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Evaluation of the structure-bioactivity interaction in alginate-pectin films incorporated with *Licania tomentosa* seed extract for pear preservation☆

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ABSTRACT

Alginate-based films have limitations when used in isolation, including low mechanical strength, high water sensitivity, and reduced barrier properties, which can restrict their technological applicability. In this context, the present study investigated the effect of incorporating oiti seed extract on the structure and functionality of alginate-pectin biopolymer films. Small-angle X-ray scattering (SAXS) analysis revealed a concentration-dependent behavior of alginate in the extract dispersion. The profile of phenolic compounds detected in the extracts, such as vanillin (0.46 mg g^{-1}), ferulic acid (0.49 mg g^{-1}), and coumaric acid (0.47 mg g^{-1}), contributed to the rearrangement in the alginate-pectin matrix, improving the mechanical and structural performance of the films. The addition of the extract caused a significant reduction in water vapor permeability (1.93–0.94 g mm m^{-2} d^{-1} kPa^{-1}). The films incorporating the extract also exhibited significant antioxidant activity over 21 days of storage, with the 1.0% formulation showing the best balance in the retention of bioactive compounds, while higher concentrations favored biodegradability. Application of the films to minimally processed pears demonstrated that the coating method outperformed the immersion method, contributing to better visual quality, greater pH stability, and delayed surface browning. Overall, the controlled incorporation of oiti seed extract into the alginate-pectin matrix modulated the structural organization, functionality, and biodegradability of the films, highlighting their potential as a sustainable material for active food packaging.

1. Introduction

In light of the environmental challenges associated with the extensive use of petroleum-derived plastics, biopolymers have emerged as sustainable alternatives. In this context, sodium alginate has been widely investigated for coating and film applications due to its biocompatibility and renewable origin (Tammina et al., 2025). However, alginate-based films used alone present limitations, including low mechanical strength, high water sensitivity, and reduced barrier properties, which may restrict their technological applicability. Along with that, polymer concentration directly influences structural homogeneity as well as the mechanical and permeability properties of the resulting films (Firoozjah-Abedi et al., 2025; Tammina et al., 2025)

To overcome these limitations, alginate is frequently combined with other components capable of promoting intermolecular interactions, structural reinforcement, and improved functional performance (Arroyo-Esquivel et al., 2025). Nevertheless, selecting an appropriate polymeric system remains challenging, since different combinations may result in networks with distinct structural organizations and physicochemical behaviors. From this perspective, the incorporation of plant-derived bioactive extracts has been explored as a strategy to enhance film performance materiais (Kumar et al., 2025; Nordin et al., 2025; Pilehforooshha et al., 2025). Extracts rich in phenolic compounds may provide antioxidant and antimicrobial properties while establishing intermolecular interactions within the polymeric matrix, thereby modifying its structural organization and barrier properties against

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gases and water vapor (Li et al., 2026; Zhu, 2026), thereby expanding the potential application of these films in active and intelligent food packaging systems.

In this regard, the extract from oiti seeds (*Licania tomentosa),* a species native to Brazil, exhibits a high content of phenolic compounds and flavonoids and is associated with antioxidant properties (Alves et al., 2021; Silva et al., 2021). Its incorporation into polymeric films represents a strategy for valorizing Brazilian biodiversity resources in the development of functional packaging materials. Beyond enhancing antioxidant activity, this extract may influence film flexibility, structural cohesion, and barrier performance. Previous studies have demonstrated the feasibility of incorporating plant extracts into natural polymer matrices, resulting in materials with tailored functional properties (Bertolo et al., 2023; Daget et al., 2025; Mulla et al., 2025; Pires et al., 2022; Rashid et al., 2023; Yayla et al., 2025).

Considering that both alginate concentration and the incorporation of bioactive extracts may induce reorganization within the polymeric network (Nokab-El et al., 2026; Silva et al., 2026), the application of advanced structural characterization techniques becomes essential to elucidate these modifications. In this sense, nanoscale analytical approaches such as small-angle X-ray scattering (SAXS) can provide relevant information regarding structural heterogeneity, intermolecular organization, and domain formation in biopolymeric systems (Nogueira et al., 2023). Understanding these nanoscale features is fundamental for establishing structure property relationships and supporting the rational optimization of film formulations.

In this context, the present study evaluates the effects of alginate concentration, alginate-pectin mixture, and the incorporation of oiti seed extract on the structural and functional performance of biopolymer films. Moreover, the applicability of the optimized formulations was evaluated in minimally processed pears to determine their effectiveness in preserving quality attributes during storage. Unlike many previous studies in which alginate concentration is selected empirically and plant extracts are incorporated without detailed phenolic characterization, this work systematically investigates polymer ratios and characterizes the phenolic profile of the oiti extract prior to incorporation. This integrated approach enables correlations between film formulation, molecular interactions, and technological properties, providing novel insights into the design of sustainable polysaccharide-based films. By promoting biodegradable packaging and enhancing food preservation, these materials may reduce reliance on conventional plastics, minimize postharvest losses, and contribute to improved food security.

2. Materials and methods

2.1. Reagents

Sodium alginate (C6H9O7Na; MW 216.12 g/mol; purity >90%) (extracted from seaweed), pectin (9000-69-5 galacturonic acid ≥74.0% on a dry basis) (extracted from citrus peel), sodium hydroxide PA, and absolute ethyl alcohol were purchased from Sigma-Aldrich® (St. Louis, MO, USA). Folin Ciocalteu reagents, 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox), 2,2-diphenyl-1-picrylhydrazyl (DPPH$^{\bullet}$), 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid), diammonium salt (ABTS$^{\bullet+}$) were purchased from Sigma-Aldrich® (St. Louis, MO, USA). All other reagents and chemicals used in the experiments were of analytical grade.

2.2. Extract optimization and extract preparation

The parameters for preparing the extracts used in this study were defined based on an experimental design based by Waseem et al. (2023). Each combination of extraction method and solvent was subsequently evaluated through phytochemical screening and antioxidant activity analyses in order to identify the most suitable extract for incorporation into the films. The extracts were obtained using solid-solvent ratio of 1:40 (*w/v*) in a completely randomized design (CRD) in a 3 × 2 factorial scheme. The factors evaluated consisted of three concentrations of hydroethanolic solvent (40%, 60%, and 80% *v/v*) and two extraction methods (maceration and ultrasonic bath). For the maceration procedure, the extraction was conducted under constant magnetic stirring at 400 rpm for 1 h, followed by sonication in an ultrasonic bath for 30 min at 35 °C, with all treatments performed in triplicate. The resulting extracts were subjected to antioxidant assays using the DPPH method and total phenolic analysis to evaluate the extraction performance. Based on the results (TS1), the condition that combined 40% ethanol (*v/v)* and maceration at 400 rpm in a magnetic stirrer (AGT-ANA.AQ) for 60 min was the most suitable. Immediately afterwards, the samples were filtered through filter paper and stored at 10 °C until the time of film development.

2.2.1. Total phenolics, antioxidants, and phenolic acid profile

Total phenolic compounds were determined using the Folin–Ciocalteu reagent, following the methodology described by Waterhouse (2002). Absorbance was read in a digital spectrophotometer at 750 nm. Results were expressed as milligrams of gallic acid equivalents (GAE) per gram of dry sample. The DPPH assays were performed according to the methodology described by Rufino et al. (2007). Results were expressed as a percentage of inhibition, according to Eq. (1), with absorbance measured at 517 nm. Where AA is the absorbance of the sample and AB is the absorbance of the control.

$$\%\text{inhibition} = [1 - ((\text{AA})/\text{AB})] \times 100 \quad (1)$$

Phenolic acids were quantified according to Gao et al. (2024), with minor modifications. Approximately 1 g of sample was extracted with 30 mL of 40% ethanol (*w/v*) under agitation (2000 rpm, 60 min), followed by centrifugation and filtration (0.22 μm PTFE membrane). Analyses were performed using an HPLC-DAD system (Agilent 1260 Infinity II) equipped with a Zorbax C18 column. The mobile phases consisted of 5% formic acid in water (A) and acetonitrile (B), at a flow rate of 0.8 mL min^{-1}, column temperature of 30 °C, injection volume of 20 μL, and a total run time of 30 min. Detection was carried out between 295 and 350 nm. Identification was based on comparison of retention times and UV spectra with authentic standards, and quantification was performed using external calibration curves (0.0625–10 mg L^{-1}). Results were expressed as mg GAE 100 g^{-1}. All analyses were conducted in triplicate

2.3. Structural determination of the optimal sodium alginate concentration by small-angle X-ray scattering (SAXS)

A preliminary structural evaluation was conducted using small-angle X-ray scattering (SAXS) to investigate the interaction between sodium alginate and oiti seed extract at the molecular level. The main objective was to assess the behavior of the extract within polymer matrices of low, intermediate, and relatively higher concentrations, in order to understand how polymer content influences polymer versus extract interactions and structural organization. For this purpose, dilute alginate solutions (0.2, 0.3, and 0.5% *w/v*) containing 6% (*w/w*) extract were prepared. These lower concentrations were selected to ensure adequate scattering conditions and minimize the effects of multiple scattering, common in highly viscous or concentrated systems. Based on the scattering profiles, the formulation with the highest alginate concentration demonstrated a more cohesive structural organization, indicating a continuous and stable polymer network. Therefore, a concentration of 2% (*w/v*) sodium alginate was selected for the next stage of the study.

SAXS analyses were performed by sealing the solutions in fixed quartz capillaries, measurements followed the protocol described by Nogueira et al. (2023) and were carried out at the SWING beamline of the SOLEIL synchrotron (Gif-sur-Yvette, France), using a photon energy of 12 keV. The scattered intensity was collected with a detector positioned at ~6.0 m from the sample. To prevent radiation-induced

aggregation that could interfere with the low-q region, a first exposure was conducted with a short acquisition time (~0.2 s), followed by a longer exposure (~15 s) using an expanded beam to improve the signal-to-noise ratio at high q. The solvent intensity (ultrapure water) measured in the same capillary was subtracted from the sample intensities. Data sets were merged to generate a single scattering curve covering a q-range from 1.03 × 10^{-3} to 0.18 $Å^{-1}$, after removal of inconsistent points. Measurements were performed at 30 °C. The scattering data were analyzed using SasView 6.0.1 software, and the results were interpreted to correlate the organization of the nanostructure with the optimal concentration of sodium alginate for the film samples.

2.4. Experimental design of film-forming

After establishing the sodium alginate concentration, a second experimental phase was undertaken to develop and screen the most suitable film-forming formulations. A total of 14 formulations were prepared (TS3) with three different concentrations of ethanolic oiti seed extract (0.5, 1.0, and 1.5% *w/v*). As a preliminary screening step, all formulations were subjected to water vapor permeability (WVP) test, and some samples resulted in structural failure before the completion of the 7 days test period. Therefore, only the formulations that maintained structural integrity throughout the test were selected for subsequent analyses.

2.5. Film development

The film-forming solutions were prepared using sodium alginate and pectin in a ratio of 1:1 (*w/w*). Both biopolymers were dissolved in distilled water under constant magnetic stirring at until complete homogenization and formation of a uniform polymer matrix. After solubilization, 35 mL of the film-forming solution was poured into polypropylene containers with dimensions of 16.4 cm × 12.0 cm × 5.2 cm. At the end of the process, the films formed were carefully removed from the supports and stored in a desiccator containing silica gel until further physical-chemical and structural characterization (Fig. 1). The samples were coded in: CAP (control); AP0.5 (Alginate-pectin with 0.5% of extract); AP1.0 (Alginate-pectin with 1.0% of extract); AP1.5 (Alginate-pectin with 1.5% of extract).

2.6. Physical and mechanical properties

2.6.1. Thickness, tensile strength, elongation at break, and Young's modulus

For the mechanical properties (tensile strength (MPa), elongation at break (%), and Young's modulus (MPa), the films were conditioned for 72 h in an oven with 75% relative humidity at 25 °C. The specimens were cut into strips of 70 mm × 15 mm wide, with an initial gripper separation of 50 mm and a gripper separation speed of 12.5 mm min^{-1}. The specimens were verified using a static test instrument from Shimadzu, Japan, operating by ASTM D882-12 specifications, with six replicates for each treatment (ASTM, 2012). The film thickness was measured with a digital caliper (Mitutoyo-Co, Japan) with an accuracy of 0.001 mm. The average thickness of each film was determined by averaging four random positions on the film samples by Saravana Kumar et al. (2020).

2.6.2. Water solubility

The solubility parameter of the samples was determined as proposed by Tavassoli et al. (2025). The film samples were cut into 2 × 2 cm pieces and weighed. Then, the film pieces were dried in an oven at 105 °C for 24 h to reach constant weight. Subsequently, the dried films were directly immersed in 40 mL of distilled water at 25 °C for 24 h. Then, the samples were collected and dried again in an oven at 105 °C for 24 h to reach a constant weight. The results were expressed as the percentage of dry matter of the solubilized film after 24 h of immersion in water.

2.6.3. Water vapor permeability (WVP)

Water vapor permeability was performed according to ASTM 96-95 (2000). The film samples were fixed in a hermetically sealed glass permeation cell containing 50 mL of distilled water. The initial mass of the system was measured and stored in a desiccator at 25 °C with silica

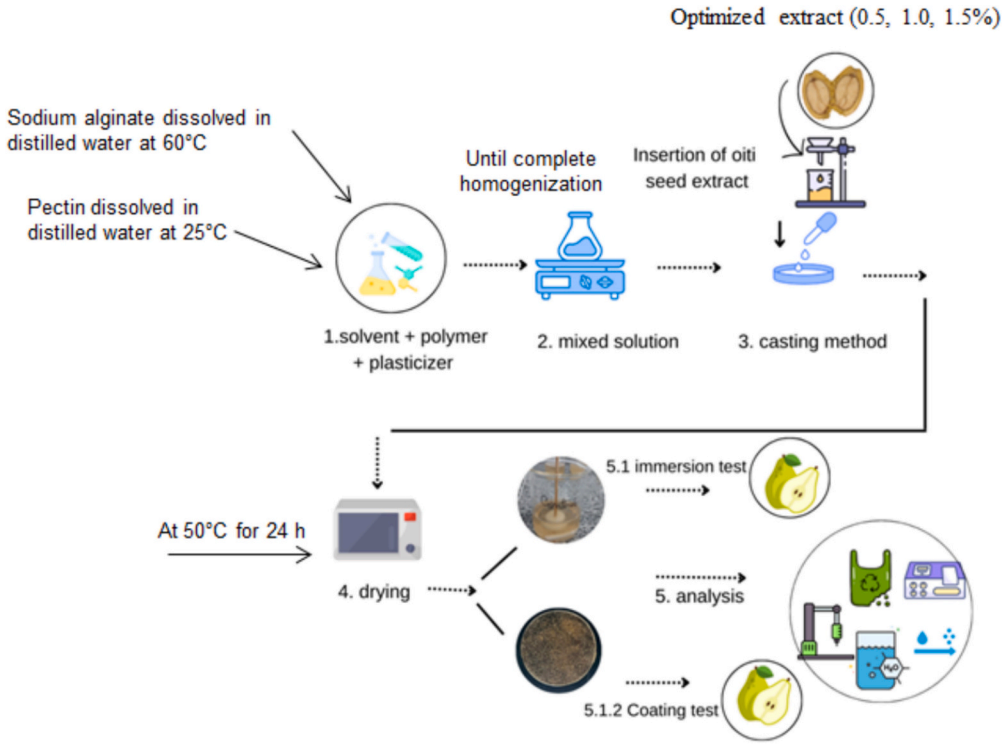

Fig. 1. Representative diagram of optimized films production.

gel. After that, the system was weighed every 24 h for 7 days. The results were expressed in g mm m^{-2} d^{-1} kPa^{-1}

2.6.4. Scanning electron microscopy (SEM)

The microstructure of the film samples was studied using a scanning electron microscope (SEM) (STEM-FEG). The film sample was cut into small pieces (≈ 1 cm^2), and a gold evaporation machine (SPUTTERING; SCD 050) was used to deposit the gold layer on the film samples (Bal-Tec Maschinenbau AG, 2012). The micrographs were recorded with an accelerating voltage of 20 kV and magnifications of ×500 and ×1000.

2.7. Fourier transform infrared spectroscopy (FTIR)

Samples of polymeric film with oiti seed extract were characterized by Fourier transform infrared spectroscopy (FTIR) using a Shimadzu® IR Prestige-21 spectrophotometer with attenuated total reflectance (ATR) attachment, at times 0, 7, 14 and 21. The analysis conditions were: 1000–4000 cm^{-1} region; at room temperature, using 20 accumulations and a resolution of 4 cm^{-1}.

2.8. Analysis of bioactivity in films over 21 days

For oxidative stability analysis, the film samples were kept in desiccators throughout the analysis period under a controlled temperature of 20 °C. The samples of films with oiti extract insertion were subjected to flavonoid, total phenolic, FRAP, and DPPH at times 0, 7, 14 and 21 to verify the capacity of the polymeric system to preserve active compounds over time. For this, 1 g of each sample was weighed and diluted in 50 mL of a 60% ethanol solution every seven days. Then, the samples were subjected to identification procedures for total phenolic and flavonoid compounds, as well as antioxidant potential, using the DPPH and FRAP methods.

2.8.1. Total phenolic and flavonoid content

The determination of total phenolic compounds was performed using the Folin-Ciocalteau reagent, according to the methodology described by Schiassi et al. (2018), with readings being performed on a digital spectrophotometer at an absorbance of 750 nm. Subsequently, 100 μL of the extracts were added to 2500 μL of 10% (*v/v*) Folin-Ciocalteau reagent. After this procedure, an aliquot of 2000 μL of 4% (*w/v*) sodium carbonate was added to the samples. The mixture was then shaken and incubated in the dark for 120 min for subsequent reading on a spectrophotometer. The results were expressed in milligrams of gallic acid equivalent (GAE) per gram (mg GAE g^{-1}). Total flavonoid content was evaluated according to Herald et al. (2012). The absorbance of the solutions was measured at 510 nm. Total flavonoid content was determined from the catechin standard curve with the concentration ranging from 50 to 500 mg L^{-1}. The results were expressed as milligrams of catechin equivalent per 100 g of sample (mg 100 CE g^{-1}).

2.8.2. Antioxidant potential

The ferric reduction assay (FRAP) was determined according to Benzie and Strain (1996), with modifications for use in microplates. The FRAP solution was prepared by adding 2.5 mL of TPTZ solution (10 mmol L^{-1}) diluted with HCl (40 mmol L^{-1}), 2.5 mL of ferric chloride hexahydrate (20 mmol L^{-1}), and 25 mL of sodium acetate buffer solution (pH 3.6). In a tube, 90 μL of the obtained extracts were added, together with 2.70 mL of the FRAP reagent and 270 μL of distilled water. The tubes were kept protected from light at 37 °C for 5 min. The absorbance of the solutions was measured at 593 nm. The reducing power of iron was determined from an ascorbic acid standard curve, and the results were expressed in mg of ascorbic acid equivalent per 100 g of sample (mg AAE 100 g^{-1}). The antioxidant activity was assessed using the DPPH method, as proposed by Brand-Williams et al. (1995). The method consists of a 30 min reaction of the free radical DPPH with the sample. The reaction medium remained at rest, protected from light, at room temperature, for 30 min. The absorbance of the solutions was measured in a digital spectrophotometer reader at a wavelength of 517 nm. The results were calculated based on the radical scavenging capacity and their consumption in the reaction medium and expressed as a percentage of inhibition.

2.9. Biodegradability test

For the biodegradability test, the methodology of Kumnerdsiri et al. (2024) was adopted with modifications. The test specimens, with a surface area of 3 cm^2, were weighed on an analytical balance and placed in plastic containers containing untreated organic soil. The containers were kept in a location isolated from light and at a temperature of 25 ± 5 °C, with the soil maintained at a consistently moist state. The samples buried in the soil inside a container were arranged in the following order: soil layer (25 g), sample, and another soil layer (25 g). The samples were moistened daily with 10 mL of distilled water for 7 days.

2.10. Application in food matrix

To verify the applicability of polymeric films with oiti seed extract insertion, the films were tested over 9 days on samples of minimally processed pears (*Pyrus communis*), using the following parameters: pH, Acidity, and DPPH. To coating test the samples were packaged in polyethylene (PE) bottles, used exclusively as inert containers to hold the fruit during storage. This configuration was designed to simulate the typical conditions of commercial packaging used for minimally processed fruits, in which the plastic containers serve only as structural support, while the covering material provides the main barrier to moisture and gas transfer. To immersion test the samples were dried at 25 °C in a forced-air oven for 24 h before the analysis. All samples were stored in a BOD incubator at a temperature of 10 °C and in the presence of light, simulating conditions similar to those found in refrigerated supermarket displays.

To measure pH and acidity, samples were collected every 3 days. A batch of three samples from test 1 was collected, and these samples were subjected to successive washings to remove the covering. After this procedure, 5 g of the samples were weighed and diluted in 50 mL of distilled water. The pH was then measured, followed by the titratable acidity. The DPPH method was used to verify the antioxidant capacity of the films. For this analysis, approximately 2 g of the sample from the same batch was weighed. Both test's followed the same procedure, except for the washing step, as this step was only necessary for the immersion samples. In both assays, two control groups were established: pears samples with no edible film (Blank); control pears samples with control edible film (basic formulation). The evaluation was performed regarding the visual aspects observed in the samples from both tests. The procedures were adapted from methodologies previously reported by Rodríguez et al. (2020) and Kadirvel et al. (2022).

2.11. Statistical analysis

The results were expressed as mean ± standard deviation. Tukey's test was used to detect differences in means at a significance level of 5% ($p < 0.05$) using Statistica 10.0 software (StatSoft, Inc., Tulsa, OK, USA).

3. Results and discussion

3.1. Total phenolics, antioxidants, and phenolic acid profile of the extract

The high antioxidant activity observed in the seed fraction indicates its potential as a source of bioactive compounds for technological applications. The free radical scavenging capacity ranged from approximately 75.77% to 87.33% (Table S1), which is associated with the presence of phenolic metabolites capable of acting as reducing agents and neutralizing reactive oxygen species (Borges et al., 2022). In this

context, the content of phenolic compounds and flavonoids becomes particularly relevant for the development of active packaging materials, since, when incorporated into natural polymeric matrices such as alginate and pectin, these metabolites can impart antioxidant properties to the films, contributing to the reduction of oxidative processes in foods during storage. This behavior can be partially explained by the profile of phenolic acids identified in the seed fraction (Table S2).

Among the detected compounds, metabolites derived from the phenylpropanoid pathway stand out, such as p-coumaric, caffeic, and gallic acids, which are recognized for their contribution to the antioxidant activity of plant extracts (Golmakani et al., 2025). Caffeic acid (0. 20 mg g^{-1}) exhibits the ability to inhibit lipid peroxidation processes, whereas gallic acid (0.11 mg g^{-1}) presents high reducing capacity and is frequently associated with the antioxidant activity of phenolic rich extracts (Ashokan et al., 2025; Shahid et al., 2025; Silveira et al., 2025). Alongside the previous findings to these compounds, vanillin, ferulic acid, and coumaric acid derivatives were also identified (Table S2). These phenolics, mainly belonging to the hydroxycinnamic acid group, exhibit antioxidant and antimicrobial properties. Beyond that, they can interact with polysaccharide matrices through hydrogen bonding, influencing the microstructure and mechanical behavior of polymeric films (He et al., 2025; Mikus & Galus, 2026) which may contribute to improving the functional properties of alginate and pectin films applied in active food packaging systems.

3.2. Structural determination of the optimal sodium alginate concentration by small-angle X-ray scattering (SAXS)

The SAXS profiles of the film-forming solutions containing alginate and ethanolic oiti seed extract exhibited two distinct scattering regimes across the investigated q-range. In the low-q region (10^{-3} 10^{-2} $Å^{-1}$) (Fig. 2), a pronounced curvature in the scattering intensity was observed, which is characteristic of large-scale electron density fluctuations. This behavior is consistent with that described by the Debye–Bueche model, commonly applied to heterogeneous matrices containing structural domains of different densities. Such a regime is typically associated with systems that are not fully uniform, possibly containing agglomerated regions or domains of larger characteristic length. In the intermediate-*q* region (10^{-2} 10^{-1} $Å^{-1}$) (Fig. 1) the scattering intensity displayed an approximately linear decay in log–log scale, which is compatible with power-law behavior ($I(q) \propto q - \alpha$). This type of response is generally attributed to contributions from internal interfaces and/or fractal structural features, suggesting a more pronounced contrast between different structural regions of the system. An increase in alginate concentration enhanced the intensity within this regime, indicating that more concentrated systems may present more cohesive polymer networks and interfaces with greater structural definition. Additionally, a global increase in scattering intensity was observed as the alginate concentration increased, which is consistent with a higher density of scattering centers in the solution.

In particular, the formulation containing 0.5% (*w/v*) alginate exhibited a more pronounced deviation in the low-q region, where higher intensity and stronger curvature were observed compared to the less concentrated systems. This behavior suggests that increasing the polymer concentration predominantly affects the structural organization at larger length scales, reflected by an extended correlation range and enhanced heterogeneity in the low-q regime. In contrast, the qualitative similarity of the power-law behavior observed for all formulations indicates that the general nature of the interfacial scattering remains comparable, despite differences in intensity and contrast. Although such interpretations should be considered cautiously due to the integral and average nature of SAXS analysis, the qualitative trends observed here support the notion that lower polymer concentrations (Fig. 2) tend to result in less structurally connected networks with less-defined interfaces, whereas higher polymer concentrations (Fig. 2) appear to lead to more organized and potentially more stable colloidal networks.

The results demonstrated how solvent-to-extract ratios and polymer concentrations impact the microstructure of the system. A similar behavior was observed by Nokab-El et al. (2026), where the SAXS analysis applied to alginate hydrogels showed that the hydrogel at a lower concentration (0.75%) presented a higher peak at q (0.10 $Å^{-1}$), while for the 1.4% hydrogel the value was shifted to a lower q (0.04 $Å^{-1}$). Yuguchi et al. (2000) confirmed in their studies that SAXS profiles can change according to different concentrations of molecules. Thus, it is suggested that for better results of active films in terms of structural

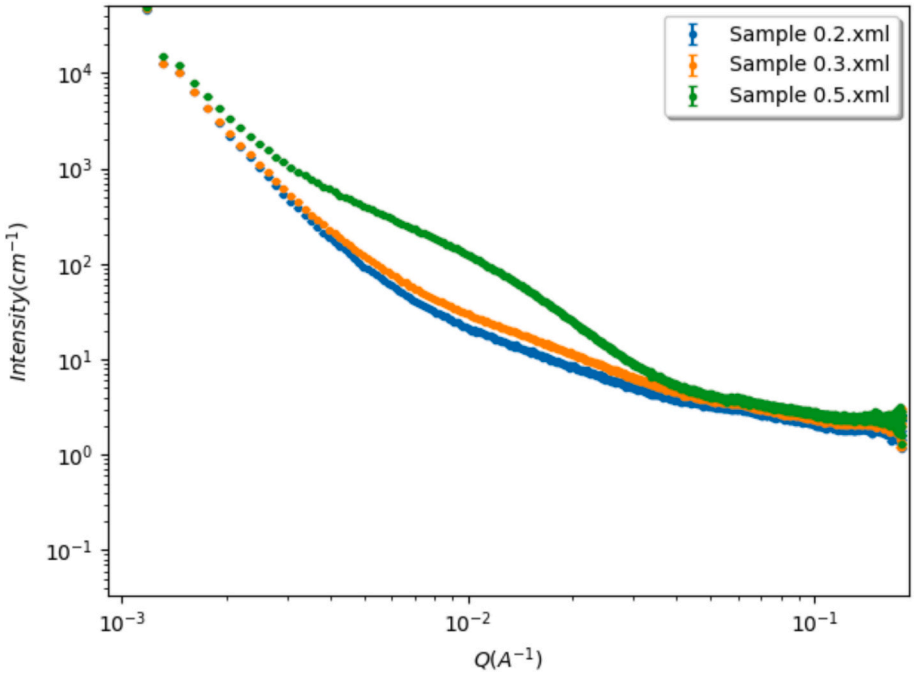

Fig. 2. SAXS graph for film-forming solutions based on sodium alginate at different concentrations. Note: Sample 0.2 (0.2% film-forming solution with 6% extract); Sample 0.3 (0.3% film-forming solution with 6% extract); Sample 0.5 (0.5% film-forming solution with 6% extract).

properties, small concentrations of extracts in systems with a higher proportion of polymers allow greater stability of the system, since unlike nanocapsules, active films need to have more particles of the extracts dispersed in the solution, as they occupy a larger area when applied to a food matrix. Thus, a higher density and better dispersion of the particles containing extracts are essential to ensure uniform coverage and effective release of the active compounds when applied to a food matrix.

3.3. Optimized active films

3.3.1. Thickness, tensile strength, elongation at break, and Young's modulus

In the present study, the incorporation of oiti seed extract at different proportions resulted in a significant increase in film thickness (15–44 μm) (Table 1). This behavior can be attributed to the increase in the total solid content of the film forming solution due to the addition of compounds present in the plant extract, such as phenolic metabolites and other low molecular weight constituents (Esfandiari et al., 2025). Similar effects have been reported in polysaccharide based films containing plant extracts or bioactive compounds, in which the increased concentration of components in the film forming solution directly influences the structural and dimensional characteristics of the resulting films (Nastasi et al., 2025; Kanimozhi et al., 2025).

Regarding the mechanical properties (Table 1), significant differences were observed between the control film and the formulations containing the extract. The control sample presented the lowest tensile strength (~0.40 MPa), whereas the films containing the extract exhibited markedly higher values, with the AP1.0 formulation reaching (~4.35 MPa). This improvement can be attributed to the combined effect of the alginate–pectin matrix and the presence of phenolic compounds derived from the oiti seed extract. Polysaccharides such as alginate and pectin are known to form cohesive networks through intermolecular hydrogen bonding (Pan et al., 2024) however; the incorporation of phenolic compounds may further reinforce this network by acting as multifunctional interaction sites.

Phenolic acids and flavonoids typically contain multiple hydroxyl groups capable of forming hydrogen bonds with the carboxyl and hydroxyl groups present in polysaccharide chains, promoting stronger intermolecular associations and enhanced structural stability (Lai et al., 2025; Li et al., 2025). In this context, the AP1.5 (Table 1) formulation exhibited superior mechanical performance in terms of tensile strength, flexibility, and elongation at break, suggesting that higher extract concentrations intensified these intermolecular interactions and contributed to the formation of a more cohesive and mechanically resistant film structure.

On the other hand, the deformation capacity of the films also increased significantly with the combination of polymers, with the 0.5% group showing the highest value (~32%). The control, on the other hand, presents a lower performance (~19%). This parameter indicates that the supplemented films are more elastic, a desirable characteristic in food packaging. The Young's modulus reflects the rigidity of the material. The data indicate that the rigidity increases considerably in the films with the addition of extract, especially with the 0.5% formulation (~52 MPa), suggesting greater resistance to elastic deformation. The control presents the lowest modulus (~5 MPa), demonstrating that it is a more malleable and less structured material (Table 1).

The mechanical behavior of the films may also be influenced by the phenolic profile of the oiti seed extract. Phenolic compounds such as p-coumaric acid, ferulic acid, caffeic acid, and gallic acid contain hydroxyl groups capable of establishing hydrogen bonds with polysaccharide chains present in alginate and pectin matrices. These intermolecular interactions can promote stronger cohesion within the polymeric network, contributing to improvements in tensile strength and stiffness (He et al., 2025; Mikus & Galus, 2026; Pan et al., 2024).In addition, the aromatic structure of hydroxycinnamic acids may favor secondary interactions with the polymer chains, leading to a more compact and organized matrix (Li et al., 2025).

3.3.2. Water solubility (%) and water vapor permeability (WVP)

Water solubility is a crucial parameter in the evaluation of polymeric films, since it directly influences their packaging functionality (Stoica et al., 2024). Depending on the purpose of the product, different degrees of solubility may be desirable. In applications that require greater structural integrity and protection against moisture, such as minimally processed fruits, films with low solubility are preferable, as they slow degradation and prolong food stability. On the other hand, in products for immediate consumption or with low moisture content, such as baked goods and confectionery, a higher solubility may be beneficial, as it favors biodegradability and the controlled release of active compounds (Sharma et al., 2024). The data obtained (Table 1) indicate that the AP1.5 formulation presented the lowest solubility rate (54.63%). This behavior may be associated with the phenolic profile of the oiti seed extract, which contains phenolic acids capable of interacting with the alginate–pectin matrix (TS1 and TS2). The hydroxyl and carboxyl groups present in these phenolic compounds (FS1) can establish hydrogen bonding interactions with the hydroxyl and carboxylate groups of the polysaccharide chains, promoting a more compact and cohesive polymer network. Such interactions may reduce chain mobility and limit the diffusion of water molecules into the matrix, thereby decreasing film solubility. In contrast, the CAP (62.48%), AP0.5 (60.81%), and AP1.0 (59.74%) samples exhibited higher solubility values, suggesting that lower concentrations of the extract lead to a less interconnected polymer structure, which facilitates water penetration and polymer dissolution. These results indicate that the concentration of phenolic compounds plays an important role in modulating the structural organization and water sensitivity of the films.

Regarding water vapor permeability (WVP), a critical parameter for food preservation, the incorporation of oiti seed extract promoted a significant reduction in this property in the active films (1.93–0.94 g mm m^{-2} d^{-1} kPa^{-1}) compared with the control film (4.32 g mm m^{-2} d^{-1} kPa^{-1}). This reduction may be attributed to the increased incorporation of the extract, which is rich in phenolic compounds and flavonoids (TS1 and TS2).These bioactive compounds can establish hydrogen bonds and other intermolecular interactions with pectin and alginate chains, promoting structural rearrangements within the polymer network and leading to a more compact and cohesive matrix with reduced porosity (Pan et al., 2024; Cazón et al., 2025). Consequently, the diffusion of water molecules through the film structure becomes more restricted, resulting in improved moisture barrier properties. This

Table 1
Mechanical and water vapor barrier properties of alginate-pectin films.

Films	Tk (μm)	TS (Mpa)	EAB (%)	MY (Mpa)	WVP (g·mm·m^{-2}·d^{-1}·kPa^{-1})	SW (%)
CAP	15.0 ± 0.02 ^{d}	0.40 ± 0.19^{d}	19.51 ± 4.51^{d}	4.69 ± 0.73^{d}	4.52 ± 0.8 ^{a}	62. 48 ± 1.36 ^{a}
AP 0.5	29.0 ± 0.5^{c}	4.35 ± 0.95^{a}	32.19 ± 5.62^{a}	52.15 ± 13.33 ^{a}	1.78 ± 0.53^{c}	54.63 ± 2.25^{c}
AP 1	34.0 ± 0.01^{b}	2.65 ± 0.24^{c}	30.33 ± 5.54^{b}	30.36 ± 10.58^{c}	1.93 ± 0.52^{b}	59.74 ± 7.93^{b}
AP1.5	44.0 ± 0.12 ^{a}	3.42 ± 1.78^{b}	21.69 ± 10.0^{c}	48.96 ± 12.32^{b}	0.94 ± 0.58^{d}	46. 48 ± 8.67^{d}

Notes: Tk (thickness), TS (tensile strength); EAB (elongation at break) MY (Young's modulus); WVP (water vapor permeability) and WV (water solubility). Results are expressed as average (number of replicates = 3) ± standard deviation. Results were statistically compared by Tukey-test and the differences were indicated by different letters in the row.

interpretation is further supported by the microstructural analysis, in which the control film exhibited more porous and heterogeneous regions, whereas the films containing 1% and 1.5% extract showed smoother surfaces and more continuous and interconnected internal structures, indicating greater cohesion within the polymer matrix (Fig. 4).

Corroborating the results observed in the present study, Jariyapamornkoon et al. (2026) reported similar findings when evaluating polymeric films based on alginate and pectin incorporated with tannic acid. The authors observed that the addition of this polyphenolic compound significantly improved the barrier properties of the films, as evidenced by the reduction in water vapor permeability (WVP). Films containing tannic acid exhibited significantly lower WVP values (2.7 and 2.6 g mm m^{-2} d^{-1} kPa^{-1}) compared with the control film (3.8 g mm m^{-2} d^{-1} kPa^{-1}). These results suggest that the incorporation of phenolic acids reduces the diffusion of water molecules through the film structure, thereby improving its moisture barrier properties.

3.4. Fourier transform infrared spectroscopy (FTIR)

FTIR is a qualitative spectroscopic approach to identify the interactions that occur in the film during polymer mixing or modification (Kumar et al., 2014). In general, it is noted that the films presented similar chemical structures, as seen in Fig. 3. In the spectra of the control sample (Fig. 3A), it is observed that, over the 21 days, there are small variations in the intensity of bands, especially in the regions of 1000–1200 cm^{-1}, 1600–1700 cm^{-1} and 3200–3600 cm^{-1}. These bands are associated, with C—O and C—C stretching of polysaccharides, vibrations of carbonyls (C═O), and hydroxyl groups (O—H) characteristic of hydrogen bonds (Torlopov et al., 2025). The slight intensification in the 1600–1700 cm^{-1} band over time may be related to the reorientation or partial degradation of the uronic acid bonds of alginate (Torlopov et al., 2025). The 3200–3600 cm^{1} region, in turn, shows relative stability, indicating little change in the hydrogen network in the absence of phenolic extract (Gieroba et al., 2023). On the other hand, in the formulation with 0.5% extract (Fig. 3B), more evident changes are already observed over time, especially in the 1000–1200 cm^{-1} and 3200–3600 cm^{-1} regions. The higher intensity in the region of 3200–3600 cm^{-1} indicates an increase in hydrophilic interactions, possibly due to the presence of phenolic compounds that promote hydrogen bonds with the carboxylic and hydroxyl groups of the polymer matrix (Lei et al., 2019; Li et al., 2024). The band at 1600–1700 cm^{-1} shows slight intensification, which may be associated with the stabilization of the polymer network by interactions between carbonyls and phenols present in the extract, hindering hydrolysis processes.

Fig. 3C, corresponding to the formulation containing 1.0% extract, shows more pronounced changes in the main spectral regions compared to the other samples. In the 1000–1200 cm^{-1} region, an increase in band intensity is observed, suggesting a greater structural reorganization of the polysaccharide chains within the film matrix. Similarly, the band located between 1600 and 1700 cm^{-1}, mainly associated with the stretching vibrations of carbonyl groups, exhibits considerable amplification, which may indicate the incorporation of oxygenated phenolic compounds from the extract and their interaction with the polymeric matrix. Furthermore, the broad band in the 3200–3600 cm^{-1} region becomes more intense and shows a slight shift over time, indicating the strengthening of intermolecular interactions, particularly hydrogen bonding between hydroxyl groups of the phenolic compounds and the pectin and alginate chains (Assis et al., 2017; Lei et al., 2019).

These spectral changes are consistent with the results observed in the cross-sectional microstructure (Fig. 4, C2), in which the sample containing 1% extract exhibited a more homogeneous structure, with clean and continuous edges and no visible internal defects. This behavior suggests the formation of a more cohesive and organized polymeric matrix, likely resulting from the establishment of intermolecular interactions, such as hydrogen bonding and hydrophobic interactions, between the biopolymers and the bioactive compounds present in the extract.

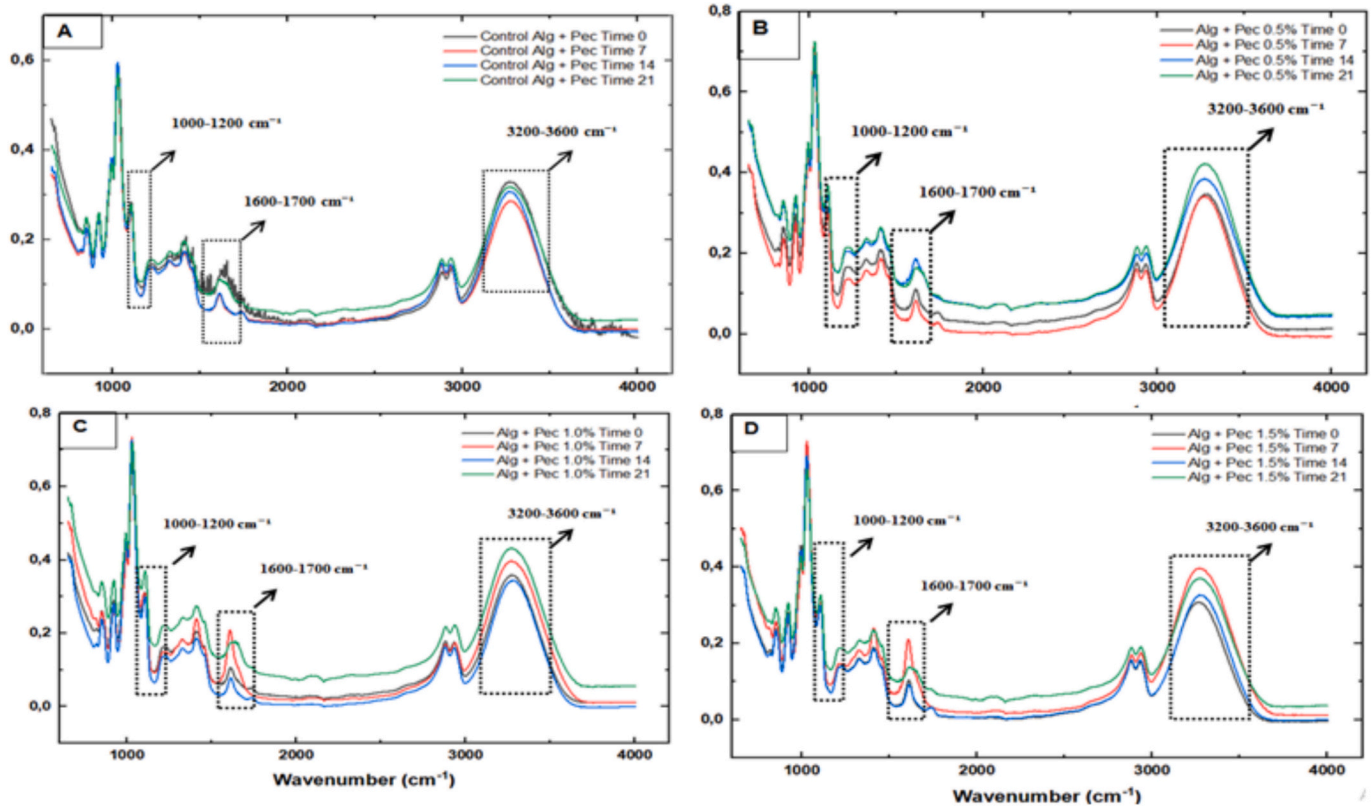

Fig. 3. FTIR spectra of the control samples (A), 0.5% (B), 1% (C), and 1.5% (D) for the storage at time (0, 7, 14, 21).

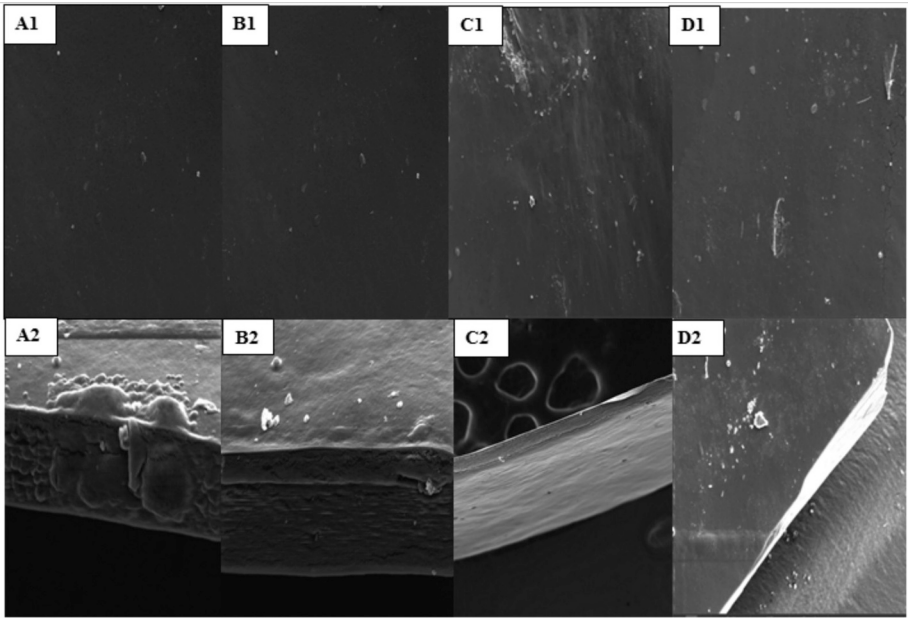

Fig. 4. Scanning electron microscopy of the surface and cross-section of the control film samples (A1 and A2); 0.5% (B1 and B2); 1% (C1 and C2); 1.5% (D1 and D2) (500×).

The spectra of the formulation with the highest extract concentration (1.5%) (Fig. 3D) present the most expressive changes among all samples. The band at 3200–3600 cm^{-1} demonstrates a significant increase in intensity during storage, indicating strong intermolecular interaction and a high density of hydrogen bonds. The bands between 1000 and 1200 cm^{-1} and 1600–1700 cm^{-1} are also noticeably intensified, which may indicate the formation of a more robust three-dimensional network between the functional groups of the phenolic extract and the polysaccharides, with direct effects on the thermal, mechanical and barrier stability of the films (Benbettaïeb et al., 2019).

3.5. Scanning electron microscopy (SEM)

The microstructure of the films is shown in Fig. 4. The control film (Fig. 4A1) exhibited a smooth and uniform surface; however, its internal morphology displayed a highly irregular structure, with evidence of porosity and collapsed regions (Fig. 4A2). This suggests a fragile and disorganized matrix, likely resulting from the absence of phenolic compounds, which can act as intermolecular stabilizing agents within the polymeric matrix (Van Rooyen et al., 2023). Corroborating this observation, the incorporation of oiti seed extract at concentrations starting from 1% resulted in regions with clean and continuous edges and no visible internal defects (Fig. 4C1–C2). This condition indicates the formation of a more cohesive matrix with improved extract distribution, which may be associated with the establishment of intermolecular interactions, such as hydrogen bonding and hydrophobic interactions between the polymers and the bioactive compounds present in the extract (Li et al., 2024).

On the other hand, increasing the extract concentration to 1.5% led to a thicker and more heterogeneous morphology, with the presence of surface deposits or aggregates. The irregular edges and less compact appearance (Fig. 4D1–D2) suggest the occurrence of phase separation or matrix saturation, resulting in structurally weaker regions. This behavior may be attributed to the incompatibility between the excess extract and the capacity of the polymer matrix to disperse it homogeneously (Hoque & Janaswamy, 2024; Shah et al., 2025).

The micrographs of the study further corroborate that the structure of the films depends on the concentration of added extract, a behavior already observed by Lawal et al. (2024). In their studies, the authors observed a relatively smooth surface in the control samples of films prepared without the addition of extract; however, the films with the addition of 2.5% and 3% of Khalas variety extract exhibited a distinct textured surface with noticeable patterns, with characteristics resembling a network or web structure, indicating a significant increase in surface roughness compared to the samples without the addition of extract (Thakur et al., 2022).

3.6. Analysis of bioactive in films over 21 days

The analysis of the antioxidant stability of the active films over 21 days revealed significant differences between the formulations, particularly in terms of the presence of phenolic compounds, flavonoids, and the maintenance of antioxidant activity, as measured by FRAP and DPPH. The control films, free of plant extract, did not present detectable levels of bioactive compounds at any of the times (Table 2), confirming that the polymeric matrix of alginate and pectin, alone, does not confer a significant antioxidant effect, corroborating results described by Jiménez et al. (2024), who observed similar behavior in base films without functional additives. With the addition of oiti seed extract, the data demonstrated marked increases in the evaluated parameters. At time zero, all concentrations tested (0.5%, 1.0%, and 1.5%) presented high levels of total flavonoids and phenolics, with emphasis on the film with 1.0% (6398.01 mg GAE g^{-1} and 464.36 mg 100 CE g^{-1}, respectively). However, the stability of these compounds over time varied between formulations. The rapid degradation observed in the film with 0.5% on the 7th day, when FRAP and DPPH values dropped drastically, shows that lower concentrations were not able to preserve the antioxidant compounds for prolonged periods, as also reported by Lopes et al. (2020) in films with unstable phenolic extracts.

On the other hand, the film with 1.0% demonstrated progressively more efficient retention of antioxidant activity up to the 21st day, especially in the DPPH analysis (with 5.57% inhibition), indicating a moderate capacity for controlled release of active ingredients, a behavior consistent with the sustained release model proposed by Batista et al. (2024) for polysaccharide-based films. The formulation with 1.5%, although it started with a lower content of phenolic compounds (207.60 mg GAE g^{-1}) presented the highest antioxidant activity by FRAP (163.81 mg AAE 100 g^{-1}) and DPPH (73.96% inhibition) at the

Table 2
Phytochemical analyses and antioxidant potential in films developed with the addition of oiti seed extract.

Stability analysis of active films				
Time	CAP Flavonoids	Phenolics	FRAP	DPPH
0	nd.	nd.	8.0 ± 0.02[a]	9.97[a] ± 0.04[a]
7	nd.	nd.	nd.	1.88 ± 0.01[b]
14	nd.	nd.	nd.	nd.
21	nd.	nd.	nd.	nd.
AP 0.5				
0	4670. 52 ± 0.14[a]	399.37 ± 0.18[a]	105.41 ± 0.19[a]	18.73[a] ± 0.03[a]
7	nd.	361.00 ± 0.03[b]	20.45 ± 0.01[b]	2.65 ± 0.02[b]
14	nd.	nd.	nd.	nd.
21	nd.	nd.	nd.	nd.
AP 1.0				
0	6398.01 ± 0.08[a]	464.36 ± 0.59[a]	132.04 ± 0.05[a]	58.69 ± 0.15[a]
7	nd.	219.38 ± 0.04[b]	15.25 ± 0.01[b]	30. 90 ± 0.015[b]
14	nd.	nd.	nd.	22.87 ± 0.03[c]
21	nd.	nd.	nd.	5.57 ± 0.01[d]
AP 1.5				
0	5738.05 ± 0.07[a]	207.60 ± 0.01[a]	163.81 ± 0.14[a]	73.96 ± 0.01[a]
7	nd.	nd.	nd.	68. 91 ± 0.05[b]
14	nd.	nd.	nd.	67.03 ± 0.02[c]
21	nd.	nd.	nd.	18.03 ± 0.06[d]

Equal lowercase letters in the same column do not differ by Tukey's test or *t*-test at a 5% significance level. Flavonoids = mg 100 CE g^{-1}; Phenolics = expressed in mg GAE g^{-1}; FRAP = expressed in mg AAE 100 g^{-1}; DPPH = expressed as % inhibition; CE = catechin equivalent; GAE = gallic acid equivalent; AAE = ascorbic acid equivalent.

initial time, with slower degradation in the first 14 days (still with 67.03% inhibition of the DPPH radical), suggesting that, even with a lower total content of compounds, the antioxidant efficacy may be related to the higher relative concentration of metabolites with high reducing activity.

Based on the aspects observed over 21 days, the results indicate that the capacity of the polymeric network formed by pectin and alginate to stabilize the bioactive compounds of the oiti seed extract is limited and depends on specific chemical interactions. This effect may be associated with a structural limit for the retention of bioactive compounds, leading to a saturation process of the polymeric matrix after a specific period. This hypothesis is supported by studies by Delgado-Ospina et al. (2021), which emphasize that the bioactivity of plant extracts depends not only on the quantity but also on the specific chemical composition of their constituents, such as flavones, tannins, and phenolic acids. Moreover, the significant degradation of antioxidants between the 14th and 21st day, observed in all formulations, may be associated with oxidation reactions and the photosensitivity of phenolic compounds, as discussed by Pereira et al. (2022). In summary, the data indicate that the extract concentration influences not only the initial antioxidant activity, but also the functional stability of the films over time, with the formulation with 1.5% being the one that presented the best sustained antioxidant performance up to the 14th day and significant residual performance on the 21st day, which suggests its greater potential for applications in active packaging with prolonged bioactive properties.

3.7. Biodegradability test

As observed in Table 3, the macroscopic evaluation of the structural integrity of the films over seven days revealed notable differences between the formulations, particularly in terms of resistance to degradation in a humid environment. The control sample, free of oiti seed extract, maintained greater structural cohesion, demonstrating a lower apparent degradation rate compared to the samples containing plant extract. The films incorporated with 0.5%, 1.0%, and 1.5% of extract showed evident signs of degradation, characterized by rupture, fragmentation, and loss of the continuous structure, suggesting that the addition of the extract contributed to the increase in the biodegradability of the polymer matrix. This effect may be associated with the presence of water-soluble phenolic compounds, which, when released in the presence of moisture, result in the weakening of the polymer network (Cazón et al., 2025).

Furthermore, the periodic addition of water simulates conditions of high environmental humidity, favoring the partial solubilization of the film constituents and accelerating matrix hydrolysis processes, a typical phenomenon in materials composed of natural polysaccharides, such as alginate and pectin. This behavior is widely described in the literature, with polysaccharides being susceptible to enzymatic or non-enzymatic degradation in humid environments, through hydrolysis mechanisms and subsequent oxidation of the glycosidic chains (Van Rooyen et al., 2024). Notably, the films with 1.5% extract, although presenting greater antioxidant resistance at time zero, demonstrated a greater degree of structural disintegration, which may indicate an inverse relationship between mechanical stability and the concentration of soluble bioactive compounds. The observed visual deterioration, therefore, not only highlights the biodegradability of the formulations enriched with plant extract but also reinforces their potential for use in biodegradable and environmentally safe packaging, especially in systems where accelerated decomposition is desirable after use.

3.8. Application in food matrix and subjective test

At the initial time (day 0), the pH values of the samples ranged from 4.55 to 5.40 (Fig. 5), with no statistically significant difference ($p < 0.05$) between the untreated sample and the film control, with the highest value recorded for the untreated sample (5.40). However, after nine days of storage (time 9), a slight overall reduction in pH was observed, with values ranging from 4.41 to 5.14 (Fig. 5A), especially in the samples subjected to immersion and coating treatments. This decrease may be associated with natural acidification processes resulting from the degradation of organic compounds present in both the fruit matrix and the film material (Postružnik et al., 2024). Notably, some formulations, such as 1.0% and 1.5%, showed greater stability in pH and acidity parameters (Fig. 5A and B), which suggests that the presence of bioactive extracts in the films may have exerted a protective effect, reducing microbial metabolic activity and, consequently, delaying acid formation (Bertolo et al., 2023).

On the other hand, the untreated control sample exhibited the most significant pH variation over the evaluated period, decreasing from 5.40 to 4.41 (Fig. 5A), which indicates a greater susceptibility to microbial and oxidative degradation, as well as a more pronounced acidification of the system. This behavior confirms the importance of treatments with bioactive coatings in maintaining the physical and chemical stability of foods during storage. Similar studies corroborate these findings, such as that of Rodríguez et al. (2020), who found that the use of papaya and pectin-based films enriched with moringa extract was efficient in preserving the pH of pears during nine days of storage. In this study, the untreated sample showed a sharp drop in pH from the sixth day onwards, differing significantly from the other formulations with extracts, which reinforces the role of bioactive compounds in attenuating degradation processes.

The reduction in the percentage of DPPH was observed in all samples over the nine days of storage, evidencing the progressive degradation of the antioxidant capacity. However, the 1.5% sample showed the lowest relative loss (56.82% inhibition), in contrast to the untreated sample, which showed a reduction of 69.94% (Fig. 5C), demonstrating that the coating treatment contributed significantly to the preservation of the antioxidant activity, possibly by limiting the exposure of the bioactive compounds to light, oxygen and environmental variations. In contrast, some formulations showed more pronounced decreases, such as at 0.5%

Table 3
Visual characteristics observed in samples of pears treated by coating and immersion over 9 days and biodegradability over 7 days.

Untreated	Hyphae	Odor	Appearance	Firmness	Color Day 1	Color Day 9	BD Day 1	BD Day 7
Untreated	–	Satisfactory	Unsatisfactory	Unsatisfactory			—	—
Control IM	+	Unsatisfactory	Unsatisfactory	Unsatisfactory			—	—
Control CO	+	Satisfactory	Average	Satisfactory				
0.5IM	+	Unsatisfactory	Unsatisfactory	Unsatisfactory			—	—
0.5CO	–	Satisfactory	Satisfactory	Satisfactory				
1.0IM	–	Satisfactory	Unsatisfactory	Unsatisfactory			—	—
1.0CO	–	Satisfactory	Satisfactory	Satisfactory				
1.5IM	–	Satisfactory	Unsatisfactory	Unsatisfactory			—	—
1.5CO	–	Satisfactory	Satisfactory	Satisfactory				

Note: +: presence; −: absence. **BD** (Biodegradability). **IM** (Immersion test); **CO** (Test by coating).

(93.61% inhibition) and 1.0% (92.49% inhibition), suggesting instability of the antioxidant compounds against extrinsic factors, such as oxidation and photodegradation (Sani et al., 2025). Similar results were obtained by Kadirvel et al. (2022), who reported a 52.27% reduction in antioxidant activity in tomatoes coated with films containing *Carica papaya* and *Annona squamosa* seed extracts over 14 days, reinforcing the hypothesis that formulations with higher extract content and application by coating are more efficient in preserving bioactive compounds.

Visual observations conducted over nine days (Table 3) revealed significant differences between the immersion and coating treatments. Hyphal formation was visually observed in the control samples (coated control and immersed control), as well as in the sample immersed at 0.5% during storage, suggesting greater susceptibility to microbial deterioration under these conditions. In contrast, the samples subjected to coating treatment maintained better visual quality, exhibiting a lighter color and firmer structure over time. However, it is important to emphasize that these observations are based on qualitative visual assessment, complementary microbiological analyses would be necessary to confirm the antimicrobial efficacy of the films and better evaluate their role in extending the product's shelf life. In contrast the samples treated by immersion showed more pronounced darkening from the third day onwards, compromising visual acceptability (Table 3). This behavior reinforces the hypothesis that the application method directly interferes with the physical-chemical and sensory stability of the coated fruits.

The more evident darkening observed in the samples treated by immersion (Table 3) can be explained by the fact that the immersion process exposes the fruit tissue to a high-humidity environment without a persistent protective barrier, which facilitates oxygen diffusion and intensifies oxidative reactions involving endogenous phenolic compounds naturally present in the pear matrix (Moon et al., 2020). In contrast, the application of the alginate-pectin based coating without direct contact with the fruit forms a continuous layer on the fruit surface, limiting oxygen transfer, which influences different parameters, including coloration. The incorporation of oiti seed extract may have further contributed to color preservation, providing antioxidant capacity and reinforcing intermolecular interactions within the polymeric matrix, improving its barrier performance (Sani et al., 2025).

4. Conclusion

This study evaluated the influence of alginate concentration, alginate–pectin blending, and the incorporation of oiti seed extract on the structural organization and functional performance of biopolymer films. Small-Angle X-ray Scattering (SAXS) provided valuable insights into the internal organization of the polymer network, demonstrating that optimized polymer ratios improved cohesion and structural stability. The phenolic profile of the oiti extract, rich in antioxidant compounds, played a key role in modulating the physicochemical properties of the films. Formulations containing 1–1.5% extract exhibited superior barrier properties, mechanical strength, and greater stability of antioxidant compounds during storage. When applied to minimally processed pears,

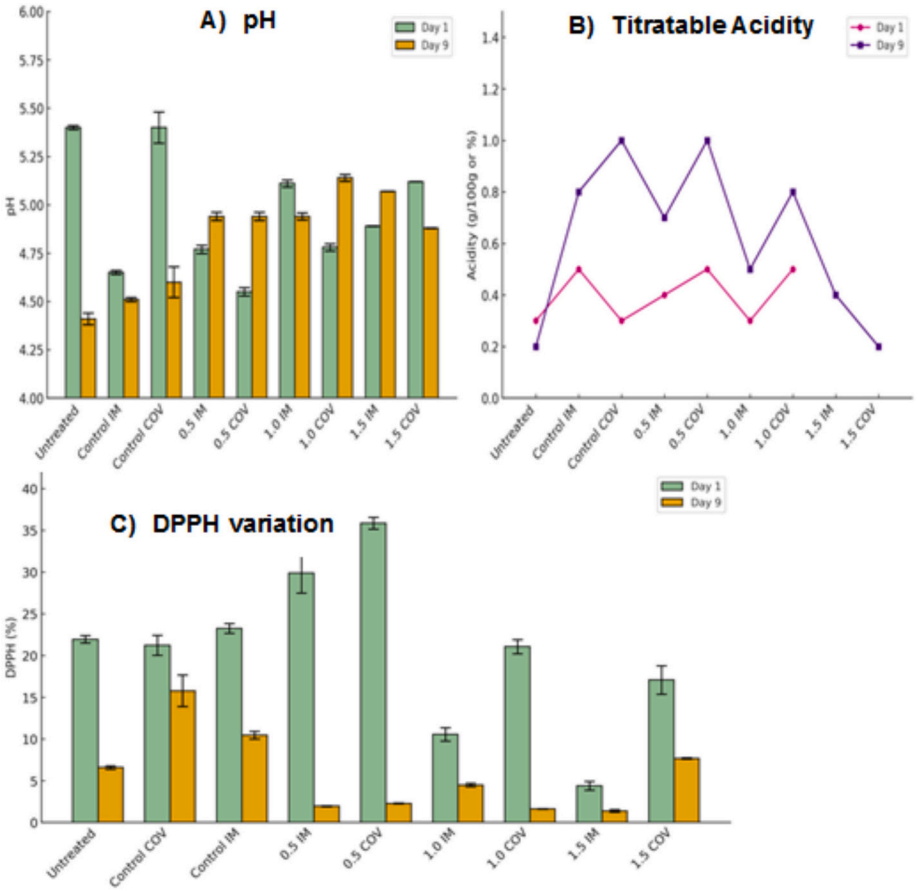

Fig. 5. (A) Analysis of pH of pears immersed and covered with films; (B) acidity of pears immersed and covered with films; (C) analysis of antioxidant capacity by the DPPH method in samples of pears immersed and coated with polymer films added with oiti seed extract.

immersion treatments were not suitable; however, coatings containing 1% and 1.5% extract effectively preserved antioxidant compounds and reduced enzymatic browning. In addition, all films showed rapid biodegradation within seven days, highlighting their potential as sustainable packaging materials.

These results demonstrate that the incorporation of oiti seed extract significantly influences the structural organization and functional performance of alginate-based films. Nevertheless, further studies are required to improve film stability in aqueous environments, evaluate antimicrobial activity, and develop scalable processing strategies to support industrial application.

CRediT authorship contribution statement

Luana Regina Pereira Alves: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rômulo Alves Morais:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation. **Hermanny Matos Silva Sousa:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Paulo Eduardo Peres de Sá Peixoto Júnior:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation. **Glêndara Aparecida de Souza Martins:** Writing – review & editing, Visualization, Validation, Supervision, Software, Data curation.

Consent for publication

All authors have given their consent for publication.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2026.148938.

Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author upon reasonable request.

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