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ORIGINAL RESEARCH

Production of Na-Alginate based biodegradable active films using bio-waste for cherry tomato packaging applications

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Abstract The development of sustainable food packaging is one of the most promising approaches to reducing the negative impact of petroleum-based plastics on the environment and health. This study aimed to develop alginate-based active films incorporating banana, pomegranate, and citrus peels, to characterize their properties, and to assess their potential for food packaging applications. For the first time, these fruit peels were systematically compared within the same study, providing unique insights into their relative performance in film formation. In addition, citric acid (CA), a non-toxic cross-linker, was used instead of conventional salts, increasing both safety and sustainability. To benefit from their inherent antioxidant properties, the peels were incorporated directly into the film formulations. Sodium alginate (Na-Alg), a biocompatible polymer, served as the film matrix. The four synthesized films were evaluated in terms of crystallinity, thermal stability, chemical composition, physical properties, and applicability in tomato packaging. Notably, the addition of fruit peels not only enhanced the antioxidant activity of the films but also reduced their water vapor transmission rate (WVTR), effectively minimizing weight loss in the coated tomatoes. Overall, this work demonstrates the potential of incorporating fruit peels to transform food waste into value-added, eco-friendly packaging materials, thereby extending food shelf life and reducing environmental impact.

Keywords Na-Alg films · Fruit peel waste · Active packaging · Citric acid cross-linking · Shelf-life extension

Introduction

Active packaging is defined as an innovative approach that goes beyond the basic protective and preservative functions of traditional packaging systems, providing enhanced performance (Bastarrachea et al. 2015). It can function by releasing active substances into the surrounding atmosphere or by absorbing components that can degrade the quality of food, such as oxygen, moisture, and free radicals. The shelf life of foods is extended by these active compounds, which incorporate antioxidant and antibacterial properties into the film. This offers a promising solution to food waste caused by spoilage.

Plastics are often preferred as food packaging materials, but they lead to serious environmental pollution problems and raise concerns about the use of plastic packaging (Asdagh et al. 2021). There is growing interest in biodegradable, safe packaging materials as alternatives to plastic packaging. Polysaccharides, proteins, and lipids are often preferred

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in the production of biodegradable packaging materials (Sani et al. 2022). These packages can extend the shelf life of food products and improve their quality by acting as selective barriers to moisture transfer, oxygen uptake, and volatile flavor compounds (Nur Hanani et al. 2019).

Due to their low cost and abundance, wastes from crops would be considered the best source for biopolymer production (Soofi et al. 2021). Crop processing waste can be used as a source of antioxidants and antimicrobials, reducing the need for synthetic preservatives (Bastarrachea et al. 2015). In previous studies, active films were successfully obtained from lemon waste (Soofi et al. 2021), apple skin peels (Du et al. 2011), avocado peels and seeds (Merino et al. 2021), pomegranate peels (Rathinavel et al. 2024), orange peels (Cotrim et al. 2024), rice husk (Srivastava et al. 2023, 2024), and sugarcane bagasse (Srivastava et al. 2025).

Citrus peel, banana peel, and pomegranate peel are significant sources of antioxidants among fruit waste due to their high content of bioactive compounds such as anthocyanins, flavonoids, and terpenoids (Sulaiman et al. 2011; Boukroufa et al. 2017; Kaderides et al. 2020). Additionally, these peels contain compounds such as lignin, cellulose, and hemicellulose, which must be converted into more valuable products.

Alginate is an anionic and hydrophilic polysaccharide derived from brown algae and can be safely used in food and biomedical applications. This biocompatible, biodegradable and non-toxic polymer can readily cross-link with metal ions (Dudeja et al. 2023; Das et al. 2019). Panahi and Mohsenzadeh (2022) evaluated how Na-Alg coating affected the microbiological, chemical, and sensory aspects of cold chicken breast flesh enriched with *Ferulago angulata* essential oil. The antioxidant properties of FAEO, when combined with the Na-Alg coating, significantly improved the shelf life of chicken flesh and delayed deterioration. Another research reported that alginate-based edible coatings enhanced with Myrtle and Rosemary extracts containing antioxidant components increased beef meat's free radical scavenging capacity over a 12-day storage period at 2 °C, consequently increasing its shelf life (Smeti et al. 2025). Citric acid (CA), which is abundant in citrus fruits, is widely used in the food industry due to its low cost and food-derived nature and allows cross-linking reactions with biopolymers containing –OH groups. Although traditional methods use chemicals such as glutaraldehyde or boric acid, their toxic effects limit their use in food applications. Therefore, CA is preferred as a low-cost, non-toxic, and natural cross-linker that can stabilize polysaccharide structures (Sharmin et al. 2021). Bucak (2023) formed cross-linked spheres by adding the Na-Alg polymer dropwise to the CA solution, unlike traditional methods. In this study, thin-film synthesis was carried out by immersing Na-Alg in a CA solution. As reported in the literature, thin film synthesis was carried out by dipping Na-alginate solution into CA solution (Senturk Parreidt et al. 2018; Hilbig et al. 2020; Zhou et al. 2022).

In the literature, there are no studies on the production of films that can be used as active packaging, cross-linked with citric acid using Na-Alg, and enriched with antioxidants from fruit peels. In this study, pomegranate peels, banana peels, and citrus peels were preferred for biodegradable packaging film synthesis in order to obtain polysaccharides and protective phenolic compounds cheaply and easily. Thus, it is aimed to evaluate the peels that pose a serious problem for the environment. The thin films were formed by blending pomegranate peels, banana peels, and citrus peels with alginate polymer, and the films were cross-linked with CA. And then, the synthesized films were evaluated using different methods for composition (FTIR), thermal profile (DSC, TGA), crystallinity (XRD), and physical properties (swelling, WVTR, moisture content, etc.). Finally, the films were tested for their suitability as packaging material for cherry tomatoes, evaluating their protective performance in a real food system.

Experimental

Materials

Na-Alg was supplied from Carl Roth (Art.-Nr. 9180.2, Molar mass (M) 300,000–350000 g/mol). Tween 80 (CAS-No. 9005–65–6), 2,2-diphenyl-1-picrylhydrazyl (Lot 0000132450), and Gallic acid (CAS-No. 149–91–7) were used from Merck. Citric Acid Anhydrous (CAS-No. 77–92–9) and Glycerol (CAS-No. 56–81–5) were purchased from Tekkim. Deionized water (Millipore) was used in all experiments. All fruits were sourced at their natural harvest time.

Fully ripe bananas and pomegranates were specifically selected to ensure consistency in peel composition. Washington navel oranges (*Citrus sinensis* cv. Washington Navel) were used for the 'citrus' samples.

Synthesis of films

The peels were first washed with plenty of water and cut into thin slices. They were left to dry in a laboratory for 2 days. Then, the peels were dried in an oven at 40 °C for 4 days. Oven-dried peels were ground into powder using a coffee grinder with sharp stainless-steel blades before analysis. The powdered samples were sieved through a 0.5 mm diameter sieve and kept at −20 °C for thin-film synthesis. The thin-films were developed using the solution casting method with some modifications (Terzioğlu et al. 2021). For the alginate film (AF), 0.5 g of alginate, 150 µL of Tween 80, and 150 µL of glycerol were dissolved in 25 mL of water by stirring overnight. For alginate-based peel films, 0.5 g of alginate, 0.5 g of peel, 150 µL of Tween 80, and 150 µL of glycerol were dissolved in 25 mL of water by stirring overnight. The mixed film solutions were centrifuged at 4000 rpm for 30 min to remove air bubbles and undissolved particles. Film pre-solutions with a total volume of 25 mL were poured into petri dishes and dried at 40 °C for approximately 48 h. The film pre-solutions were prepared and examined by immersing them in different cross-linker solutions ($FeCl_3$, $AlCl_3$). Data are not shown due to low mechanical properties, instability, and very hard, especially discoloration of the pomegranate peeled ones. CA was selected as the best cross-linker for film pre-solutions. The films separated from the petri dish were kept in 10% (w/w) CA solution for 30 min in accordance with the recommendations of Bucak 2023. Then, they were kept in distilled water for 30 min to remove excess CA and impurities. The film made from banana peel was named ABF, the film made from pomegranate peel was named APF, and the film made from orange peel was named ACF.

Characterization technique of films

Fourier Transform Infrared (FTIR) spectra of AF, ABF, ACF, and APF were recorded on a Shimadzu Spectrometer in the range between 400 and 4000 cm^{-1} with Attenuated Total Reflectance (ATR).

Differential scanning calorimetry (DSC) was carried out for AF, ABF, ACF, and APF using DSC 60 (METTLER TOLEDO/TGA 1 STARE System) at a heating rate of 10 °C min^{-1} and temperature interval between 25 and 400 °C in dynamic nitrogen atmosphere.

Thermogravimetric analysis (TGA) was carried out for AF, ABF, ACF, and APF with a Thermogravimetric Analyzer (METTLER TOLEDO/DSC 1 STARE System) at a heating rate of 10 °C/min in a dynamic nitrogen atmosphere and temperature interval between 25 and 700 °C.

The crystal structures of AF, ABF, ACF, and APF were determined using X-ray Diffraction Diffractometer (XRD) (Rigaku Smart Lab) with CuKα (1.54 Å) radiation, scan step size of 0.05°, scan speed of 1°min^{-1}, and 2θ range of from 10 to 45°.

Both the hardness (*H*) and Young's modulus (*E*) of the films were measured using a Hysitron TI 950 TriboIndenter nanoindenter equipped with a Berkovich tip. Tests were performed according to the Oliver-Pharr analysis method using a 4 x 4 analysis matrix under 500 µN peak load and presented as mean value (Oliver and Pharr 1992).

Film mass, thickness, and moisture content

Alginate-peel thin films were weighed in triplicate with an electronic balance and recorded. Film thicknesses were measured from random positions of each film with the aid of a digital micrometre. The moisture content of the films was determined using the oven-drying method, by drying the samples at 105 °C ± 2 °C for 24 h to a constant weight, in accordance with the procedure described by Giteru et al. (2015).

Water vapor transmission rate (WVTR)

The water vapor permeability of AF, ABF, ACF, and APF films was measured with the modified gravimetric cup method at 25 °C in 43–45% relative humidity (Dhumal et al. 2019). The films were selected on the basis of the absence of bubbles or holes. The film samples were conditioned for 48 h at 45% relative humidity and 25 ± 1 °C to stabilize the moisture content before the measurement. This environment was created using a saturated potassium carbonate solution; the film samples were

stored in an airtight desiccator containing this solution. As the saturated solution was known to have a relative humidity of around 45% (Greenspan 1977), the relative humidity of the environment was checked regularly during the conditioning process using a digital hygrometer, and the temperature was checked using a precision thermometer. 20 mL of deionized water was put into a glass tube with a capacity of 25 mL. Film samples cut with a diameter of 15 mm were fixed at the mouth of the tube. The change in the weights of the tubes was noted at 1-h intervals for 8 h. To calculate the WVTR of the films, first g/h was determined from the slope of the time-weighted gain graph. The WVTR was then calculated using the following formula by dividing this value by the cross-sectional area (m^2) of the film. This process was repeated 3 times, and WVTR was given as an average.

$$WVTR = \frac{\Delta m}{A \times t} \quad (1)$$

where the Δm is the mass of water vapor transmitted (g), A is the area of the sample (m^2), and t is the time duration (h).

Swelling values

Swelling values of AF, ABF, ACF, and APF samples in pH2, pH10, and distilled water at room temperature were determined gravimetrically following the method described by Li et al. (2024) with slight modifications. Film samples, which were kept in solvent for 24 h, were separated from the solvent, and excess was removed using absorbent paper. The weights of the swollen thin films were recorded, and the % swelling values were calculated using the equation.

$$Swelling\% = \frac{w_1 - w_o}{w_o} \quad (2)$$

w_o and w_1 are the weights of the films at dry and swelling states, respectively.

Antioxidant activity assessment of peels and peels containing alginate films.

Antioxidant activity of ABF, ACF, and APF films and peels was measured by the Folin-Ciocalteu method and DPPH experiments.

Folin-Ciocalteu method

The Folin–Ciocalteu method was carried out with modifications based on the procedure described by Zhao et al. (2022a). From the peel samples (banana, citrus, and pomegranate), 1.25 g was weighed, and 25 mL of methanol was added. Maceration was done by mixing in the mechanical mixer for 24 h, and the extraction of the active substances was ensured. At the end of the period, the mixtures were filtered, and the filtrates were stored at −20 °C until the time of analysis. A stock solution of 10 mg/mL was prepared by dissolving 1 g of gallic acid in 100 mL of methanol. Solutions with concentrations of 1—0.03125 mg/mL were prepared from this stock solution, respectively. 40 µl of these solutions were taken, and 2400 µl of distilled water, 200 µl of undiluted Folin reagent, and 600 µl of 20% sodium carbonate were added, and the tubes were mixed by hand. After incubation for 2 h at room temperature and in the dark, the absorbance of the reaction mixture was measured at 765 nm using a UV–Vis spectrophotometer (JASCO V-730) against a blank solution (methanol). The standard linear regression equation for the absorbance concentration of gallic acid was $y = 1.193x - 0.0369$.

The total phenolic content (TPC) was calculated according to the Folin-Ciocalteu method by using the methanol extracts of the peels with the same method. Film samples cut in a 3×3 cm^2 area were shaken in 100 mL of methanol at 25 °C for 120 min. The TPC of the methanol phase was determined by the Folin-Ciocalteu method. All results are expressed as mg gallic acid equivalent (GAE)/g film.

DPPH (2,20-diphenyl-1-picrylhydrazyl) radical scavenging assay

The method of Carli et al. (2022) was used to explain the DPPH radical scavenging activity of films and peels. In the DPPH method, the methanol extracts extracted for the Folin-Ciocalteu method were used. 100 µl was taken from the extracts, and 1.9 mL of DPPH solution (6.10^{-5} M) was added to it. The solution was kept in the dark for 30 min, and absorbances were measured using a UV–Vis spectrophotometer at 517 nm against a blank solution (methanol). The films, cut into small pieces, were weighed at 10 mg and placed in test tubes. 1.9 mL

of DPPH solution was added to it and left in the dark for 30 min. Measured at 517 nm and calculated using Eq.

$$Inhibition\% = \frac{A_{control} - A_{sample}}{A_{control}} * 100 \quad (3)$$

where the absorbance of the DPPH solution is expressed as $A_{control,}$ and the absorbance of the film solution is expressed as A_{sample}.

Application of hydrogel films for fresh cherry tomato preservation

Investigation of the usability of peel-based thin films for the packaging of cherry tomatoes was carried out by modifying the previously reported method (Zhao et al. 2022b). Cherry tomatoes purchased from the local market were washed several times to remove impurities and dried in the laboratory before the experiment. The fruits were divided into six groups and packed with no film, polyethylene film, AF, ABF, ACF, and APF films. The packaging experiments were carried out in a laboratory environment at a temperature of 21–24 °C. The cherry tomatoes were documented by photographs during storage. Cherry tomatoes preserved in a bag made of Low-Density Polyethylene (LDPE) material used for food storage were used as a positive control sample, while uncoated tomatoes were used as a control group. The weight loss of the cherry tomatoes was determined on the 5th and 10th day of storage using an electronic balance (RADWAG AS 220.R2 Plus, Poland) and calculated using the following formula.

$$Weight\ loss(\%) = \frac{(W1 - W2)}{W1} \times 100 \quad (4)$$

where W1 is the initial weight of the tomato, and W2 is the final weight.

Data analysis

Film mass, thickness, moisture content, and weight loss were analyzed using SPSS according to analysis of variance (ANOVA). Means were compared using Duncan's multiple range test.

Results and discussion

Physical properties of peel-based films

The thicknesses of AF, ABF, ACF, and APF films were measured by digital micrometre and presented in Table 1. The thinnest film thickness was AF film with 116.7 µm. Thickness increased in ABF, ACF, and APF films. This could be explained by the increase in solid content with the addition of crust to the film pre-solution and the surface roughness of the films. AF film was white. With the addition of the peel, the banana film was dark brown, the citrus film was light yellow, and the pomegranate film was dark yellow. Although film mass and thickness were significantly ($p < 0.01$) affected by film types according to ANOVA, moisture content was not. The highest film mass was obtained from ACF, with the value of 851.6 mg, followed by APF, in the same statistical group, with the value of 843.1 mg. For thickness, the minimum values were observed in AF and ACF, which were in the same statistical group, with the values of 116.7 and 120.0 µm, respectively.

Swelling property of films

The swelling capacity of the film is an important indicator of its water resistance, suitability for food packaging applications, and potential for biodegradability.

Table 1 Physical properties of AF, ABF, ACF, and APF films

The values were presented as mean ± standard error of the mean. Letters showed different groups in their own column

Film type	Film mass (mg)	Thicknesses (µm)	Moisture content (%)
AF	718.9 ± 3.9^{b}	116.7 ± 4.7^{b}	31.75 ± 2.60
ABF	730.7 ± 9.8^{b}	233.3 ± 9.4^{a}	34.75 ± 3.72
ACF	851.6 ± 18.2^{a}	120.0 ± 8.2^{b}	22.15 ± 2.30
APF	843.1 ± 16.8^{a}	223.3 ± 4.7^{a}	29.69 ± 1.38
p	0.001	0.001	0.210

A packaging material with a higher swelling index may be advantageous for absorbing excess surface moisture from high-humidity food products, helping to maintain product quality and extend shelf life. Therefore, the maximum swelling percentages of the peel-based thin films were calculated gravimetrically in acidic, basic, and neutral (water) conditions, and the results are presented in Fig. 1. When the swelling ratios in water were examined, it was seen that the addition of citrus or pomegranate to the thin films did not significantly change the swelling percentage. Na-Alg is a hydrophilic polymer that can absorb large amounts of water molecules. From the swelling experiments, it was observed that the swelling behaviour of the thin films was highly pH dependent. In acidic conditions, the carboxyl group (–COO–) in the structure of Na-Alg is converted into carboxylic acid form (–COOH), and the polymer structure becomes uncharged, thus reducing the swelling value. Under basic conditions, the carboxyl groups are ionized (–COO–), and the free volume between polymer chains increases due to electrostatic repulsion, thereby increasing the equilibrium swelling of the hydrogels (Akalın 2023). Moreover, the results showed that APF films had the highest degree of swelling at three pH levels. This swelling behaviour could be explained by the presence of many phenolic –OH groups in pomegranate peel. The total phenolic amounts presented in Table 4 also supported this result. The results were found to be consistent with the literature (Zhu et al. 2024; Li et al. 2024).

ATR-FTIR

To understand the nature of interactions of alginate peel-based thin films, FTIR spectra of AF, ABF, APF, and ACF samples are taken. FTIR spectra of thin films were shown in Fig. 2. Strong absorptions at 3433 cm^{-1} were due to the alcoholic O–H bond of alginate, and phenolic O–H bond of flavonoids. These findings were found to be consistent with those reported by Yoon et al. (2024). The wide bands were related to the formation of intermolecular and intramolecular hydrogen bonds. 2924 cm^{-1} represented the aliphatic C–H stretch. The band at 1721 cm^{-1} in the films represented the C=O stretching vibration of

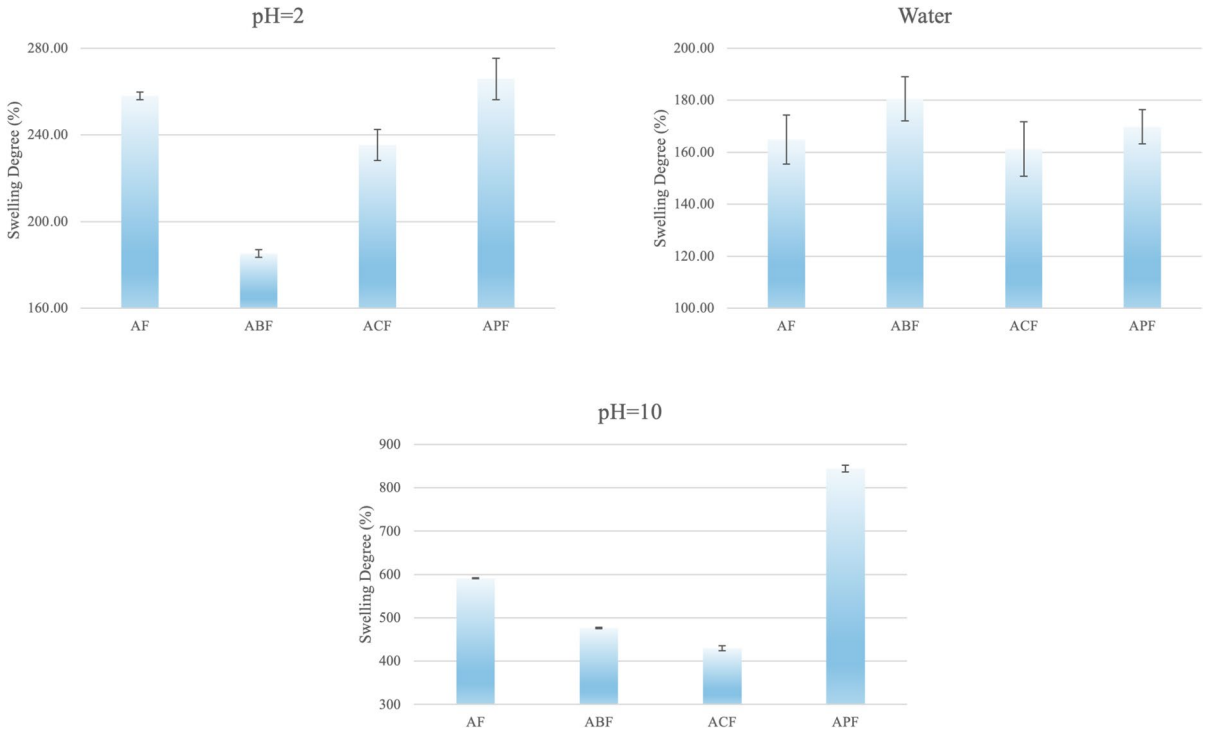


Fig. 1 Swelling degree of AF, ABF, ACF, and APF films

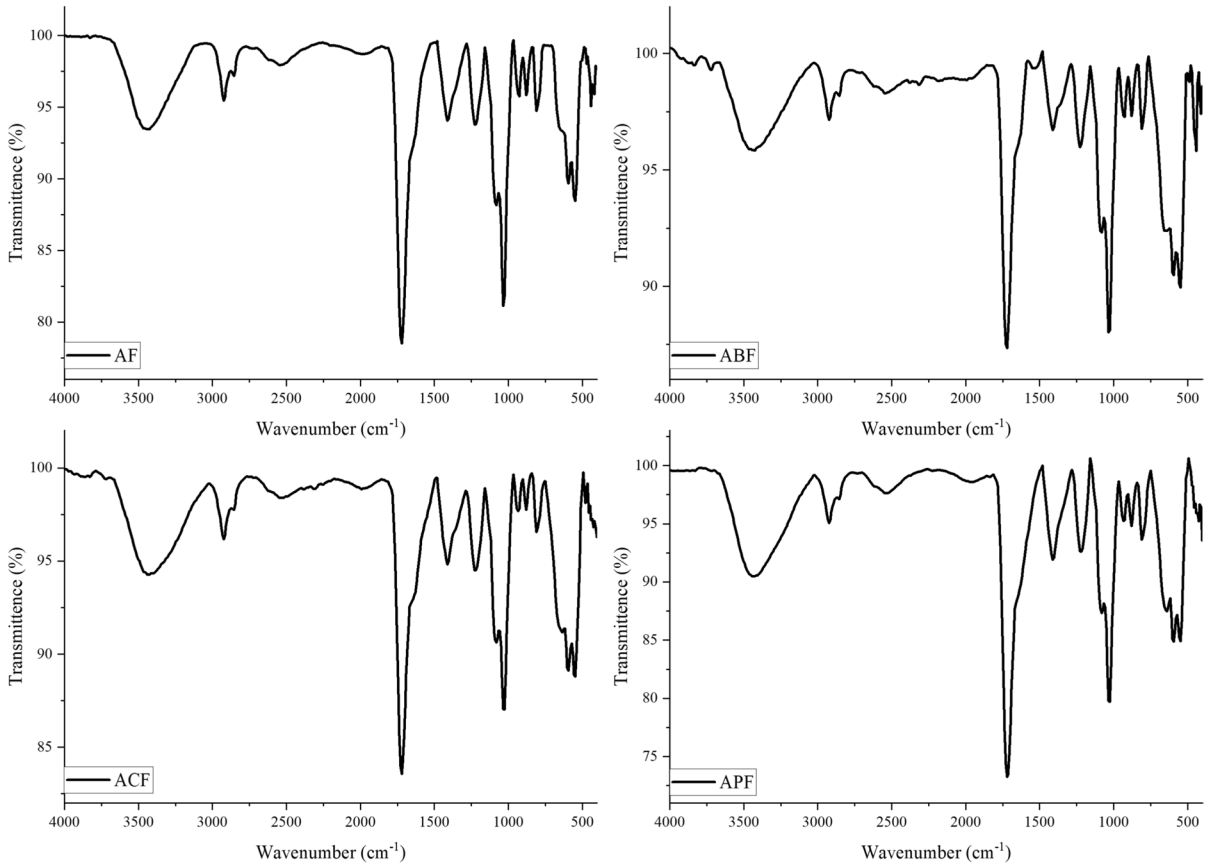


Fig. 2 FTIR spectra of AF, ABF, ACF, and APF films

acid derivatives (Kumar et al. 2020). The wavenumbers of 1543 cm^{-1} and 1412 cm^{-1} were attributed to the asymmetric and symmetric carbonyl group (COO–) stretching. In the literature, the OH stretching vibrations reported for Na-Alg at 3271 cm^{-1} and the asymmetric and symmetric vibrations of the carbonyl group (COO–) reported at 1597 cm^{-1} and 1412 cm^{-1} were found in the FTIR spectra of the films at 3433 cm^{-1}, 1543 cm^{-1}, and 1412 cm^{-1}, respectively. These spectral changes in the FTIR spectra confirm that the alginate molecules were cross-linked with CA (Bucak 2023). The 1080 cm^{-1} and 1026 cm^{-1} wavelengths were due to pyranosyl ring stretching from the alginate skeleton. Since no significant shifts, broadening, or new peaks in the bands of the functional groups (e.g. –OH and –COOH) were observed in the FTIR spectra of the ABF, ACF, and APF films. Therefore, the interaction between alginate and shells was assumed to be physical (e.g. van der Waals forces or weak electrostatic attraction) rather than chemical (Moghadam et al. 2023; Yoon et al. 2024).

Thermal profiles of films (TGA and DSC)

The thermal profiles of thin film samples were investigated by TGA and DSC analyses (Figs. 3 and 4). T_g and T_m temperatures, char yields, decomposition temperatures, and decomposition percentages are listed in Table 2. From the TGA curves, it was seen that the film samples lost sample weight in at least two stages at different temperatures. The weight loss was the percentage of the thermal degradation of the thin films, the dehydration of the substance, and the degree of decomposition given (Kebelmann et al. 2013). The mass loss in the first phase between 0 and 100 °C was defined as the weight loss resulting from the evaporation of absorbed or physically bound water. The second-stage weight losses observed in the

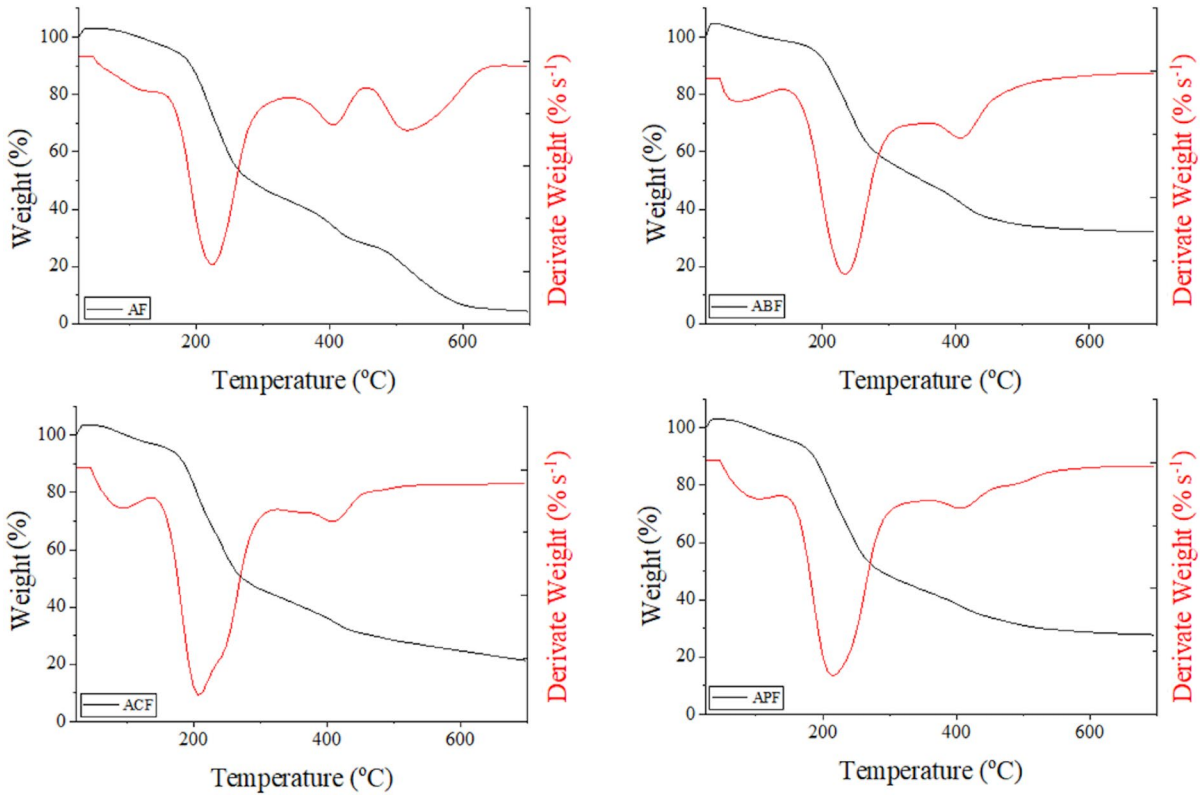


Fig. 3 TGA thermograms of AF, ABF, ACF, and APF films

TGA curves of thin films were mainly attributed to the decomposition of residual lipid compounds such as ketones and aldehydes, the cleavage of glycosidic bonds of ligno-cellulosic compounds, and thermal depolymerisation. In addition, it might be related to the dissociation of residual esters and proteins (Bediako et al. 2019). Thermal decomposition was completed at about 500 °C. This final stage could result in the breakdown of all remaining natural organic groups and the production of residues. Reaching the residue amounts of thin films from the TGA curves was possible. Accordingly, the residue amounts of the peel films were ABF 33%, APF 24%, and ACF 30%. It could be said that these high rates were due to lignin decomposition at high temperatures (Demirbas 2004). Kabenge et al. (2018) reported that banana biomass contains ligno-cellulosic components such as cellulose, hemicellulose, and lignin, with banana peels containing approximately 9% lignin and 10% ash. Ayala et al. (2021) stated that citrus peels contain about 19.8% lignin and 0.052% ash. Skrt et al. (2022) found that pomegranate peels have a lignin content of 12.2%. Surprisingly, in our results, ABF had the highest char yield among the films. Since the lignin in the peel increased with maturity, it was thought that this might be due to the maturity level of the banana used in the study (Emaga et al. 2011).

DSC thermograms (Fig. 4) showed a different T_g value depending on the addition of the peel to the film synthesis. The T_g temperatures of the peel alginate thin films were approximately the same. The AF sample had a higher T_g value than the film samples containing the peel. Accordingly, it showed a plasticizing effect for the alginate film of pomegranate, banana, and citrus peels. Bucak (2023) reported that Na-Alg's melting point is 150 °C. When Na-Alg was cross-linked using CA, and peel was added to the alginate matrix, the melting temperatures increased to nearly 200 °C, as listed in Table 2. This variation suggests enhanced free volume in the alginate-peel composite films.

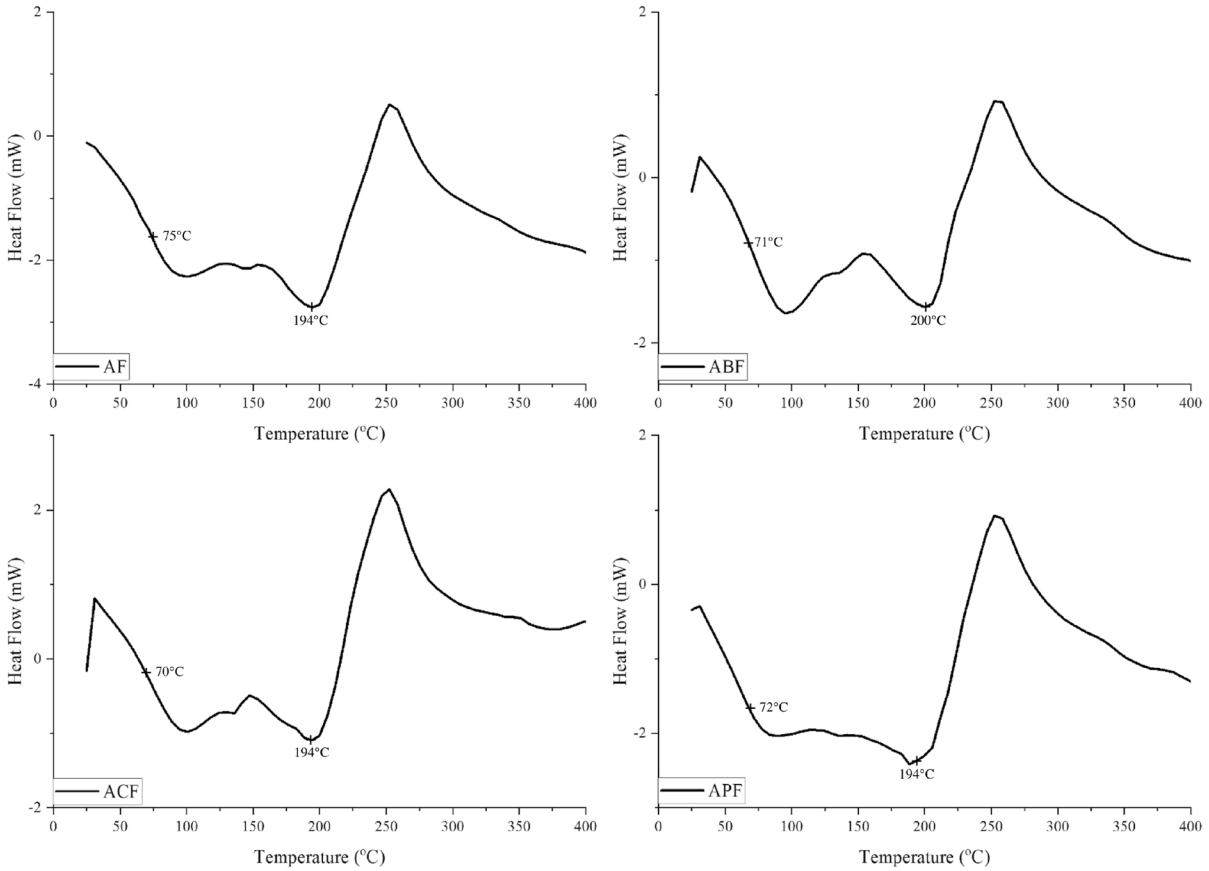


Fig. 4 DSC thermograms of AF, ABF, ACF, and APF films

Table 2 Decomposition temperatures and % weight loss values obtained from TGA thermograms

Films	Td_1		Td_2		Td_3		T_g (°C)	Tm (°C)	Char yield (%)
	Td_1 (°C)	Weight loss (%)	Td_2 (°C)	Weight loss (%)	Td_3 (°C)	Weight loss (%)			
Na-Alg*	252	37.4	371	9.8	594	15.9	80	150	18.7
AF	230	54.8	402	15.8	534	23.4	75	194	6.01
ABF	243	48.1	416	14.2	–	–	71	200	33.15
ACF	223	51.22	393	12.9	–	–	70	194	30.16
APF	226	52.2	417	15.3	–	–	72	194	24.77

*This data was retrieved from Bucak (2023)

XRD

X-ray diffraction patterns can be used to characterize the degree of crystallinity of the films. This reflects the uniformity of the molecular arrangement in the film and has a strong correlation with the physical properties of the film, such as mechanical, optical, and barrier properties. The XRD patterns for banana, citrus, pomegranate powder, and AF, ABF, ACF, APF film samples are shown in Fig. 5. XRD analysis results revealed that all films predominantly exhibited an amorphous structure. The characteristic broad peak observed at a 2θ angle of ~ 25° in the AF film is due to the amorphous nature of the NaAlg matrix.

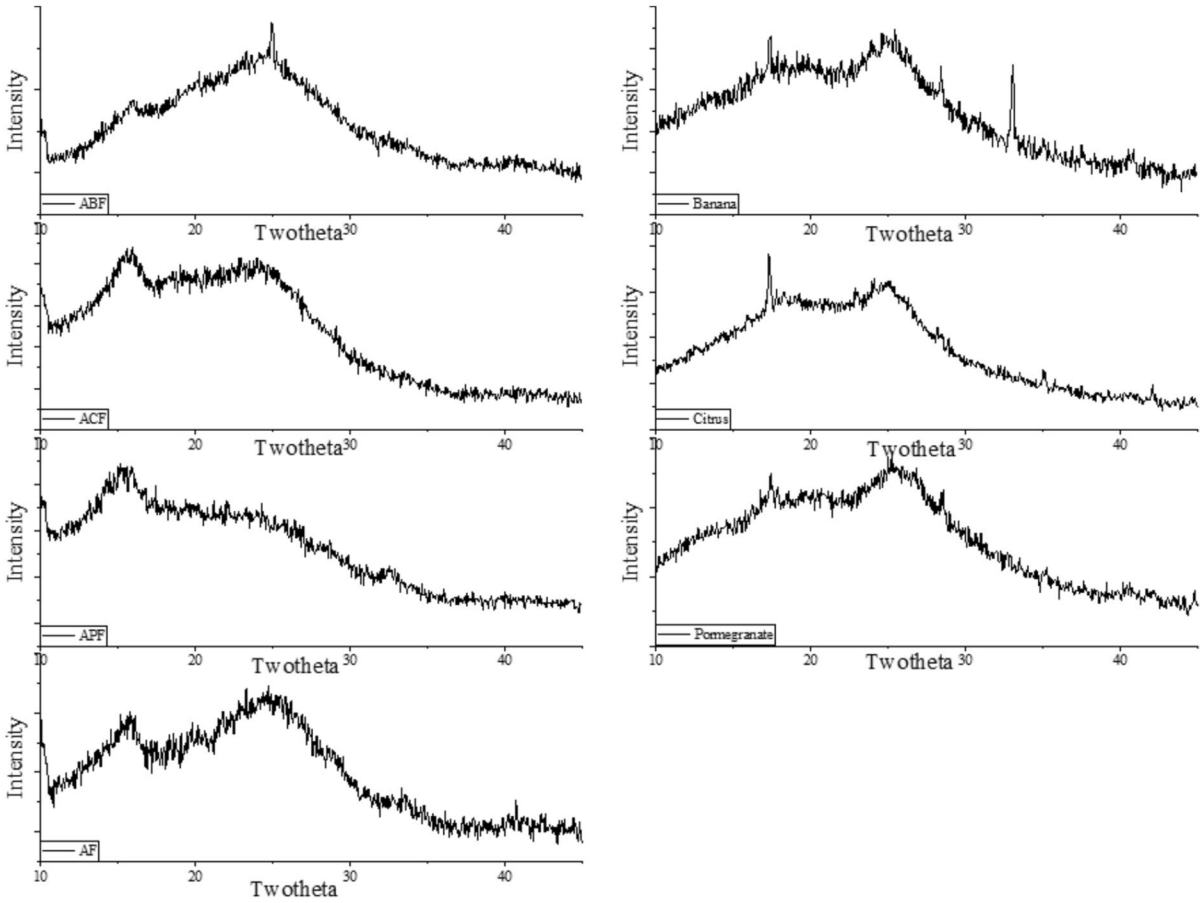


Fig. 5 XRD patterns of banana, citrus, pomegranate powder, and AF, ABF, ACF, APF films

Banana, orange, and pomegranate peels also exhibit a broad peak centered at $2\theta = 17°$ and $2\theta = 25°$ in their XRD patterns, although less intense in banana peels. Tolkou et al. (2024) and Bezerra et al. (2024) also reported similar results. The addition of fruit peels to alginate films caused changes in the density and profile of this amorphous peak, indicating that it affects the packing arrangement of the polymer chains. Comparison of numerical density values also supports this finding. For example, compared to the control film (AF), a significant decrease in relative density values in the characteristic amorphous halo region (~25°) was observed, especially in films with added pomegranate (APF) and citrus (ACF) peels. In conclusion, XRD analysis revealed that the addition of fruit peel reduced the structural regularity of alginate films, thereby enhancing their amorphous character. According to Bahraminejad et al. (2023), good miscibility of a film caused an increase in its amorphous property. The observed changes in the XRD profiles might indicate good interaction and dispersion of the peel particles within the alginate matrix. The amorphous components, such as pectin, were likely to interact with the fibrous structures through hydrogen bonding, thereby reducing the overall crystallinity and structural order of the films (Yun and Liu 2024).

WVTR and nanomechanical properties

One of the most important parameters that significantly affects the shelf life of packaged food products is WVTR. Having a high WVTR of the film matrix can accelerate microbial degradation reactions and quality degradation. It is therefore very important to calculate the WVTR of the synthesized packaging

material (Hlaing et al. 2025). The WVTR values of AF, ABF, ACF, and APF thin films are listed in Table 3. WVTR of control group AF (42.11(g/h m^2)) was higher than WVTR of waste-based thin films (31.62 (g/h m^2), 33.97 (g/h.m^2), 22.22 (g/h m^2) for ABF; ACF; and APF respectively.) Although direct microscopic analysis (e.g., SEM or TEM) was not available in the current study, the reduction in WVTR could be due to the presence and possible uniform distribution of impermeable particles from the peels, which could impede water vapor diffusion through the matrix, as also suggested by Andrade et al. (2016). This assumption was indirectly supported by previous SEM analyses of flours from fruit and vegetable residues, which revealed granular and fibrous particles of different sizes and shapes that might contribute to tortuous pathways within the film structure. A pomegranate-based APF was found to have the lowest water vapor permeability. The addition of pomegranate peel to the Na-Alg film reduced the WVTR of the film by 20%. Kumar et al. (2021) reported that pomegranate peel improved the WVTR of chitosan thin film by phenolic compounds.

Nanomechanical properties such as Young's modulus and hardness are parameters that must be considered to protect food packaging from physical damage (Andrade et al. 2016). To better characterize the mechanical properties, nanoindentation measurements were performed to evaluate the hardness of the synthesized films. However, reliable data could not be obtained for the AF film, likely due to its soft nature, which resulted in insufficient resistance to the indenter tip. The results for the remaining three films are presented in Table 3. The ABF film had the highest Young's modulus and rigidity values. This indicates that the high cellulose and lignin content in banana peel forms strong physical interactions with the alginate matrix to form a hard and rigid structure. Cellulose-enriched films were reported to be harder because the cellulose interacts strongly with the matrix, restricting the chain movement of the biopolymer matrix (Azeredo et al 2012). The ACF and APF films had lower E and H values. This suggested that lower fiber density in citrus and pomegranate peel might have reduced film rigidity.

Table 3 Nanoindentation and WVTR of alginate bio-waste films

Film type	*E* (MPa)	*H* (MPa)	WVTR (g/h m^2)
AF	–		42.11 ± 3.35
ABF	2540	193.0	31.62 ± 8.27
ACF	539	38.2	33.97 ± 4.29
APF	585	26.1	22.22 ± 4.59

Antioxidant capacity of peels and alginate peel films

Fruits usually turn brown due to oxidation, which depletes nutrients like vitamin C and carotene while greatly altering their appearance and flavor (Chang et al. 2023). Polyphenols can act as antioxidants by intervening in oxidation chain reactions, donating a hydrogen atom, scavenging free radicals, or chelating metals (Lu et al. 2022). Banana, citrus, and pomegranate peels are rich in polyphenols, so they have a high antioxidant effect (Yun et al. 2023). DPPH radical scavenging activity is a well-established method for evaluating the antioxidant effects of specific compounds or foods. The higher the DPPH radical scavenging activity, the stronger the antioxidant capacity (Gulcin and Alwasel 2023). In this study, the antioxidant activity of both the films and peels was determined using total phenolic content (TPC) and DPPH radical scavenging activity. DPPH and TPC values of AF, ABF, ACF, and APF films are shown in Table 4. It was observed that the film obtained from the peel with higher antioxidant properties exhibited higher antioxidant properties compared to the AF film. As the pomegranate peel contains the highest total phenolic compound, the pomegranate peel-based thin films (APF) also demonstrated the highest antioxidant effect. The use of antioxidant-rich films, such as polyphenols, in the coating of fruits extends the shelf life of the coated fruit. The main reason for this is that intermolecular interactions

Table 4 DPPH and total phenolic compounds of the films

	Banana peel	Citrus peel	Pomegranate peel	AF	ABF	ACF	APF
DPPH (%)	93.1	74.5	94.2	4.8	56.1	53.4	92.6
Total phenolics (mg GAE g^{-1})	51.3	60.2	189.5	27.2	29.7	28.9	145.8

are one of the most important factors determining film barrier properties. Polyphenols in the film structure provide a protective effect by slowing down the formation of free radicals that can degrade the texture of the fruit. Furthermore, such films prevent moisture loss and oxidative stress by reducing water vapor and gas permeability, thus increasing the resistance of the fruit to both microbial and physical spoilage (Yong and Liu 2021). As a result, alginate films containing banana peel, citrus peel, or pomegranate peel had the potential to be used for packaging and shelf-life extension of perishable foods due to their antioxidant effects.

The DPPH method was utilized to elucidate the radical scavenging activity of alginate peel-based thin films and peels employed in film synthesis. The DPPH radical scavenging ability of peels used in peel-based alginate film synthesis was investigated, and the results showed that the peel from pomegranate, banana, and citrus had radical scavenging abilities of 94.16%, 93.05%, and 74.51%, respectively. The DPPH radical scavenging ability of the pomegranate alginate film was found to be 92.58%. In contrast, the peel-free alginate film exhibited a significantly lower DPPH radical scavenging capacity, with a value of only 4.7%. The high DPPH radical scavenging ability of the peels was attributable to their elevated content of polyphenols. A similar effect had been observed in the pomegranate alginate thin film. It was observed that the DPPH activity of the banana and citrus-based alginate films was less than the DPPH radical scavenging ability of the peels. This phenomenon might be attributed to the interaction between the alginate polymer and the structure of the peels during the film synthesis process. Consequently, the incorporation of alginate resulted in a radical quenching effect on polyphenols (Yong and Liu 2021). The DPPH radical scavenging ability was found to be 56.13% for ABF and 53.35% for ACF. Our findings were consistent with those reported in the paper Kadam et al. (2021) in that in the films to which pine needle extracts were added to chitosan-based films, the films without the extract showed the lowest antioxidant properties, and the antioxidant properties of the films increased with the addition of phenolic extract.

Application of hydrogel films for fresh cherry tomato preservation at room conditions

As shown in Fig. 6, weight loss increased progressively during storage in room conditions. On day 5, the weight losses of the edible films AF, ABF, ACF, and APF were found to be 10.26, 6.82, 4.51, and 5.20%, respectively. The weight of the positive control and control tomato was 0.83 and 14.11%, respectively. ANOVA findings revealed significant differences between groups ($p < 0.05$). Duncan's multiple range test revealed that group C was considerably higher than all other groups ($p < 0.05$), whereas group AF was higher than ABF, APF, ACF, and PC ($p < 0.05$). Group ABF was substantially greater than APF, ACF, and PC ($p < 0.05$). APF and ACF did not show a significant difference ($p > 0.05$); however, both were greater than PC ($p < 0.05$). The lowest values were seen in the PC group. According to the 10th day measurements, the weight losses of the edible films AF, ABF, ACF, and APF were 19.79, 9.72, 8.79, and 8.28%, respectively, while the weight losses of the positive control and control tomatoes

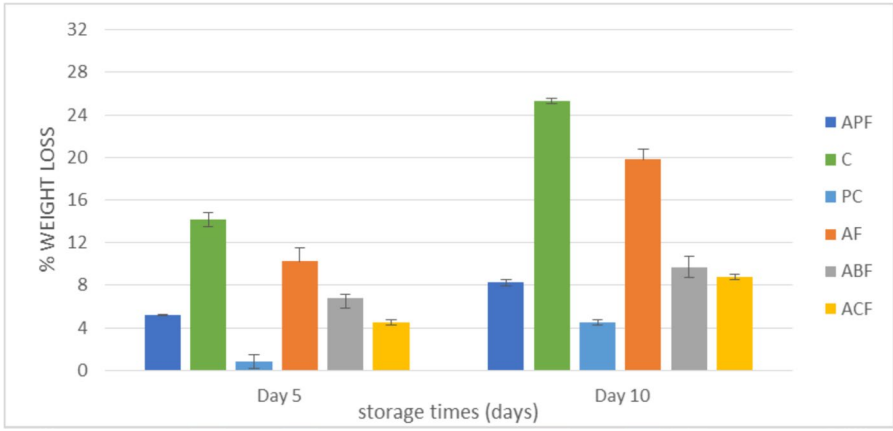


Fig. 6 Changes in % weight loss of cherry tomato samples during storage at room conditions. PC: positive control tomatoes, C: no coating tomatoes. All experiments were conducted in duplicate, and data are given as mean ± SD

were 4.51 and 25.26%, respectively. As a result of the statistical analysis, the C group was significantly higher than all other groups ($p < 0.05$). The AF group had significantly higher values compared to ABF, ACF, APF, and PC groups ($p < 0.05$). The ABF group was significantly higher than the ACF, APF, and PC groups ($p < 0.05$). Although no significant difference was observed between the ACF and APF groups ($p > 0.05$), both groups were significantly higher than the PC group ($p < 0.05$). These results agree with those reported by Abdillah and Charles (2021), who reported that applying an edible coating to tomatoes reduced the weight lost during storage.

Cherry tomatoes are classified as a climacteric fruit with a relatively short post-harvest life and are usually consumed fresh, making them susceptible to foodborne illness caused by surface pathogens. Therefore, the development of effective protection measures during transport and storage is crucial. Effective packaging and preservation technologies, such as edible coatings, are in high demand to extend shelf life. These coatings form a protective layer that partially blocks stomata and lenticels, reducing moisture loss through transpiration and limiting gas exchange during respiration, which ultimately helps the fruit stay fresh for longer (Dos Reis et al. 2015).

Appearance change is the most direct means of assessing the quality of cherry tomatoes (Xiang et al. 2021). Shrinkage, defined as the deformation of fruit and vegetables during storage, is mainly due to water loss by evaporation and transpiration through natural pores and respiration (Lai et al. 2022). The bio-waste-added coated groups showed better visual appearances than the AF group. This was due to the higher water vapor permeability of the film in the AF group and the fact that alginate alone did not show sufficient film properties (Fig. 7). Senturk Parreidt et al. (2018) noted that Na-Alg exhibits poor properties when used as a coating material alone, but the film structure was strengthened when used with different fillers. The bio-waste-based films used in this study demonstrated potential as fruit packaging materials, successfully prolonging the shelf life of cherry tomatoes by inhibiting their deterioration.

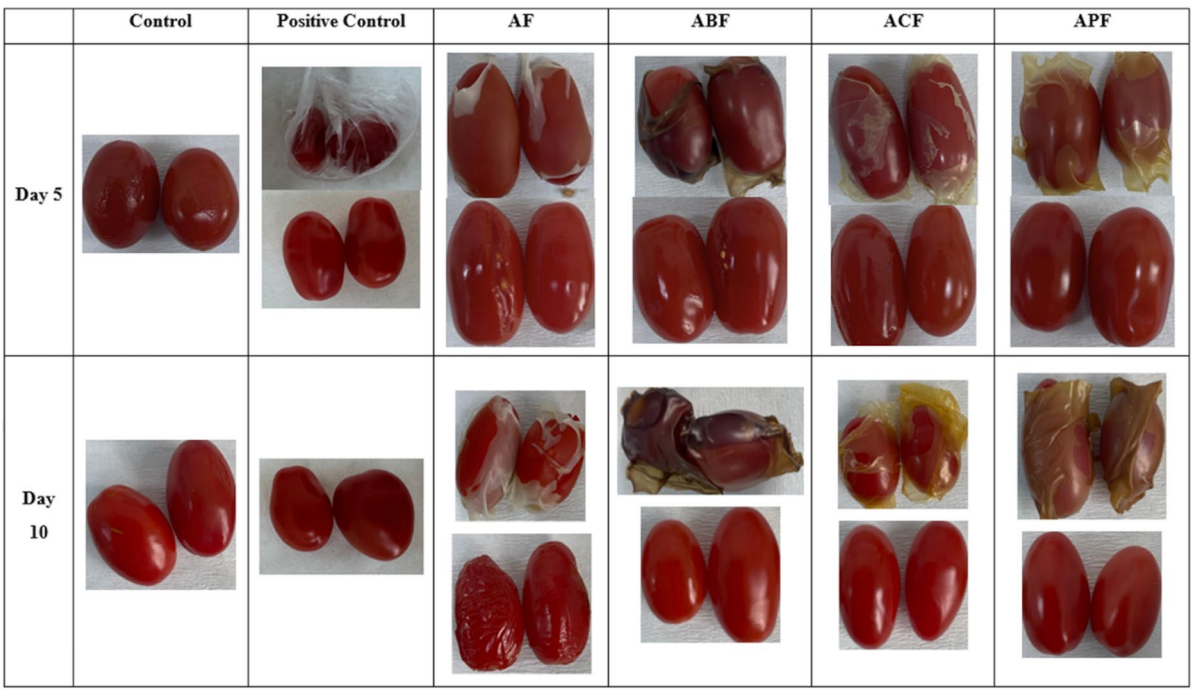


Fig. 7 Changes in the visual appearance of cherry tomatoes during storage. Upper images show the tomatoes coated with alginate-based films, while lower images present the same tomatoes after removal of the coating at the same storage days. Control is uncovered and uncoated tomatoes; Positive control is uncoated tomatoes stored in a LDPE bag

Conclusions

In contrast to previous studies, this work compares the properties of edible films derived from various fruit peels classified as waste and evaluates their ability to extend the shelf life of coated cherry tomatoes. We synthesized citric acid cross-linked alginate-based films by incorporating banana peel, citrus peel, and pomegranate peel individually, and investigated their suitability for tomato packaging. Coating cherry tomatoes with peel-based films significantly reduced water loss and shrinkage. The polyphenols in the peel had an antioxidant effect, and the homogeneous distribution of the peel particles in the matrix reduced water vapour permeability, slowed down moisture loss, prevented oxidative degradation, and thus prolonged shelf life. By detailing how these films made from waste affect quality parameters during storage, this study lays the foundation for sustainable, environmentally friendly packaging solutions.

This study had some limitations. In particular, it contained no SEM images, no data on mechanical strength (e.g., tensile tests), and no data on biodegradability. Future research should address these shortcomings by scaling up the production process and evaluating applicability, which would better emphasise the commercial potential of the developed films.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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