at 45 ± 1 °C. Finally, the dried polymer was removed from the tray and stored in a desiccator with silica gel (Scharlab, Barcelona, Spain) at room temperature until use.

2.3. Broccoli Discards Extraction

Broccoli discards were lyophilized in a freezer dryer (Sublimator 30 EKS) at $-40\text{ }^{\circ}\text{C}$ and a vacuum of 0.2 mbar was applied for 48 h. Lyophilized samples were ground with a Waring Commercial 7010 HS blender (Torrington, CT, USA) and sieved to obtain a powder with a particle size of 4–2 mm. Samples were subsequently stored under vacuum in polyethylene bags ($22 \times 30\text{ cm}$, $90\text{ }\mu\text{m}$) at room temperature until analysis.

Extractions were carried out in a BÜCHI E-914 Speed Extractor (Postfach, Switzerland) according to Rozalén et al. [30]. Briefly, 1.5 g of sample was homogenized with approximately 32 g of sand as a dispersing agent and packed with 37 g of sand above and below to fill the stainless steel 80 mL extraction cell, leaving 1 cm free upper space. A cellulose acetate filter (BÜCHI) was also placed at the top and bottom of each cell to avoid sample particles leaking into the cells. The extraction was carried in a single cycle, using ethanol as the solvent at $40\text{ }^{\circ}\text{C}$ and pressure at 100 bar as follows: hold for 28 min, heat-up 1 min, discharge 3 min, flush with solvent 2 min and flush with N_2 5 min.

The resulting ethanolic extract was evaporated in a Multivapor BÜCHI P-6 parallel evaporator at $40\text{ }^{\circ}\text{C}$ and 100 mbar. The flasks were stored for 30 min in a desiccator before weighing. Subsequently, the resulting dry matter was dissolved in ethanol at 10 mg/mL and the pH was recorded.

2.4. Production of the QB-BDe Films

Four types of films were prepared in three independent replicates, varying the BDe concentration (0, 2.5%, 5% and 10% *w/v*). The concentration range selected for incorporation of the extract into the film matrix was established on the basis of a previous literature review and a preliminary optimization stage [6,31–33]. An initial screening was carried out using concentrations between 0% and 5% (*w/w*). This exploratory phase confirmed that the ethanolic extract did not adversely impact the fundamental barrier properties of the films and revealed that antifungal and antioxidant activities at the lowest incorporation levels were minimal. Consequently, the concentration range was expanded, and the lower limit was set at the level at which a reproducible and functionally relevant bioactive response was observed. This stepwise approach, based on both bibliographic evidence and empirical optimization, ensured the selection of extract concentrations capable of exerting measurable bioactivity while preserving the structural integrity of the film matrix. The film-forming solutions were prepared dissolving the polymer (1.8% *w/v*) together with 35% glycerol and 15% polysorbate 20 (*w/w* based on the polymer weight) in clove hydrosol [13,25]. The solution was heated to $45 \pm 2\text{ }^{\circ}\text{C}$ for 30 min with constant stirring at 1000 rpm. Subsequently, the mixture was stored until the temperature decreased to $30\text{ }^{\circ}\text{C}$, and BDe was then added at different concentrations with stirring for 15 min. Air bubbles were removed using a vacuum pump and the film solutions were cast at a surface density of 0.55 g/cm^2 onto Petri dishes of 55 and 140 mm diameter. Finally, the samples were dried in an air convection oven (Heraeus, Hanau, Germany) at $25\text{ }^{\circ}\text{C}$ overnight and stored at room temperature in a desiccator containing a saturated solution of magnesium nitrate hexahydrate (52% relative humidity) for at least 48 h until their characterization.

2.5. Density, Viscosity, and pH of the Film Solutions

The density of the coatings was calculated using a 25 mL pycnometer and applying the follow Equation (1):

$$D = (W_s + p - W_p) / (W_w + p - W_p) \quad (1)$$

where $W_s + p$ is the weight of the sample and pycnometer, W_p is the weight of empty pycnometer, and $W_w + p$ is the weight of the water and the pycnometer.

The viscosity of the coatings was measured with a rotational viscometer (Visco Basic Plus, Fungilab, Barcelona, Spain) equipped with a low viscosity adapter (LCP/B). Measurements were taken at 12 rpm and 25 ± 1 °C. The pH was measured with a GLP 22 pH-meter (Crison, Barcelona, Spain). Both tests were performed in triplicate.

2.6. Characterization of the QB-BDe Films

2.6.1. Moisture Content and Water Solubility

The moisture content (MC) and water solubility (WS) of the films were determined in triplicate according to Dick et al. [34] with minor modifications. The MC was determined gravimetrically. The films were cut into circles 2 cm in diameter, and their initial weight was recorded. The samples were then dried in an oven at 105 °C (J.P. Selecta, Barcelona, Spain) for 24 h and MC was calculated as the difference between the initial sample weight and the weight of the dried film (W_i). The procedure used to measure the WS films was to immerse in 30 mL of distilled the resulting dried film and to stirrer it in an orbital shaker (OVAN, Barcelona, Spain) at 150 rpm and 22 °C for 24 h. Finally, the samples were filtered with a pre-weighed desiccated filter paper, and the undissolved fractions of the film retained on the filter paper were dried in an oven at 105 °C for 24 h. The resulting dried material was weighed (W_f), and the WS was calculated using the following Equation (2):

$$WS (\%) = [(W_i - W_f) / W_i] \times 100 \quad (2)$$

2.6.2. Water Vapor Permeability

The water vapor permeability (WVP) of the films was determined in triplicate according to Ortiz de Elguea-Culebras et al. [35] based on the ASTM E96/E96M-16c [36] with some modifications. Briefly, circular films (55 mm diameter) were adhered to the top of permeation cells ($1.22 \times 10^{-2} \text{ m}^2$) containing 50 mL of distilled water, placed inside a desiccator with silica gel (0% RH, 24 °C) and weighed along 10 h at 2 h intervals. The WVP was calculated with the following Equation (3):

$$WVP (\text{gs}^{-1} \text{m}^{-1} \text{Pa}^{-1}) = (WVTR \times L) / (\Delta P) \quad (3)$$

where WVTR is calculated by dividing the slope of the straight line (g/s) by testing area (m^2), L is the film thickness (m), and ΔP is the water vapor partial difference (Pa) across the two sides of the film.

2.6.3. Thickness and Mechanical Properties

The thickness (mm) was measured in triplicate at three different points of the sample using an IP65 Coolant-Proof digital micrometer (Mitutoyo, Tokyo, Japan) with a precision of ± 0.01 mm. The mechanical properties of films were determined using a TA-XT2i-Plus texture analyzer (Stable Micro Systems Ltd., Godalming, Surrey, UK) according to the ASTM E96/E96M-16 standard method [37]. Nine strips of film, each measuring 2×10 cm, were tested for each film type. Film strips were placed between a tensile grip (A/MTG) with an initial distance of 80 mm, and the force and deformation were recorded at a speed of 0.00083 m/s until the film broke. The tensile strength (TS) and Young's Modulus (YM) were expressed in MPa, and elongation at break (EB) as % elongation.

2.6.4. Color and Opacity

The CIEL*a*b* coordinates of the films were determined using a Minolta CR-400 colorimeter (Minolta, Tokyo, Japan) in reflection mode. Measurements were taken in triplicate on films placed in 140 mm diameter plates. The colorimeter was configured with a D65 illuminant, a 10° standard observer angle, and a CR-A33a cone. Calibration was

performed with a white standard color plate ($L^* = 97.24$, $a^* = 0.09$ and $b^* = 1.86$). The opacity of the films was calculated in triplicate according to the Hunter Lab method [37] using the following Equation (4):

$$\text{Opacity}(\%) = [(Y_b)/Y_w] \times 100 \quad (4)$$

where Y_b is the opacity on a black standard, and Y_w is the opacity on a white standard.

2.6.5. Water Contact Angle

The surface hydrophobicity of the films was evaluated in triplicate by measuring the water contact angle using the sessile drop technique on an OCA 11 Dataphysics goniometer (DataPhysics Instruments GmbH, Filderstadt, Germany). Following the methodology of Gomes et al. [38], a water droplet (5 μL) was deposited at different points on the film surface. Images of the droplet shape were then captured via a digital camera, and the contact angle was automatically calculated by the system software using the Laplace-Young equation. At least four measurements were performed per tested film.

2.7. Fourier-Transform Infrared Spectroscopy (FTIR)

Fourier-Transform Infrared Spectroscopy (FTIR) spectra of the films were recorded on a VERTEX 80v FTIR spectrometer (Bruker Optics, Karlsruhe, Germany) equipped with a Platinum Attenuated Total Reflection (ATR) accessory. Following the procedure described by Gomes et al. [38], spectra were acquired in the wave number range of $4000\text{--}400\text{ cm}^{-1}$ at a resolution of 4 cm^{-1} . To facilitate comparison between samples, the absorbance of each spectrum was min-max normalized to a scale of 0 to 1.

2.8. Light Transmittance

Transmittance (%) of film samples ($4 \times 0.8\text{ cm}$) was measured in triplicate on both sides using a UV-Vis GENESYS 150 spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA) by spectrum scanning (wavelengths from 200 to 900 nm) following the method of Dick et al. [34].

2.9. Scanning Electron Microscopy

Films were cut into pieces of $0.5 \times 0.5\text{ cm}$ and analyzed without a conductive coating [13]. Samples were secured onto the specimen holder and scanning electron microscopy (SEM) micrographs were captured on a JEOL 6490LV electron microscope (Tokyo, Japan) operating at 20 kV.

2.10. Total Phenolic Content

The total phenolic content (TPC) of the film was quantified in triplicate using the Folin–Ciocalteu method according to Codina et al. [13]. Film samples were dissolved in water (6.25 mg/mL), after which 150 μL of the solution was mixed with 750 μL of the redox reagent (Sigma-Aldrich) and allowed to react at room temperature for 5 min. Subsequently, 600 μL of 0.7 N sodium carbonate (Sigma-Aldrich) was added to the mix, and the final mixture was incubated for 2 h in the dark at room temperature. The absorbance was then measured at 765 nm using a UV-Vis GENESYS 150 spectrophotometer (Thermo Fisher Scientific) against a blank of distilled water. A standard curve was generated using gallic acid across a concentration of 0 to 100 $\mu\text{g/mL}$ and the TPC of the films was expressed as milligrams of gallic acid equivalent per gram of film (mg GAE/g film).

2.11. Scavenging Activity of DPPH

The 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging activity of the film was determined in triplicate using the method described by Codina et al. [13]. A 150 µL sample of film (6.25 mg/mL in water) was combined with 1.85 mL of DPPH (0.1 mM in ethanol) and incubated in the dark at room temperature for 30 min. The absorbance was then measured at 515 nm. The inhibition activity (%) of DPPH radicals was calculated according to the following Equation (5):

$$\text{DPPH inhibition(\%)} = [(A_0 - A_1) / A_0] \times 100 \quad (5)$$

where A_0 is the absorbance of DPPH, and A_1 is the absorbance of samples. The samples were measured in triplicate.

2.12. Antifungal Activity

The antifungal activity of the films was evaluated against a panel of mold strains provided by the University of Castilla-La Mancha and the University of León (deposited in the Spanish Type Culture Collection as CECT20939). The strains used were *Penicillium nordicum* M32, *P. expansum* QZ1, *P. commune* 301, *Aspergillus jensenii* 501, and *A. puulaauensis* 1A05, all isolated from cheeses factories [39,40]. Prior to the assay, mold strains were cultured for 7 d at 25 ± 1 °C. Spores were collected using a solution containing Tween 20 suspended in sterile saline solution (0.9% *w/v*) and then diluted at $1\text{--}2 \times 10^6$ colony forming units (CFU)/mL. For each assay, 100 µL of the prepared inoculum was spread onto the surface of duplicate Potato Dextrose Agar (PDA) plates (Merck, Darmstadt, Germany) [41]. Films were cut into 10 mm diameter discs and placed in the center of the inoculated PDA plate. Plates were incubated for 7 days at 25 ± 1 °C. As a reference, film discs of 10 mm were made with a commercial coating of polyvinyl acetate containing natamycin at a concentration of 1.5 mg/mL (Derplast Inmersión 3 E-Pro S/S, DOMCA, Granada, Spain). Plates were examined for halos of growth inhibition. Images were captured with a Counterpart flash instrument (IUL S.A., Barcelona, Spain) and the diameter of inhibition zones was measured four times (in mm) using ImageJ v1.52a (NIH) software. The percentage of growth inhibition was calculated with the following Equation (6):

$$\text{Inhibition(\%)} = [(A_c - A_f) / A_c] \times 100 \quad (6)$$

where A_c refers to the plate diameter less the film diameter and A_f is the growth zone. The samples were measured in triplicate.

2.13. Statistical Analysis

In this study, three independent replicates were made for each type of film (3×4), and three different samples from each replicate were used for each test. Statistical analysis of data was performed using SPSS software (IBM SPSS Statistics version 25; IBM Corp., Armonk, NY, USA). Normality was assessed using the Shapiro–Wilk test and Q–Q plots for each treatment group, and homogeneity of variances was verified using Levene’s test. No significant deviations from normality ($p > 0.05$) nor heteroscedasticity were detected; therefore, analysis of variance (ANOVA) was considered appropriate. Tukey’s post hoc test was calculated using a confidence level of 95% to determine significant differences between the samples according to the BDe concentration in each formula.

3. Results and Discussion

3.1. Properties of the Film Solutions

The pH, density, and viscosity of the film-forming solutions are summarized in Table 1. The pH of the BDe was measured at 4.74 ± 0.02 . No significant differences between samples were found for pH (4.4–4.6), density (0.99–1.01 g/mL), or viscosity (112.2–119.3 cp). The uniformity in pH is attributed to the extract and the coating solution possessing nearly identical values. These viscosity values are comparable with established pharmaceutical excipients, such as hydroxypropyl methylcellulose (80–120 cp) or a gum arabic-pectin mixture (120 cp) [42,43].

Table 1. Effect of ethanolic extract of broccoli discards (BDe) concentration on the solution properties of the film ¹.

Parameters	Control	Broccoli By-Product Extract (BDe)			<i>p</i> -Value
		2.5%	5%	10%	
pH (24 °C)	4.62 ± 0.02	4.40 ± 0.01	4.43 ± 0.01	4.51 ± 0.03	0.170
Density (g/mL)	1.01 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	0.99 ± 0.00	0.410
Viscosity (cp ²)	119.30 ± 0.03	109.29 ± 1.49	112.17 ± 1.73	113.52 ± 1.80	0.668

¹ mean $\pm$ SD; ² cp: centipoise.

3.2. Characterization of the QB-BDe Films

3.2.1. Moisture Content, Water Vapor Permeability, Solubility, and Thickness

Properties related to the water affinity of films are essential for determining their potential to preserve stored products. While MC and WS of the films were not significantly influenced by the treatment, both thickness and WVP increased significantly with the addition of the extract (Table 2). The values obtained in this study (MC: 34.0–36.7%; $WVP \times 10^{-8}$: 2.0–2.26 g s^{−1} m^{−1} Pa^{−1}; WS: 67.9–70.7%; thickness: 102.2–120.3 μ m) are consistent with those reported by Codina et al. [13] for QB films dissolved in water (MC: 41.0%; WVP : 2.0 g s^{−1} m^{−1} Pa^{−1}; WS: 76.8%; thickness: 96.2 μ m). Film permeability is directly influenced by the nature of its constituent polymers [44]. BDe is rich in hygroscopic polymers such as pectins, which have high water-retention capacities [15,45]. Consequently, a higher concentration of BDe not only yields a thicker film due to increased total solids but also enhances permeability. A similar trend was observed in carboxymethyl cellulose and polyvinyl alcohol bio-composite films containing lyophilized broccoli sprout seed extract (0.7%, 1.4%, and 2.1%); the formulation with the highest extract concentration exhibited significantly greater thickness and permeability than the control [3]. Although the relative increase in WVP after BDe addition (14%) was moderate, the absolute magnitude indicates a weak moisture barrier. However, this does not limit its application to certain foods. Corn starch films loaded with limonene particles, whose permeability values were similar to those obtained in this study ($2.26\text{--}7.04 \times 10^{-8}$ g s^{−1} m^{−1} Pa^{−1}) extended the shelf life of rice cakes to five days regarding control [46]. Other examples of active films based on starch or pectin isolated from different plant sources with similar WVP values have been shown to preserve different foods such as nuts, bakery items and fruits [47–49]. This is due to the great ability of these polymers to carry and release a variety of active compounds, including antioxidants, flavorings, antibrowning and antimicrobial compounds, among others [50,51].

Table 2. Influence of the increasing concentration of ethanolic extracts of broccoli discards (BDe) on moisture, water vapor permeability (WVP), water solubility, thickness, mechanical properties (tensile strength, elongation at break, young's modulus), color, including opacity and color coordinates (L, a, b*) and contact angle of the films ¹.

Parameters		Control	Broccoli By-Product Extract (BDe)			p-Value
			2.5%	5%	10%	
Moisture (%)		36.67 ± 0.95	35.04 ± 1.12	34.32 ± 1.64	33.95 ± 1.18	0.108
WVP × 10 ⁻⁸ (g s ⁻¹ m ⁻¹ Pa ⁻¹)		1.98 ± 0.12 ^a	2.05 ± 0.09 ^{ab}	2.14 ± 0.07 ^{ab}	2.26 ± 0.07 ^b	0.031
Water Solubility(%)		70.24 ± 5.91	67.88 ± 5.76	70.70 ± 4.81	70.02 ± 5.41	0.923
Thickness (μm)		102.22 ± 8.19 ^a	113.19 ± 3.42 ^{ab}	114.79 ± 3.14 ^{ab}	120.31 ± 6.75 ^b	0.029
Mechanical properties	Elongation at break (%)	112.13 ± 0.94 ^a	117.30 ± 1.63 ^b	116.27 ± 1.14 ^b	116.47 ± 1.81 ^b	0.036
	Tensile strength (MPa)	1.48 ± 0.29 ^a	3.62 ± 0.58 ^b	4.15 ± 0.14 ^b	3.79 ± 0.37 ^b	<0.001
	Young’s Modulus (MPa)	18.17 ± 2.58	20.28 ± 3.15	21.97 ± 1.42	20.80 ± 2.31	0.350
	L*	76.40 ± 3.45 ^c	71.43 ± 3.38 ^{bc}	67.62 ± 3.03 ^{ab}	63.15 ± 2.16 ^a	0.004
Color	a*	1.93 ± 0.53 ^c	1.52 ± 0.37 ^c	0.43 ± 0.10 ^b	−0.42 ± 0.15 ^a	0.165
	b*	30.62 ± 5.68 ^a	40.43 ± 2.19 ^b	44.60 ± 2.29 ^b	46.54 ± 1.13 ^b	0.002
	Opacity (%)	20.17 ± 1.33 ^a	21.31 ± 1.36 ^{ab}	22.26 ± 1.81 ^{ab}	24.00 ± 0.51 ^b	0.041
Contact angle (°)		20.45 ± 0.93 ^a	22.4 ± 0.3 ^b	20.55 ± 1.17 ^a	20.17 ± 0.52 ^a	0.004

^{a–c} superscripts in the same row indicate significant differences ($p < 0.05$) between quince by-products films at different concentrations of broccoli by-products extract (BDe); ¹ mean ± SD.

Numerous strategies have been explored to improve the water vapor barrier of the films. Different preparation methods to elaborate more hydrophobic films are widely reported: electrospinning, modification of hydrophilic biopolymers, addition of hydrophobic compounds (lipids, plasticizers or emulsifiers) and modification of hydrophilic film surfaces by vapor deposition, self-assembly, and layer-by-layer deposition by repeatedly casting/dipping/spraying [50,52,53]. These strategies highlight the potential for future optimization, strengthening the applied relevance of QB active films and enabling their adaptation to a broader range of food-packaging scenarios.

3.2.2. Mechanical Properties

Critical parameters that describe the mechanical behavior of a film include EB, TS, and YM. As shown in Table 2, the incorporation of BDe led to a concurrent increase in both EB (112.5–117.3%) and TS (1.5–4.2 MPa). These results are consistent with QB-based films dissolved in water (EB: 106.7%; TS: 2.0 MPa) and corn starch bio-based films (EB: 128.6%; TS: 2.9 MPa) reported in the literature [13,54]. Furthermore, YM values (18.2–20.8 MPa) were comparable with those reported for pectin- (21.8 MPa) and starch-based (22.5 MPa) films [55,56]. These components were previously identified in QB-based films via thermogravimetric analysis [13] and further confirmed by FTIR in the present study (see Section 3.3). The enhancement of mechanical properties following the addition of BDe aligns with previous findings [2,3]. Broccoli extracts are rich in low-molecular-weight phenolics (flavonoids, phenolic acids), soluble sugars and other small metabolites that can interact with polysaccharide/protein chains via hydrogen bonding and van der Waals forces [6]. This structural enhancement combined with the plasticizing effect exerted by residual ethanol (which enhances chain mobility) during film drying likely explains the simultaneous improvement in both TS and EB [57,58].

3.2.3. Color and Opacity

As food packaging, a film must ensure both food protection and an aesthetic appeal that meets consumer expectations. In this study, all formulations yielded homogeneous, continuous films with a distinctive glossy (yellow) finish. The incorporation of BDe induced a visible shift toward a greenish and more opaque appearance (Figure 1 and Table 2).

Colorimetric analysis showed that L^* (lightness) increased, a^* (redness/greenness) did not vary significantly and b^* (yellowness/blueness) increased with increasing extract concentration. These results indicate that higher concentrations of BDe significantly reduce film transparency while simultaneously shifting the chromaticity toward more pronounced green and yellow hues. The predominantly yellow hue of the films is likely attributable to carotenoids present in the quince matrix [59]. The subsequent increase in the b^* coordinate upon BDe addition further suggests the contribution of yellow pigments inherent to broccoli [60]. Conversely, the characteristic green pigmentation of broccoli, primarily derived from chlorophyll, accounts for the significant decrease in a^* values [23]. Furthermore, the thermal degradation of chlorophyll during film processing may be associated with the reduction in L^* and the corresponding increase in opacity [61]. The control film exhibited significantly lower opacity (20.2%) compared with the BDe-enriched formulations (21.3–24.0%). These opacity values are consistent with values reported from chia seed-based films [41].

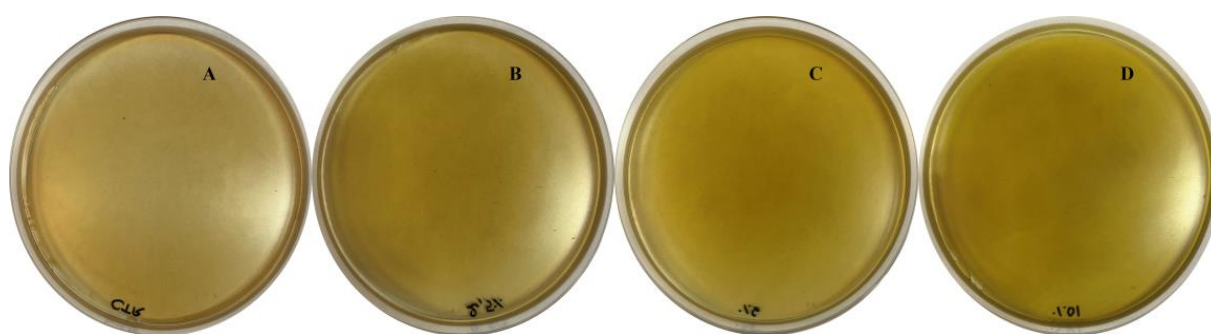


Figure 1. Appearance of the different films in Petri dishes: control (A), 2.5% (B), 5% (C) and 10% broccoli by-product extract (BDe) (D).

3.2.4. Water Contact Angle

The WCA is a key indicator of the interaction of the film with water (hydrophobicity) and ambient humidity. This parameter is governed by the chemical nature of the constituent polymers and surface topography (roughness) [62]. As summarized in Table 2, all formulations exhibited low WCA values (20.2–22.4°), reflecting the inherently hydrophilic nature of the biopolymer matrix. These results align with previous studies on pectin- and starch-based films, which typically report WCA values well below 90° [63,64]. Orhoto-hwo et al. [2] compared starch-based films enriched with broccoli by-products powder *versus* extracts and observed that those made from powder possessed higher WCA values (76.5–77.4°) due to increased surface roughness, whereas extract-enriched films were more homogeneous and hydrophilic (42.9–47.8°). In the present study, the low WCA values are consistent with the observed high surface homogeneity. Notably, a slight increase in WCA was noted at the 2.5% BDe concentration. We hypothesize that at higher concentrations, the extract may begin to disrupt the matrix homogeneity or weaken internal bonding through phase separation or increased porosity.

3.3. Fourier-Transform Infrared Spectroscopy

FTIR was employed to investigate structural changes and intermolecular interactions within the film matrix upon the incorporation of different BDe concentrations (Figure 2). The spectral profile displayed characteristic absorption bands at 3400–3100 cm^{-1} , 2875–2925 cm^{-1} , 1500–1700 cm^{-1} , 1400 cm^{-1} , 1228 cm^{-1} , 1027 cm^{-1} and 916–771 cm^{-1} , corresponding to the functional groups of the film components. The spectral profiles for all formulations were practically identical, indicating that no new covalent

species were formed. The broad band at $3400\text{--}3100\text{ cm}^{-1}$, attributed to the stretching vibrations of --OH groups and extensive hydrogen bond interactions, showed intensity variations likely due to non-covalent interactions between the extract phenolics and the biopolymer matrix [10]. A decrease in --OH band intensity with increasing extract concentration may be explained by the formation of molecular aggregates and the associated increase in film thickness [65,66]. These findings suggest that the interaction between the matrix and BDe is primarily physical rather than a chemical modification of the polymer backbone. Similar spectral profiles have been reported for polysaccharide and chitosan films loaded with plant extracts [6,57,67]. Specific aliphatic C--H stretching (from --CH_2 and --CH_3 groups) was identified between 2925 and 2875 cm^{-1} [68]. The peak at 1600 cm^{-1} is assigned to the --C=O stretching of carboxylate ions (COO^-) from non-esterified galacturonic acids, typical of low-methoxyl pectins [69]. Furthermore, the sharp peak at 1029 cm^{-1} corresponds to C--O--C and C--O stretching vibrations, characteristic of glycosidic bonds in hemicellulose (e.g., xylose, arabinose, and galactose) [2]. The fingerprint region ($917\text{--}711\text{ cm}^{-1}$) confirms the presence of cell wall material (pectin, cellulose, and hemicellulose). Specifically, the band at 899 cm^{-1} arises in C_1 group/ring vibrations in cellulose, indicating β -glycosidic linkages. Bands at 914 and 830 cm^{-1} denote the ring vibrations of α -(1,4) galacturonic acid units, the backbone of pectin molecules [70]. Finally, galactomannans within the hemicellulose molecules were identified at 807 cm^{-1} [69]. These results are complemented by the thermogravimetric analyses of Codina et al. [13], which also identified cellulose and hemicellulose in QB films. As a result of the limitations of FTIR in the context of the present study, these results provide qualitative compositional information but cannot elucidate more detailed interaction mechanisms. This information would be reinforced using complementary analytical approaches such as x-ray diffraction, nuclear magnetic resonance, differential scanning calorimetry or dynamic mechanical analysis [69].

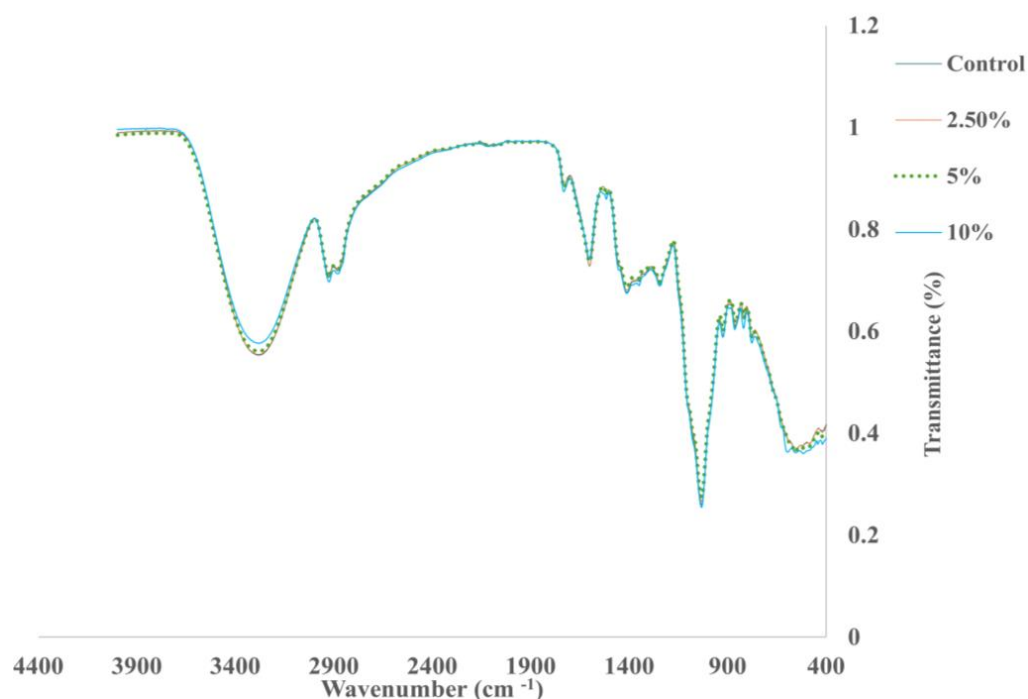


Figure 2. FTIR-ATR spectra of the control and of the films containing different concentrations of broccoli by-product extract (BDe) extract (2.5%, 5% and 10% *w/v*) measured across 400 to 4400 cm^{-1} .

3.4. Light Transmittance

Exposure to visible and, more critically, UV radiation accelerates food spoilage by inducing photo-oxidation and photo-degradation reactions [71]. Consequently, evaluating the light transmittance of packaging films in these spectral regions is essential for determining their protective capacity. The light-barrier properties of the different formulations were assessed by measuring transmittance across a broad spectrum (200–900 nm), as illustrated in Figure 3. In the UV region (200–400 nm) the transmittance values of all film formulations were near 0, indicating exceptional UV-shielding capacity. This is likely attributable to the presence of aromatic compounds (phenols, lignin, antioxidant plant extracts), as reported by others [72]. Phenolic-based UV absorbers are particularly effective due to their ability to dissipate UV energy as less harmful thermal energy [71]. In the visible (400–700 nm) and infrared (700–900 nm) regions, transmittance increased with longer wavelengths; however, the control film consistently exhibited the highest transmittance, indicating the lowest protection. The incorporation of BDe significantly decreased transmittance in a concentration-dependent manner. This decrease in transmittance in the films containing broccoli extract is likely due to the protective effect of chlorophyll, which absorbs strongly in the 400–500 nm range, and carotenoids, which absorb in the 500–620 nm range; both pigments are present in broccoli [73]. These results indicate that BDe confers greater photoprotection to films, especially in the visible and infrared regions.

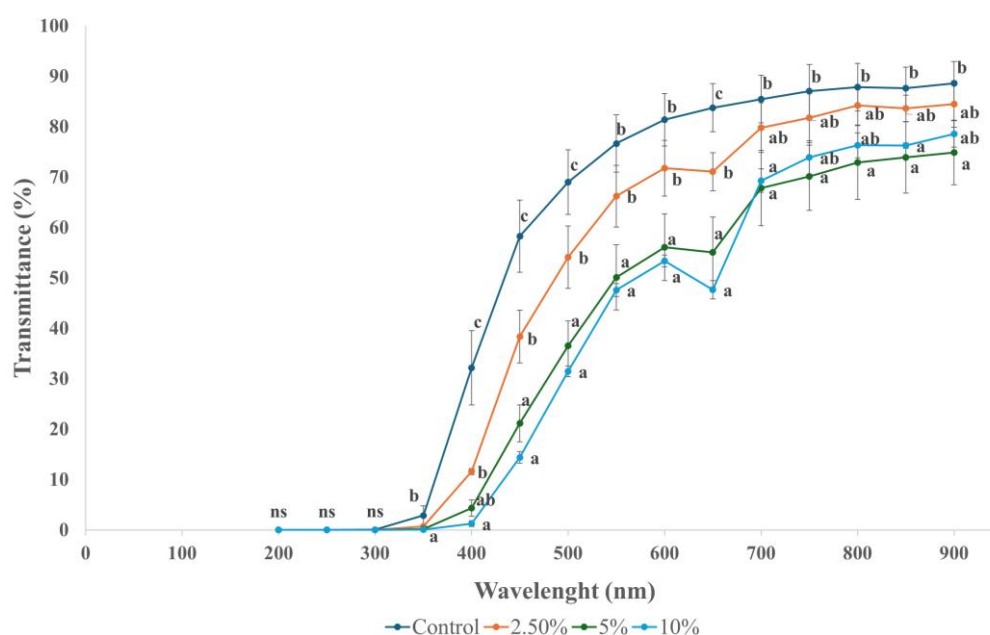


Figure 3. Light transmittance for the control and films containing different concentrations of broccoli by-product extract (BDe) (2.5%, 5% and 10% *w/v*) across different wavelengths. Superscript letters (a–c) indicate significant differences ($p < 0.05$) between film types (control, 2.5%, 5% and 10% BDe) at the same wavelength. ns denotes not significantly different.

3.5. Scanning Electron Microscopy

Scanning electron microscopy (SEM) was employed to evaluate surface morphology of the films, providing insights into the structural integration of the film-forming substrate [4]. Cross-sectional and surface SEM micrographs of the films are shown in Figures 4 and 5, respectively. In general, all formulations exhibited a compact, continuous matrix devoid of visible pores or cracks, suggesting high compatibility between components. However, closer examination of the surface morphology revealed a concentration-dependent increase in surface roughness and heterogeneity (Figure 5). While the lower extract concentration

(2.5%) maintained a highly integrated structure, the highest BDe concentration displayed large-sized localized particles (Figure 5D). This observation suggests that BDe achieves optimal interfacial interaction with the QB matrix at lower loading levels. This structural homogeneity could explain the superior performance of the 2.5% formulation. As summarized in Table 2, mechanical properties improved significantly at this threshold but plateaued with further BDe addition. The uniform dispersion of small bioactive molecules (phenolics and sugars) facilitates a more effective plasticizing effect and structural reinforcement when the molecules are well-distributed [67]. Furthermore, the peak WCA values observed for the 2.5% QB-BDe formulation are consistent with this high matrix integrity, as surface wetting is highly sensitive to homogeneity [2]. The appearance of these large-sized localized particles has been previously reported in carboxymethyl cellulose/alginate films enriched with *Thymus vulgaris* extracts [74] and carboxymethyl cellulose and polyvinyl alcohol films incorporating broccoli sprout seed extract [3], where excessive loading resulted in analogous morphological defects. However, a comprehensive chemical characterization would be required to discard the presence of co-extracted impurities that may also contribute to the formation of these surface features.

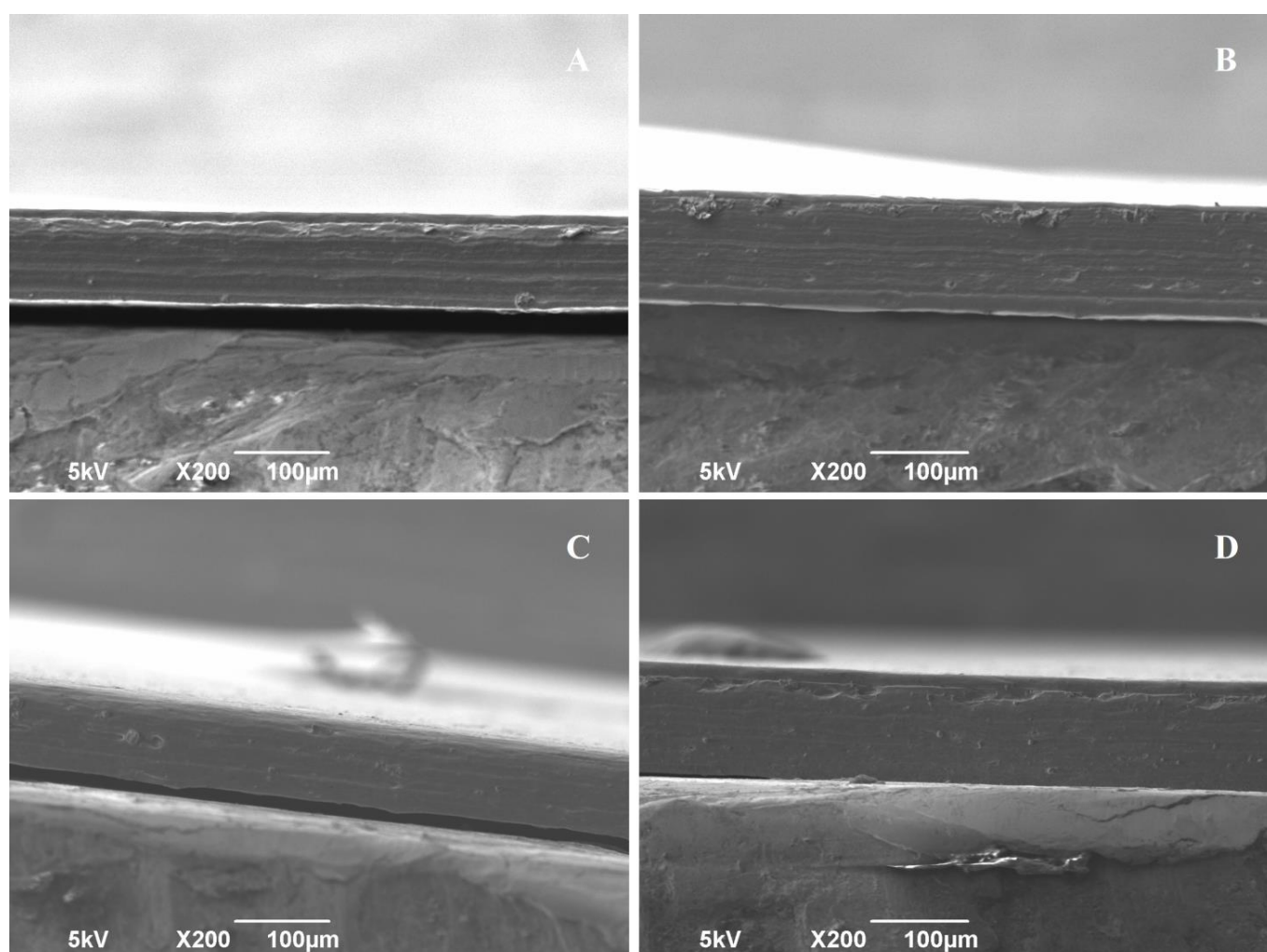


Figure 4. Scanning electron microscopy cross-sectional micrographs at 200× magnification (scale bar = 100 μm) of the quince by-products films: control (A), 2.5% (B), 5% (C) and 10% broccoli by-product extract (BDe) (D).

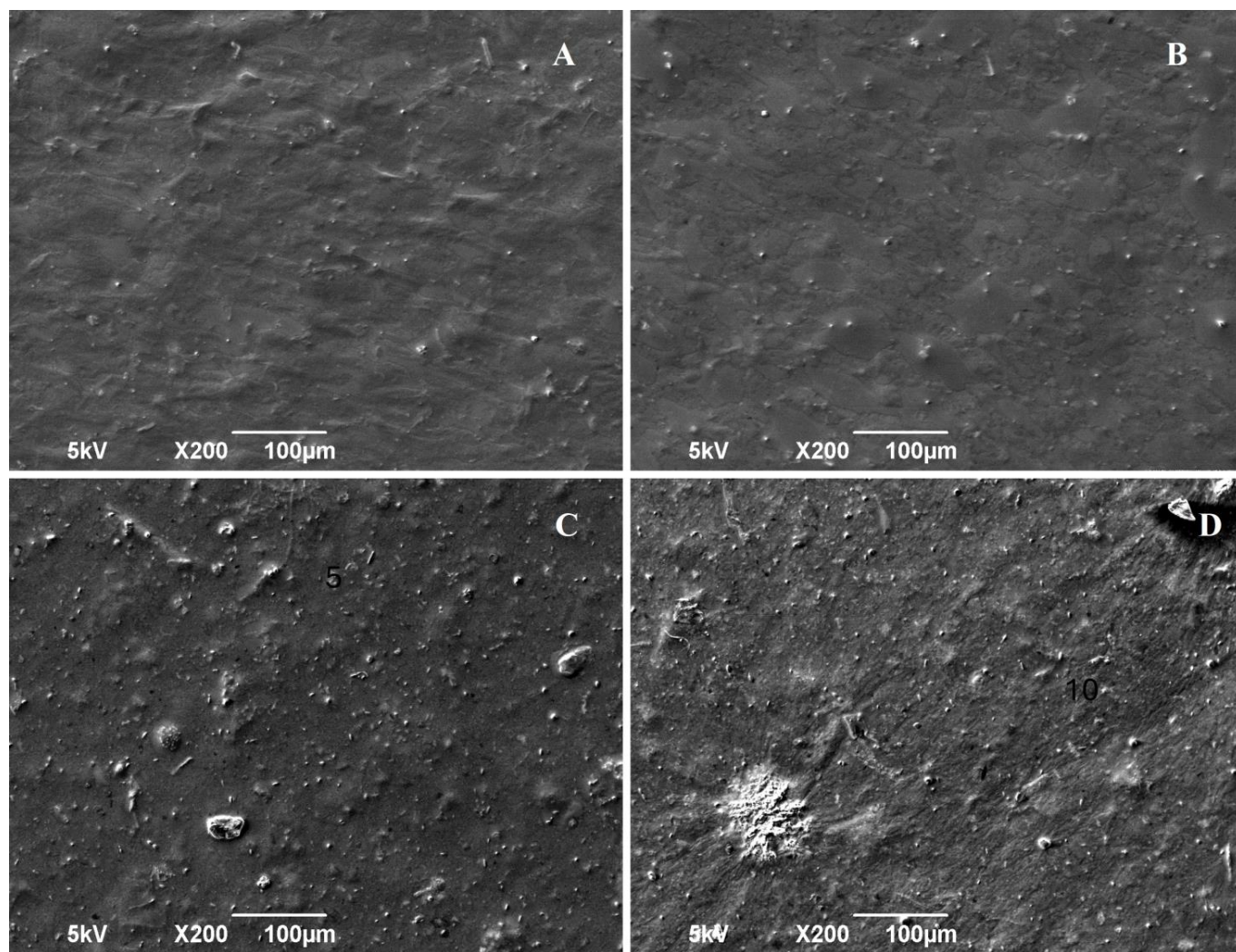


Figure 5. Scanning electron microscopy surface micrographs at 200 $\times$ magnification (scale bar = 100 μ m) of the films: control (A), 2.5% (B), 5% (C) and 10% broccoli by-product extract (BDe) (D).

3.6. Total Phenolic Content and Scavenging Activity of DPPH

The TPC of the film formulations was measured by the Folin–Ciocalteu method (Table 3). While no significant differences were observed between the control and the film with the lowest BDe concentration (17.6 and 17.8 mg GAE/g film, respectively), TPC values increased significantly at higher BDe incorporation, reaching 23.1 mg GAE/g film and 24.3 mg GAE/g film at 5% and 10% BDe formulations, respectively. This upward trend is attributed to the high phenolic content inherent in broccoli by-products. Indeed, Gudiño et al. [75] reported substantial TPC values in broccoli leaves (2435 mg GAE/100 g DW), followed by the inflorescences (1074 mg GAE/100 g DW) and stems (939 mg GAE/100 g DW). Notably, all formulations in this study exhibited higher TPC than the water-based QB films (6.6 mg GAE/g film) reported by Codina et al. [13], confirming that both the BDe and the clove hydrosol contribute significantly to the total phenolic profile of the matrix.

Table 3. Total phenolic content (TPC) measured in mg GAE/g film and antioxidant activity (DPPH inhibition) measured in (%) of quince by-products films ¹ at different broccoli by-product extract (BDe) concentrations.

Parameters	Control	Broccoli By-Product Extract (BDe)			<i>p</i> -Value
		2.5%	5%	10%	
TPC (mg GAE/g film)	17.61 ± 0.00 ^a	17.84 ± 0.11 ^a	23.15 ± 0.21 ^b	24.34 ± 0.00 ^c	<0.001
DPPH inhibition (%)	51.43 ± 8.56	53.59 ± 3.87	54.06 ± 3.33	51.85 ± 0.64	0.935

^{a–c} superscripts in the same row indicate significant differences ($p < 0.05$) between quince by-products films at different broccoli by-product extract (BDe) concentrations. ¹ mean ± SD.

No significant differences in DPPH radical scavenging activity were observed among the various film formulations (Table 3). These results together with the marked increase in antioxidant capacity compared with previously reported water-based QB films [13] suggests that the clove hydrosol is the primary contributor to this bioactive property. The composition of the clove hydrosol used in this work was previously analyzed by HPLC, revealing catechin gallate as the major constituent [76]. This compound has also been identified in aqueous clove extracts by other authors [77,78]. The potential of catechin gallate as antioxidant agent could explain the high DPPH inhibition values shown by the films [22,79]. For comparison, Ju et al. [80] reported a TPC of 10.9 mg GAE/g and a DPPH inhibition of 37.8% for wheat starch films incorporated with moringa leaf extract. The superior values obtained in the present study relative to other bio-based films underscore the high potential of these materials for active food packaging applications [81–83].

Nevertheless, the increase in TPC values resulting from extract incorporation did not translate into a proportional enhancement of the antioxidant activity exhibited by the film. The decoupling between the TPC values and DPPH radical scavenging activity has been documented previously in several active packaging systems and is consistent with known interactions between phenolic compounds and polymer matrices. Although phenolic compounds are widely used as natural antioxidants in bio-based films and edible coatings, their increased incorporation does not always result in proportional enhancements in rapid in vitro antioxidant assays such as DPPH (2,2-diphenyl-1-picrylhydrazyl) despite higher measured TPC values [84]. One possible explanation is that phenolic compounds can establish strong interactions with the polymer network, as physical entrapment, which can immobilize these molecules and reduce their accessibility to react with radicals in solutions. Phenolic–matrix interactions have been highlighted as a limiting factor for antioxidant activity expression in starch-based and composite films where the nature and strength of intermolecular interactions influence the release and functional performance of incorporated bioactive compounds [85].

Additionally, diffusion and release limitations inherent to the film structure may restrict the migration of phenolics from the bulk matrix to the surrounding medium during assays. Modeling studies on gelatin/chitosan films containing embedded phenolic acids have demonstrated that the kinetics of phenolic release are strongly dependent on diffusion barriers and the physicochemical conditions of the release environment, which can in turn impact measured antioxidant activity in assays such as DPPH [85].

Finally, phenolic compounds are susceptible to oxidative degradation or aggregation during film drying and storage. Oxidation of phenolic compounds can lead to the formation of quinones or other reaction products with reduced radical scavenging activity, and at high concentrations it may coalesce into domains that are less accessible, further diminishing measurable antioxidant activity [86]. Encapsulation and protective strategies have been shown to mitigate some of these limitations in other systems.

3.7. Antifungal Activity

To explore their application as protective food packaging, the films were tested for their inhibitory activity against mold strains previously isolated from natural cheese [41]. Antifungal activity (% inhibition) of the commercial film and the QB-BDe films against strains isolated from naturally contaminated cheeses (*A. jensenii* 501, and *A. puulaauensis* 1A05, *P. nordicum* M32) is shown in Figure 6. The films exhibited no activity against *P. commune* (301) and *P. expansum* (QZ1). Among the QB-BDe formulations, the 2.5% QB-BDe film showed the highest inhibition (15.7%) against 1A05, which was statistically comparable with the commercial film (17.1%). Furthermore, this formulation demonstrated superior antifungal activity (5.8%) against strain M32, significantly outperforming the commercial film (1.7%). For strain 501, the commercial film and the 2.5% and 5% QB-BDe films showed the highest inhibition levels (9.9%, 8.2%, and 7.8%, respectively), while the 10% QB-BDe film showed no significant difference from the control. The low inhibition by both the reference coating and the QB-BDe films indicate that these mold strains are highly resistant. Overall, the 10% QB-BDe film exhibited the weakest antifungal performance, whereas the 2.5% formulation consistently provided the greatest inhibition across the three susceptible strains. These results correlate with the physical properties observed in previous sections. Fungal proliferation is favored in humid environments; therefore, a film that fails to restrict vapor transport or possesses a highly hydrophilic surface facilitates the formation of water layers that promote conidia attachment [87,88]. As shown in Table 2, the 10% QB-BDe film was the most permeable (the highest WVP) and hydrophilic (the lowest WCA), whereas the 2.5% QB-BDe film was the least permeable (the lowest WVP along with the control) and most hydrophobic (the highest WCA). Similar relationships between moisture barrier deterioration and diminished antifungal performance have been demonstrated in active packaging films [89,90]. Moreover, cross-sectional SEM micrographs of the films revealed a concentration-dependent increase in both surface roughness and heterogeneity. This phenomenon along with the appearance of large-sized localized particles has been previously observed in biopolymer films and was linked to phase separation effects and extract migration during drying, ultimately impacting barrier performance and structural integrity [6]. This could lead to a different distribution of the extract in the film, even clustering in localized areas, which would affect its bioavailability [7].

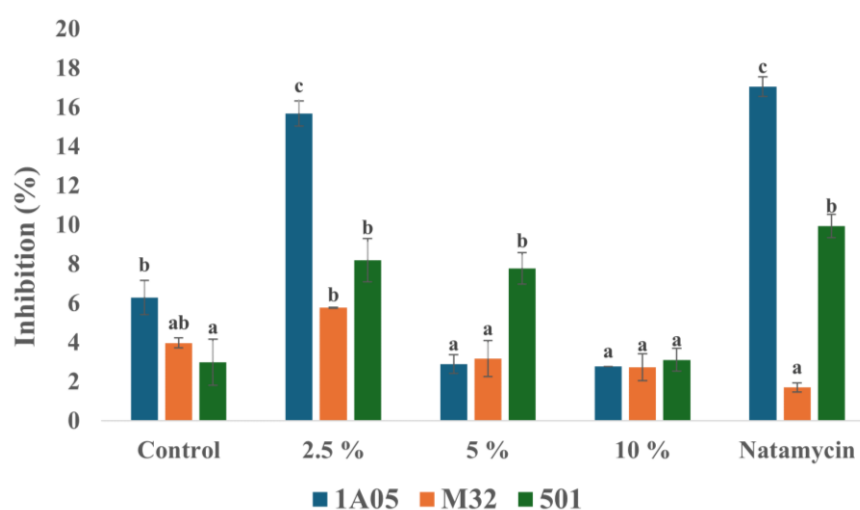


Figure 6. Antifungal activity assay of the quince by-products films at different broccoli by-product extract (BDe) concentrations (control, 2.5%, 5% and 10%) and commercial film with natamycin against 3 strains (1A05, M32 and 501). ^{a–c} superscripts in the same fungi strain (colour bar) indicate significant differences ($p < 0.05$) between quince by-products films at different broccoli by-product extract (BDe) concentrations.

These results were comparable to those reported for other bio-based films functionalized with plant extracts against *Aspergillus* and *Penicillium* species [91,92]. Moreover, although the inhibition percentages were relatively low, in some cases the antifungal effect was comparable to the commercial film containing natamycin and even exceeded it (in the case of the 2.5% formulation against M32). These results may be explained by the high intrinsic and acquired resistance exhibited against various strains of these genera, which has been widely documented in food and environmental matrices. These resistances highlight the broader adaptive capacity of these genera, making them less susceptible to antifungal agents compared with some other fungal genera. In the literature, there are numerous works that describe the antifungal potential of clove hydrosol, broccoli or quince by-products against different mold species. The catechin gallate, present in clove hydrosol, has demonstrated the ability to inhibit the growth of different molds [76,79,93]. Moreover, this compound, along with epicatechin, has also been described in ethanolic and methanolic extracts of broccoli [94,95]. Another major constituent of the clove hydrosol is eugenol [20], whose antifungal activity against various *Aspergillus* and *Penicillium* species, among others, has been widely documented [96,97].

These insights underscore the need for further optimization of active compound delivery and formulation strategies to enhance antifungal efficacy in practical applications. Implementing encapsulation strategies could potentially enhance the stability and bioavailability of the extract, allowing for a more controlled and effective release [98].

4. Conclusions

The incorporation of broccoli by-product extracts into a QB film formulated with clove hydrosol yielded a bioactive coating with significantly enhanced mechanical and functional properties. This study serves as a critical preliminary step toward food-scale applications, demonstrating that low-concentration extract loading (2.5%) produces a homogeneous matrix with optimal performance. Specifically, the 2.5% QB-BDe formulation exhibited the highest antimicrobial efficacy, the most robust water vapor barrier, and superior structural integrity. Moreover, the present work demonstrates that clove hydrosol can serve simultaneously as a solvent. The compatibility demonstrated between these components supports future exploration of advanced delivery strategies to further enhance the bioavailability and controlled release of the extract. By functionalizing a bio-based matrix with a secondary agri-food residue, this research achieves a dual-valorization strategy that promotes the maximum utilization of natural resources. However, large-scale production would require overcoming certain technical challenges, such as purifying the extract, carefully controlling the drying kinetics, and maintaining the uniform distribution of bioactive compounds. These findings advance the circular economy and expand the current knowledge base for sustainable, green packaging materials.

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References

1. Selvam, T.; Rahman, N.M.M.A.; Olivito, F.; Ilham, Z.; Ahmad, R.; Wan-Mohtar, W.A.A.Q.I. Agricultural Waste-Derived Biopolymers for Sustainable Food Packaging: Challenges and Future Prospects. *Polymers* **2025**, *17*, 1897. [\[CrossRef\]](#)
2. Orhotohwo, O.L.; Fanesi, B.; Darko, H.S.O.; Ismaiel, L.; Lucci, P.; Pacetti, D.; Jaiswal, A.K.; Jaiswal, S. Development and Characterisation of Broccoli By-Product-Enriched Starch-Carrageenan Films for Extending the Shelf Life of Fresh-Cut Fruits. *Food Biosci.* **2025**, *69*, 106976. [\[CrossRef\]](#)
3. Alshehri, A.A.; Hamed, Y.S.; Kamel, R.M.; Shawir, S.M.S.; Sakr, H.; Ali, M.; Ammar, A.; Saleh, M.N.; Fadly, E.E.; Salama, M.A.; et al. 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. *Int. J. Biol. Macromol.* **2024**, *255*, 128346. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Lei, Y.; Wu, H.; Jiao, C.; Jiang, Y.; Liu, R.; Xiao, D.; Lu, J.; Zhang, Z.; Shen, G.; Li, S. Investigation of the Structural and Physical Properties, Antioxidant and Antimicrobial Activity of Pectin-Konjac Glucomannan Composite Edible Films Incorporated with Tea Polyphenol. *Food Hydrocoll.* **2019**, *94*, 128–135. [\[CrossRef\]](#)
5. Sani, I.K.; Geshlaghi, S.P.; Pirsá, S.; Asdaghi, A. Composite Film Based on Potato Starch/Apple Peel Pectin/ZrO₂ Nanoparticles/Microencapsulated *Zataria multiflora* Essential Oil; Investigation of Physicochemical Properties and Use in Quail Meat Packaging. *Food Hydrocoll.* **2021**, *117*, 106719. [\[CrossRef\]](#)
6. Song, Z.; Wei, J.; Cao, Y.; Yu, Q.; Han, L. 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 Chem.* **2023**, *418*, 135958. [\[CrossRef\]](#)
7. Al-Zughbi, I.; Krayem, M. Quince Fruit *Cydonia oblonga* Mill Nutritional Composition, Antioxidative Properties, Health Benefits and Consumers Preferences towards Some Industrial Quince Products: A Review. *Food Chem.* **2022**, *393*, 133362. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Rezagholi, F.; Hashemi, S.M.B.; Gholamhosseinpour, A.; Sherahi, M.H.; Hesarinejad, M.A.; Ale, M.T. Characterizations and Rheological Study of the Purified Polysaccharide Extracted from Quince Seeds. *J. Sci. Food Agric.* **2019**, *99*, 143–151. [\[CrossRef\]](#)
9. Guzelgulgen, M.; Ozkendir-Inanc, D.; Yildiz, U.H.; Arslan-Yildiz, A. Glucuronoxylan-Based Quince Seed Hydrogel: A Promising Scaffold for Tissue Engineering Applications. *Int. J. Biol. Macromol.* **2021**, *180*, 729–738. [\[CrossRef\]](#)
10. Yousuf, S.; Maktedar, S.S. Utilization of Quince (*Cydonia oblonga*) Seeds for Production of Mucilage: Functional, Thermal and Rheological Characterization. *Sustain. Food Technol.* **2023**, *1*, 107–115. [\[CrossRef\]](#)
11. Behjati, J.; Yazdanpanah, S. Nanoemulsion and Emulsion Vitamin D3 Fortified Edible Film Based on Quince Seed Gum. *Carbohydr. Polym.* **2021**, *262*, 117948. [\[CrossRef\]](#)
12. Fatima, Z.; Fatima, S.; Muhammad, G.; Hussain, M.A.; Raza, M.A.; Amin, M.; Majeed, A. Stimuli-Responsive Glucuronoxylan Polysaccharide from Quince Seeds for Biomedical, Food Packaging, and Environmental Applications. *Int. J. Biol. Macromol.* **2024**, *273*, 133016. [\[CrossRef\]](#)
13. Codina, M.C.; González, E.J.; Molina, A.; Carmona, M.; Berruga, M.I. Bio-Based Films from Quince by-Products: A Sustainable Alternative for Biodegradable Food Packaging. *Food Hydrocoll.* **2024**, *157*, 110395. [\[CrossRef\]](#)
14. Yadav, S.; Malik, K.; Moore, J.M.; Kamboj, B.R.; Malik, S.; Malik, V.K.; Arya, S.; Singh, K.; Mahanta, S.; Bishnoi, D.K. Valorisation of Agri-Food Waste for Bioactive Compounds: Recent Trends and Future Sustainable Challenges. *Molecules* **2024**, *29*, 2055. [\[CrossRef\]](#)
15. Petkowicz, C.L.O.; Williams, P.A. Pectins from Food Waste: Characterization and Functional Properties of a Pectin Extracted from Broccoli Stalk. *Food Hydrocoll.* **2020**, *107*, 105930. [\[CrossRef\]](#)
16. Krupa-Kozak, U.; Drabińska, N.; Bączek, N.; Šimková, K.; Starowicz, M.; Jeliński, T. Application of Broccoli Leaf Powder in Gluten-Free Bread: An Innovative Approach to Improve Its Bioactive Potential and Technological Quality. *Foods* **2021**, *10*, 819. [\[CrossRef\]](#)

17. Fanesi, B.; Ismaiel, L.; Nartea, A.; Orhotohwo, O.L.; Kuhalskaya, A.; Pacetti, D.; Lucci, P.; Falcone, P.M. Bioactives and Technological Quality of Functional Biscuits Containing Flour and Liquid Extracts from Broccoli By-Products. *Antioxidants* **2023**, *12*, 2115. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Yang, Z.; Cao, Z.; Yu, C.; Feng, T.; Yao, L.; Song, S.; Sun, M.; Liu, Q.; Wang, H. Impact of Using High-Pressure Homogenization on the Chemical Profile, Quality Stability and Bioactivity of Hydrosol Obtain from Rose Flower. *Food Bioprod. Process.* **2024**, *144*, 22–31. [\[CrossRef\]](#)
19. Almeida, H.H.S.; Fernandes, I.P.; Amaral, J.S.; Rodrigues, A.E.; Barreiro, M.-F. Unlocking the Potential of Hydrosols: Transforming Essential Oil Byproducts into Valuable Resources. *Molecules* **2024**, *29*, 4660. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Šilha, D.; Švarcová, K.; Bajer, T.; Královec, K.; Tesařová, E.; Moučková, K.; Pejchalová, M.; Bajerová, P. Chemical Composition of Natural Hydrolates and Their Antimicrobial Activity on *Arcobacter*-Like Cells in Comparison with Other Microorganisms. *Molecules* **2020**, *25*, 5654. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Vilas-Boas, S.M.; Pokorný, V.; Štefja, V.; Ferreira, O.; Pinho, S.P.; Růžicka, K.; Fulem, M. Vapor Pressure and Thermophysical Properties of Eugenol and (+)-Carvone. *Fluid Phase Equilib.* **2019**, *499*, 112248. [\[CrossRef\]](#)
22. Abdelmuhsin, A.A.; Sulieman, A.M.E.; Salih, Z.A.; Al-Azmi, M.; Alanaizi, N.A.; Goniem, A.E.; Alam, M.J. Clove (*Syzygium aromaticum*) Pods: Revealing Their Antioxidant Potential via GC-MS Analysis and Computational Insights. *Pharmaceuticals* **2025**, *18*, 504. [\[CrossRef\]](#)
23. Liu, M.; Zhang, L.; Ser, S.; Cumming, J.; Ku, K.-M. Comparative Phytonutrient Analysis of Broccoli By-Products: The Potentials for Broccoli By-Product Utilization. *Molecules* **2018**, *23*, 900. [\[CrossRef\]](#)
24. Li, J.; He, J.; Huang, Y.; Li, D.; Chen, X. Improving Surface and Mechanical Properties of Alginate Films by Using Ethanol as a Co-Solvent during External Gelation. *Carbohydr. Polym.* **2015**, *123*, 208–216. [\[CrossRef\]](#)
25. Jouki, M.; Yazdi, F.T.; Mortazavi, S.A.; Koocheki, A. Physical, Barrier and Antioxidant Properties of a Novel Plasticized Edible Film from Quince Seed Mucilage. *Int. J. Biol. Macromol.* **2013**, *62*, 500–507. [\[CrossRef\]](#)
26. Jouki, M.; Mortazavi, S.A.; Yazdi, F.T.; Koocheki, A. Characterization of Antioxidant–Antibacterial Quince Seed Mucilage Films Containing Thyme Essential Oil. *Carbohydr. Polym.* **2014**, *99*, 537–546. [\[CrossRef\]](#)
27. Mondéjar-López, M.; Rubio-Moraga, A.; López-Jimenez, A.J.; García Martínez, J.C.; Ahrazem, O.; Gómez-Gómez, L.; Niza, E. Chitosan Nanoparticles Loaded with Garlic Essential Oil: A New Alternative to Tebuconazole as Seed Dressing Agent. *Carbohydr. Polym.* **2022**, *277*, 118815. [\[CrossRef\]](#)
28. Al-Maqtari, Q.A.; Rehman, A.; Mahdi, A.A.; Al-Ansi, W.; Wei, M.; Yanyu, Z.; Phyto, H.M.; Galeboe, O.; Yao, W. Application of Essential Oils as Preservatives in Food Systems: Challenges and Future Prospectives—A Review. *Phytochem. Rev.* **2022**, *21*, 1209–1246. [\[CrossRef\]](#)
29. Khan, S.; Abdo, A.; Shu, Y.; Zhang, Z.; Liang, T. The Extraction and Impact of Essential Oils on Bioactive Films and Food Preservation, with Emphasis on Antioxidant and Antibacterial Activities—A Review. *Foods* **2023**, *12*, 4169. [\[CrossRef\]](#)
30. Rozalén, J.; García-Martínez, M.d.l.M.; Carrión, M.E.; Carmona, M.; López-Córcoles, H.; Cornish, K.; Zalacain, A. Adapting the Accelerated Solvent Extraction Method for Resin and Rubber Determination in Guayule Using the BÜCHI Speed Extractor. *Molecules* **2021**, *26*, 183. [\[CrossRef\]](#)
31. Siripatrawan, U.; Noipha, S. Active Film from Chitosan Incorporating Green Tea Extract for Shelf Life Extension of Pork Sausages. *Food Hydrocoll.* **2012**, *27*, 102–108. [\[CrossRef\]](#)
32. Pandia-Estrada, S.; Romero-Santivañez, R. Optimización de Películas Comestibles de Origen Marino e Incorporación de Extracto de Orégano Para La Evaluación de Sus Propiedades. *Cienc. Tecnol. Agropecu.* **2023**, *24*, e2884. [\[CrossRef\]](#)
33. Neagu, O.M. Mucoadhesive Films Based on Polyvinyl Alcohol and Bioactive Compounds for Oral Administration: Structural Characterization and Mucoadhesive Properties. *Farmacia* **2023**, *71*, 737–746. [\[CrossRef\]](#)
34. Dick, M.; Henrique Pagno, C.; Haas Costa, T.M.; Goma, A.; Subirade, M.; de Oliveira Rios, A.; Hickmann Flôres, S. Edible Films Based on Chia Flour: Development and Characterization. *J. Appl. Polym. Sci.* **2016**, *133*, 42455. [\[CrossRef\]](#)
35. Ortiz de Elguea-Culebras, G.; Bourbon, A.I.; Costa, M.J.; Muñoz-Tebar, N.; Carmona, M.; Molina, A.; Sánchez-Vioque, R.; Berruga, M.I.; Vicente, A.A. Optimization of a Chitosan Solution as Potential Carrier for the Incorporation of *Santolina chamaecyparissus* L. Solid by-Product in an Edible Vegetal Coating on ‘Manchego’ Cheese. *Food Hydrocoll.* **2019**, *89*, 272–282. [\[CrossRef\]](#)
36. ASTM E96/E96M-16; Standard Test Methods for Water Vapor Transmission of Materials. ASTM: West Conshohocken, PA, USA, 2016.
37. Costa, M.J.; Cerqueira, M.A.; Ruiz, H.A.; Fougnyes, C.; Richel, A.; Vicente, A.A.; Teixeira, J.A.; Aguedo, M. Use of Wheat Bran Arabinoxylans in Chitosan-Based Films: Effect on Physicochemical Properties. *Ind. Crops Prod.* **2015**, *66*, 305. [\[CrossRef\]](#)
38. Gomes, L.C.; Faria, S.I.; Valcarcel, J.; Vázquez, J.A.; Cerqueira, M.A.; Pastrana, L.; Bourbon, A.I.; Mergulhão, F.J. The Effect of Molecular Weight on the Antimicrobial Activity of Chitosan from *Loligo opalescens* for Food Packaging Applications. *Mar. Drugs* **2021**, *19*, 384. [\[CrossRef\]](#)
39. Ramos-Pereira, J.; Mareze, J.; Patrino, E.; Santos, J.A.; López-Díaz, T.M. Polyphasic Identification of *Penicillium* spp. Isolated from Spanish Semi-Hard Ripened Cheeses. *Food Microbiol.* **2019**, *84*, 103253. [\[CrossRef\]](#)

40. Muñoz-Tebar, N.; Molina, A.; Carmona, M.; Berruga, M.I. Use of Chia By-Products Obtained from the Extraction of Seeds Oil for the Development of New Biodegradable Films for the Agri-Food Industry. *Foods* **2021**, *10*, 620. [\[CrossRef\]](#)
41. Muñoz-Tebar, N.; González-Navarro, E.J.; López-Díaz, T.M.; Santos, J.A.; de Elguea-Culebras, G.O.; García-Martínez, M.M.; Molina, A.; Carmona, M.; Berruga, M.I. Biological Activity of Extracts from Aromatic Plants as Control Agents against Spoilage Molds Isolated from Sheep Cheese. *Foods* **2021**, *10*, 1576. [\[CrossRef\]](#)
42. Jimenez-Fernandez, M.; Perez-Tirado, D.A.; Peredo-Lovillo, A.; Luna-Solano, G. Physicochemical Characteristics and Survivability of *Lactobacillus paracasei* Encapsulated by a Gum Arabic-Pectin Mixture as Wall Material and Added to Fresh Panela Cheese. *Rev. Mex. Ing. Quim.* **2021**, *20*, 2551. [\[CrossRef\]](#)
43. Vlad, R.-A.; Pinte, A.; Pinte, C.; Rédei, E.-M.; Antonoaia, P.; Birsan, M.; Ciurba, A. Hydroxypropyl Methylcellulose—A Key Excipient in Pharmaceutical Drug Delivery Systems. *Pharmaceutics* **2025**, *17*, 784. [\[CrossRef\]](#)
44. Tyuftin, A.A.; Pecorini, F.; Zanardi, E.; Kerry, J.P. Parameters Affecting the Water Vapour Permeability of Gelatin Films as Evaluated by the Infrared Detecting Method ASTM F1249. *Sustainability* **2022**, *14*, 9018. [\[CrossRef\]](#)
45. Busato, B.; de Almeida Abreu, E.C.; de Oliveira Petkowicz, C.L.; Martinez, G.R.; Rodrigues Noleto, G. Pectin from *Brassica oleracea* var. *italica* Triggers Immunomodulating Effects In Vivo. *Int. J. Biol. Macromol.* **2020**, *161*, 431–440. [\[CrossRef\]](#)
46. Luo, S.; Chen, J.; He, J.; Li, H.; Jia, Q.; Hossen, M.A.; Dai, J.; Qin, W.; Liu, Y. Preparation of Corn Starch/Rock Bean Protein Edible Film Loaded with d-Limonene Particles and Their Application in Glutinous Rice Cake Preservation. *Int. J. Biol. Macromol.* **2022**, *206*, 313–324. [\[CrossRef\]](#)
47. Jiang, H.; Zhang, W.; Khan, M.R.; Ahmad, N.; Rhim, J.-W.; Jiang, W.; Roy, S. Film Properties of Pectin Obtained from Various Fruits' (Lemon, Pomelo, Pitaya) Peels. *J. Compos. Sci.* **2023**, *7*, 366. [\[CrossRef\]](#)
48. Bangar, S.P.; Purewal, S.S.; Trif, M.; Maqsood, S.; Kumar, M.; Manjunatha, V.; Rusu, A.V. Functionality and Applicability of Starch-Based Films: An Eco-Friendly Approach. *Foods* **2021**, *10*, 2181. [\[CrossRef\]](#)
49. Saber, B.; Golding, J.B.; Marques, J.R.; Pristijono, P.; Chockchaisawasdee, S.; Scarlett, C.J.; Stathopoulos, C.E. Application of Biocomposite Edible Coatings Based on Pea Starch and Guar Gum on Quality, Storability and Shelf Life of 'Valencia' Oranges. *Postharvest Biol. Technol.* **2018**, *137*, 9–20. [\[CrossRef\]](#)
50. Said, N.S.; Lee, W.Y. Pectin-Based Active and Smart Film Packaging: A Comprehensive Review of Recent Advancements in Antimicrobial, Antioxidant, and Smart Colorimetric Systems for Enhanced Food Preservation. *Molecules* **2025**, *30*, 1144. [\[CrossRef\]](#)
51. Frangopoulos, T.; Marinopoulou, A.; Petridis, D.; Rhoades, J.; Likotrafiti, E.; Goulas, A.; Fetska, S.; Flegka, D.; Mati, E.; Tosounidou, A.; et al. Films from Starch Inclusion Complexes with Bioactive Compounds as Food Packaging Material. *Food Bioprocess Technol.* **2025**, *18*, 5164–5179. [\[CrossRef\]](#)
52. Xie, F. Biopolymer-Based Multilayer Films and Coatings for Food Preservation: An Update of the Recent Development. *Curr. Food Sci. Technol. Rep.* **2023**, *1*, 1–12. [\[CrossRef\]](#)
53. Cui, C.; Gao, L.; Dai, L.; Ji, N.; Qin, Y.; Shi, R.; Qiao, Y.; Xiong, L.; Sun, Q. Hydrophobic Biopolymer-Based Films: Strategies, Properties, and Food Applications. *Food Eng. Rev.* **2023**, *15*, 360–379. [\[CrossRef\]](#)
54. Amiri, E.; Aminzare, M.; Azar, H.H.; Mehrasbi, M.R. Combined Antioxidant and Sensory Effects of Corn Starch Films with Nanoemulsion of *Zataria multiflora* Essential Oil Fortified with Cinnamaldehyde on Fresh Ground Beef Patties. *Meat Sci.* **2019**, *153*, 66–74. [\[CrossRef\]](#)
55. Estrada-Girón, Y.; Cabrera-Díaz, E.; Esparza-Merino, R.M.; Martín-del-Campo, A.; Valencia-Botín, A.J. Innovative Edible Films and Coatings Based on Red Color Pectin Obtained from the Byproducts of *Hibiscus sabdariffa* L. for Strawberry Preservation. *J. Food Meas. Charact.* **2020**, *14*, 3371–3380. [\[CrossRef\]](#)
56. Lai, D.S.; Osman, A.F.; Adnan, S.A.; Ibrahim, I.; Ahmad Salimi, M.N.; Alrashdi, A.A. Effective Aging Inhibition of the Thermoplastic Corn Starch Films through the Use of Green Hybrid Filler. *Polymers* **2022**, *14*, 2567. [\[CrossRef\]](#)
57. Cui, L.; Gao, S.; Song, X.; Huang, L.; Dong, H.; Liu, J.; Chen, F.; Yu, S. Preparation and Characterization of Chitosan Membranes. *RSC Adv.* **2018**, *8*, 28433–28439. [\[CrossRef\]](#)
58. Zhang, L.; Liu, Z.; Han, X.; Sun, Y.; Wang, X. Effect of Ethanol Content on Rheology of Film-Forming Solutions and Properties of Zein/Chitosan Film. *Int. J. Biol. Macromol.* **2019**, *134*, 807–814. [\[CrossRef\]](#)
59. Giuffrida, D.; Menchaca, D.; Dugo, P.; Donato, P.; Cacciola, F.; Murillo, E. Study of the Carotenoid Composition in Membrillo, Guanabana Toreta, Jobo and Mamey Fruits. *Fruits* **2015**, *70*, 163–172. [\[CrossRef\]](#)
60. Nuñez-Gómez, V.; Baenas, N.; Navarro-González, I.; García-Alonso, J.; Moreno, D.A.; González-Barrio, R.; Periago-Castón, M.J. Seasonal Variation of Health-Promoting Bioactives in Broccoli and Methyl-Jasmonate Pre-Harvest Treatments to Enhance Their Contents. *Foods* **2020**, *9*, 1371. [\[CrossRef\]](#)
61. Turkmen, N.; Poyrazoglu, E.S.; Sari, F.; Sedat Velioglu, Y. Effects of Cooking Methods on Chlorophylls, Pheophytins and Colour of Selected Green Vegetables. *Int. J. Food Sci. Technol.* **2006**, *41*, 281–288. [\[CrossRef\]](#)
62. Zhang, H.; Sundaresan, S.; Webb, M.A. Molecular Dynamics Investigation of Nanoscale Hydrophobicity of Polymer Surfaces: What Makes Water Wet? *J. Phys. Chem. B* **2023**, *127*, 5115–5127. [\[CrossRef\]](#)

63. Chen, P.H.; Kuo, T.Y.; Kuo, J.Y.; Tseng, Y.P.; Wang, D.M.; Lai, J.Y.; Hsieh, H.J. Novel Chitosan–Pectin Composite Membranes with Enhanced Strength, Hydrophilicity and Controllable Disintegration. *Carbohydr. Polym.* **2010**, *82*, 1236–1242. [\[CrossRef\]](#)
64. Basiak, E.; Lenart, A.; Debeaufort, F. How Glycerol and Water Contents Affect the Structural and Functional Properties of Starch-Based Edible Films. *Polymers* **2018**, *10*, 412. [\[CrossRef\]](#)
65. Zou, X.; Zhao, Y.; Zhu, Y.; Liu, R. Filling Aggregation-Induced Extinction Mechanism in Near-Infrared Photopolymerization for Gradient and Highly Filled Bulk Materials. *Macromolecules* **2022**, *55*, 2075–2084. [\[CrossRef\]](#)
66. Casci Ceccacci, A.; Cagliani, A.; Marizza, P.; Schmid, S.; Boisen, A. Thin Film Analysis by Nanomechanical Infrared Spectroscopy. *ACS Omega* **2019**, *4*, 7628–7635. [\[CrossRef\]](#) [\[PubMed\]](#)
67. Saied, M.; Ward, A.; Hamieda, S.F. Effect of Apricot Kernel Seed Extract on Biophysical Properties of Chitosan Film for Packaging Applications. *Sci. Rep.* **2024**, *14*, 3430. [\[CrossRef\]](#) [\[PubMed\]](#)
68. Nehdi, I.A.; Sbihi, H.; Tan, C.P.; Zarrouk, H.; Khalil, M.I.; Al-Resayes, S.I. Characteristics, Composition and Thermal Stability of *Acacia senegal* (L.) Willd. Seed Oil. *Ind. Crops Prod.* **2012**, *36*, 54–58. [\[CrossRef\]](#)
69. Liu, X.; Renard, C.M.G.C.; Bureau, S.; Le Bourvellec, C. Revisiting the Contribution of ATR-FTIR Spectroscopy to Characterize Plant Cell Wall Polysaccharides. *Carbohydr. Polym.* **2021**, *262*, 117935. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Szymanska-Chargot, M.; Chylinska, M.; Kruk, B.; Zdunek, A. Combining FT-IR Spectroscopy and Multivariate Analysis for Qualitative and Quantitative Analysis of the Cell Wall Composition Changes during Apples Development. *Carbohydr. Polym.* **2015**, *115*, 93–103. [\[CrossRef\]](#)
71. Roy, S.; Ramakrishnan, R.; Goksen, G.; Singh, S.; Łopusiewicz, Ł. Recent Progress on UV-Light Barrier Food Packaging Films—A Systematic Review. *Innov. Food Sci. Emerg. Technol.* **2024**, *91*, 103550. [\[CrossRef\]](#)
72. Zhang, Y.; Cai, P.; Cheng, G.; Zhang, Y. A Brief Review of Phenolic Compounds Identified from Plants: Their Extraction, Analysis, and Biological Activity. *Nat. Prod. Commun.* **2022**, *17*, 211069721. [\[CrossRef\]](#)
73. Luo, F.; Cai, J.-H.; Kong, X.-M.; Zhou, Q.; Zhou, X.; Zhao, Y.-B.; Ji, S.-J. Transcriptome Profiling Reveals the Roles of Pigment Mechanisms in Postharvest Broccoli Yellowing. *Hortic. Res.* **2019**, *6*, 74. [\[CrossRef\]](#)
74. Abdin, M.; Mabrouk, M.; El-Sebaiy, L.; Eissa, M.; El-Bana, M.; Salama, M.A.; El-Beltagy, A.E.; Naeem, M.A. Composite Films Based on Carboxy Methyl Cellulose and Sodium Alginate Incorporated *Thymus vulgaris* Purified Leaves Extract for Food Application: Assessment, Antimicrobial and Antioxidant Properties. *Int. J. Biol. Macromol.* **2023**, *240*, 124474. [\[CrossRef\]](#) [\[PubMed\]](#)
75. Gudiño, I.; Casquete, R.; Martín, A.; Wu, Y.; Benito, M.J. Comprehensive Analysis of Bioactive Compounds, Functional Properties, and Applications of Broccoli By-Products. *Foods* **2024**, *13*, 3918. [\[CrossRef\]](#) [\[PubMed\]](#)
76. Codina, M.C.; Gómez, M.; González, E.J.; Aranda, E.; Molina, A.; Carmona, M.; Berruga, M.I. Antifungal and Antioxidant Activity of Aromatic Plant Hydrosols and Its Potential Applications to Control Filamentous Fungi in Cheese. In Proceedings of the 28th International ICFMH Conference (FoodMicro 2024), Burgos, Spain, 8 July 2024.
77. El Faqr, O.; Bendiar, S.; Rais, S.; Elkoraichi, I.; Dakir, M.; Elouaddari, A.; El Amrani, A.; Oudghiri, M.; Mtairag, E.M. Phytochemical Characterization and Immunomodulatory Effects of Aqueous, Ethanolic Extracts and Essential Oil of *Syzygium aromaticum* L. on Human Neutrophils. *Sci. Afr.* **2022**, *18*, e01395. [\[CrossRef\]](#)
78. Adefegha, S.A.; Oboh, G.; Oyeleye, S.I.; Osunmo, K. Alteration of Starch Hydrolyzing Enzyme Inhibitory Properties, Antioxidant Activities, and Phenolic Profile of Clove Buds (*Syzygium aromaticum* L.) by Cooking Duration. *Food Sci. Nutr.* **2016**, *4*, 250–260. [\[CrossRef\]](#)
79. Tóth Hervay, N.; Konečná, A.; Eliaš, D.; Kocúřeková, P.; Jacko, J.; Súľovská, H.; Šikurová, L.; Gbelská, Y. Catechin Augments the Antifungal Efficacy of Fluconazole Against *Candida parapsilosis*. *Int. J. Mol. Sci.* **2026**, *27*, 620. [\[CrossRef\]](#)
80. Ju, A.; Baek, S.-K.; Kim, S.; Song, K. Bin Development of an Antioxidative Packaging Film Based on Khorasan Wheat Starch Containing Moringa Leaf Extract. *Food Sci. Biotechnol.* **2019**, *28*, 1057–1063. [\[CrossRef\]](#)
81. Rambabu, K.; Bharath, G.; Banat, F.; Show, P.L.; Cocolletzi, H.H. Mango Leaf Extract Incorporated Chitosan Antioxidant Film for Active Food Packaging. *Int. J. Biol. Macromol.* **2019**, *126*, 1234–1243. [\[CrossRef\]](#)
82. Hafsa, J.; Smach, M.A.; Ben Khedher, M.R.; Charfeddine, B.; Limem, K.; Majdoub, H.; Rouatbi, S. Physical, Antioxidant and Antimicrobial Properties of Chitosan Films Containing *Eucalyptus globulus* Essential Oil. *LWT—Food Sci. Technol.* **2016**, *68*, 356–364. [\[CrossRef\]](#)
83. Jouki, M.; Yazdi, F.T.; Mortazavi, S.A.; Koocheki, A. Quince Seed Mucilage Films Incorporated with Oregano Essential Oil: Physical, Thermal, Barrier, Antioxidant and Antibacterial Properties. *Food Hydrocoll.* **2014**, *36*, 9–19. [\[CrossRef\]](#)
84. Singh, A.K.; Kim, J.Y.; Lee, Y.S. Phenolic Compounds in Active Packaging and Edible Films/Coatings: Natural Bioactive Molecules and Novel Packaging Ingredients. *Molecules* **2022**, *27*, 7513. [\[CrossRef\]](#) [\[PubMed\]](#)
85. Lai, W.-F. Design of Polymeric Films for Antioxidant Active Food Packaging. *Int. J. Mol. Sci.* **2021**, *23*, 12. [\[CrossRef\]](#)
86. Ordoñez, R.; Atarés, L.; Chiralt, A. Biodegradable Active Materials Containing Phenolic Acids for Food Packaging Applications. *Compr. Rev. Food Sci. Food Saf.* **2022**, *21*, 3910–3930. [\[CrossRef\]](#)
87. Benkovičová, M.; Kisová, Z.; Bučková, M.; Majková, E.; Šiffalovič, P.; Pangallo, D. The Antifungal Properties of Super-Hydrophobic Nanoparticles and Essential Oils on Different Material Surfaces. *Coatings* **2019**, *9*, 176. [\[CrossRef\]](#)

88. Liauw, C.M.; Slate, A.J.; Butler, J.A.; Wilson-Nieuwenhuis, J.S.T.; Deisenroth, T.; Preuss, A.; Verran, J.; Whitehead, K.A. The Effect of Surface Hydrophobicity on the Attachment of Fungal Conidia to Substrates of Polyvinyl Acetate and Polyvinyl Alcohol. *J. Polym. Environ.* **2020**, *28*, 1450–1464. [\[CrossRef\]](#)
89. Sahraee, S.; Milani, J.M.; Ghanbarzadeh, B.; Hamishehkar, H. Development of Emulsion Films Based on Bovine Gelatin-nano Chitin-nano ZnO for Cake Packaging. *Food Sci. Nutr.* **2020**, *8*, 1303–1312. [\[CrossRef\]](#)
90. Figueroa-Lopez, K.; Andrade-Mahecha, M.; Torres-Vargas, O. Development of Antimicrobial Biocomposite Films to Preserve the Quality of Bread. *Molecules* **2018**, *23*, 212. [\[CrossRef\]](#)
91. Gniewosz, M.; Pobiega, K.; Kraśniewska, K.; Synowiec, A.; Chaberek, M.; Galus, S. Characterization and Antifungal Activity of Pullulan Edible Films Enriched with Propolis Extract for Active Packaging. *Foods* **2022**, *11*, 2319. [\[CrossRef\]](#)
92. Lopes, A.; Melo, A.; Caleja, C.; Pereira, E.; Finimundy, T.; Afonso, T.; Silva, S.; Ivanov, M.; Soković, M.; Tavaría, F.; et al. Evaluation of Antimicrobial and Antioxidant Activities of Alginate Edible Coatings Incorporated with Plant Extracts. *Coatings* **2023**, *13*, 1487. [\[CrossRef\]](#)
93. Molina-Hernández, J.B.; Scroccarello, A.; Della Pelle, F.; De Flaviis, R.; Compagnone, D.; Del Carlo, M.; Paparella, A.; Chaves López, C. Synergistic Antifungal Activity of Catechin and Silver Nanoparticles on *Aspergillus niger* Isolated from Coffee Seeds. *LWT* **2022**, *169*, 113990. [\[CrossRef\]](#)
94. Fratianni, F.; Cardinale, F.; Cozzolino, A.; Granese, T.; Pepe, S.; Riccardi, R.; Spigno, P.; Coppola, R.; Nazzaro, F. Polyphenol Composition and Antioxidant Activity of Two Autochthonous Brassicaceae of the Campania Region, Southern Italy. *Food Nutr. Sci.* **2014**, *5*, 66–70. [\[CrossRef\]](#)
95. Mollica, A.; Stefanucci, A.; Zengin, G.; Locatelli, M.; Macedonio, G.; Orlando, G.; Ferrante, C.; Menghini, L.; Recinella, L.; Leone, S.; et al. Polyphenolic Composition, Enzyme Inhibitory Effects Ex-Vivo and In-Vivo Studies on Two Brassicaceae of North-Central Italy. *Biomed. Pharmacother.* **2018**, *107*, 129–138. [\[CrossRef\]](#) [\[PubMed\]](#)
96. Wang, Y.; Bian, W.; Ren, X.; Song, X.; He, S. Microencapsulation of Clove Essential Oil Improves Its Antifungal Activity against *Penicillium digitatum* In Vitro and Green Mould on Navel Oranges. *J. Hortic. Sci. Biotechnol.* **2018**, *93*, 159–166. [\[CrossRef\]](#)
97. Kaur, K.; Kaushal, S.; Rani, R. Chemical Composition, Antioxidant and Antifungal Potential of Clove (*Syzygium aromaticum*) Essential Oil, Its Major Compound and Its Derivatives. *J. Essent. Oil Bear. Plants* **2019**, *22*, 1195–1217. [\[CrossRef\]](#)
98. Nogueira, G.F.; de Oliveira, R.A.; Velasco, J.I.; Fakhouri, F.M. Methods of Incorporating Plant-Derived Bioactive Compounds into Films Made with Agro-Based Polymers for Application as Food Packaging: A Brief Review. *Polymers* **2020**, *12*, 2518. [\[CrossRef\]](#)

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