Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Cold atmospheric pressure plasma pretreatment as a novel tool to tailor the functional properties of quince seed mucilage biopolymer-based edible films

javaneh karimi
Shahid Sadoughi University of Medical Sciences and Health Services
sahand sohrabi
Shahid Beheshti University of Medical Sciences
Mojtaba Moezzi Rad
Yazd University
mehdi sharifian
Yazd University
Leila Zare
Shahid Beheshti University of Medical Sciences
neda Mollakhalili Meybodi
neda_mabodi@yahoo.com

Shahid Sadoughi University of Medical Sciences and Health Services

Article

Keywords: Cold plasma, Quince seed mucilage, Edible film, Functional properties

Posted Date: August 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10664006/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on November 6th, 2026.
See the published version at https://doi.org/10.1038/s41598-026-78597-w.

Abstract

Background

Quince seed mucilage (QSM) is a promising polysaccharide for the fabrication of biodegradable edible films; however, its relatively limited functional performance restricts broader food-packaging applications.

Scope and Approach:

The present study investigated the effects of cold atmospheric plasma (CAP) treatment applied to QSM solutions at 6, 7, and 8 kV for 1, 3, and 5 min, followed by a comprehensive evaluation of the physicochemical, surface, barrier, mechanical, and thermal properties of the resulting films.

Key Findings:

CAP treatment did not significantly affect film thickness regardless of the applied processing conditions. Contact angle analysis demonstrated that the highest surface hydrophobicity was achieved under a 7 kV for 3 min plasma treatment. Water vapor barrier measurements revealed that films treated for 3 min exhibited the lowest permeability, irrespective of the applied voltage. Surface topography analysis indicated that 6 kV for 1min plasma exposure generated the greatest surface roughness, whereas increasing either the treatment duration or applied voltage produced a denser, more homogeneous, and compact film microstructure. Compared with the untreated control, CAP treatment significantly enhanced the mechanical performance of the films, with the optimum tensile properties obtained following treatment at 6 kV for 1 min. Thermal characterization by TGA and DSC further demonstrated that 5 min plasma exposure time adversely affected the thermal stability of the films, while optimized CAP conditions (3 min) provided the most favorable thermal performance.

Conclusions

Overall, the findings demonstrate that appropriately optimized CAP treatment effectively improves the structural integrity and functional performance of QSM-based biodegradable films.

1. Introduction

Due to their inherent perishability and susceptibility to environmental conditions, food products require complete protection throughout the supply chain. Food packaging functions as an integrated system, can improve food products safety and quality through the organoleptic and microbiological stability of food products (Kumari et al., 2022). Polymers classified as plastics, characterized by their adaptability, thermoformability, and extrudability, are widely used in various applications, including food packaging.

These conventional polymers are essential for preserving supply chain integrity and product safety, protecting foodstuffs through multilayered mechanisms. The user-friendly nature, high processability, and economic advantages of petrochemical-derived polymers substantiate their widespread usage and complicated substitution (Guillard et al., 2018). Polyethylene terephthalate, polystyrene, high-density polyethylene, polypropylene, and low-density polyethylene are the most common packaging materials employed in food preservation (Kumari et al., 2022). Recently, considerable safety concerns have emerged regarding the utilization of non-renewable plastics, particularly concerning the migration of toxic compounds, health-related issues, and environmental impacts (Guillard et al., 2018). Disposable, single-use plastics represent a dual hazard to environmental ecosystems and human well-being, attributable to their resistance to biodegradation and their implication in various pathological conditions, including endocrine disruption. Moreover, the accumulation of microplastics derived from synthetic polymeric packaging in the ocean severely affects aquatic planktonic communities (Ahmed et al., 2023). Given the environmental challenges and long-term sustainability considerations, alongside the slow degradation properties of petrochemical-based polymers, renewable alternatives are essential (Cheng et al., 2024).

Biopolymers, renewable and eco-friendly materials from biological sources, are favored for short-term food packaging due to their protective qualities and easy degradability (Khan et al., 2016). Quince, a member of the *Rosaceae* family, is cultivated in East Asia, South Africa, and Central Europe, with Iran being a major producer after Türkiye, China, Uzbekistan, and Morocco. Its seeds contain mucilage, a water-extractable polysaccharide-rich cellulose mixture, which can be readily extracted using water at ambient temperature. A key water-soluble component is acetyl-(4-oxymethyldiglucuronic acid)-di-xylan (Kashiri & Davtalab, 2023). Mucilaginous polysaccharides have garnered increasing research interest due to their broad applications across multiple fields. They are currently employed as delivery matrices in controlled drug release systems (Kashiri & Davtalab, 2023; Tosif et al., 2021), scaffolds for tissue engineering applications (Goksen et al., 2023; Urena-Saborio et al., 2018), and as precursors for the fabrication of edible films (Davachi et al., 2021; Dick et al., 2015). Various researches support using QSM for edible film production due to their desirable physicochemical and mechanical characteristics (Erkaya-Kotan et al., 2023; Kashiri & Davtalab, 2023; Kozlu & Elmacı, 2024).

Biopolymer films often exhibit brittleness and inadequate barrier properties due to their inherent molecular structure and limited intermolecular interactions (Basak & Annapure, 2023). This restricts their effectiveness in applications like food packaging, where mechanical durability and resistance to moisture, oxygen, and oils are crucial.

To enhance biopolymer functionality, different surface modification techniques and treatments like UV, gamma, ionizing rays, flame, and cold plasma are employed (Sani et al., 2023). Among these modification methods, cold plasma treatment is particularly popular due to its advantages in improving film properties. Cold plasma is a sustainable, nonthermal technology that enhances the functional properties of hydrocolloids, such as proteins and carbohydrates, without degrading their structure. It offers advantages like low energy consumption, short processing times, and minimal environmental

impact, making it a 'green' alternative to conventional chemical modifications (Basak & Annapure, 2023). Concurrently, numerous investigations have focused on the application of cold plasma treatment for the physical enhancement of film properties (Bahrami et al., 2022; Monjurul Hoque et al., 2022; Song et al., 2016).

This technique facilitates physicochemical modifications of material surfaces without intense heat, rendering it applicable across diverse domains, including food processing and packaging industries. CAP eliminates the need for vacuum conditions, operating instead at ambient pressure, which makes it inherently more suitable for surface engineering of biological materials and for scalable industrial uses. Various generation methods exist for producing this type of plasma, such as dielectric barrier discharge (DBD) and atmospheric-pressure plasma jet (APPJ), each exhibiting distinct operational characteristics (Li et al., 2025).

Cold plasma treatment of plant seeds can alter their surface structure, thereby influencing the subsequent extraction process of seed mucilage. As an illustration, investigations into chia seeds have demonstrated that exposure to atmospheric-pressure cold plasma enhances mucilage viscosity and improves its rheological profile, suggesting increase in both extraction yield and mucilage quality (Dick et al., 2015). Parallel findings from flaxseed studies indicate that cold plasma treatment can shorten the mucilage release time and facilitate its accelerated extraction by compromising the integrity of the seed cuticle (Dauwe et al., 2021). These researches indicates that beyond its impact on mucilage recovery, cold plasma treatment may also enhance the functional properties of mucilage when employed in the fabrication of biodegradable films. Although several studies have investigated the application of CAP to modify the physicochemical, mechanical, and thermal properties of films derived from chia seed and basil seed mucilages (Hashemi Gahruie et al., 2023; Mutlu, Kopuk, et al., 2023; Mutlu, Palabiyik, et al., 2023), demonstrating promising improvements in their functional performance, no study has yet explored the plasma-assisted modification of QSM for the fabrication of biodegradable films. Therefore, the present work addresses this research gap by evaluating the potential of CAP treatment as an innovative surface modification strategy to enhance the performance of QSM-based biodegradable film systems.

2. Materials and Methods

2.1. Materials

Quince seeds were purchased from Yazd city selling centers and stored at 5°C in closed packages until analysis. All chemicals used were of analytical grade.

2.2. Cold plasma treatment of quince seeds

Quince seeds underwent cold plasma treatment using a DBD system with air gas at atmospheric pressure. Voltage (6, 7, 8 kV) and treatment duration (1, 3, 5 min) were varied, while input voltage (90 V), frequency (28 Hz), and current (2.5 A) remained constant. For each treatment, 10g of seeds were placed

in a beaker, 2.5 cm from the plasma jet nozzle to prevent displacement. Seeds were manually shaken for homogeneity during the 1-, 3-, or 5-minute treatment intervals (Hashemi Gahruie et al., 2023; Mutlu, Kopuk, et al., 2023). **Table 1** shows the various types of plasma treated quince seeds.

2.3. Mucilage extraction of quince seeds

Mucilage was extracted from quince seeds following the procedure proposed by Mutlu et al. (Mutlu, Palabiyik, et al., 2023) and Emir Coban et al. (Emir Coban et al., 2024), with minor modifications. The mucilage was formed by steeping quince seeds in distilled water at a ratio of 1:100 (w/v) for 2 h at 80°C. After one centrifugation cycle of 10 min at 9,000 × g, the samples were spread onto drying trays and dried at 50°C for 24 h. The dried mucilage was placed into sealed containers, sieved through a 30-mesh screen, and then stored at 4°C until further analyses were conducted.

2.4. Preparation of quince seeds mucilage edible films

Film preparation was carried out based on the method reported by Emir Coban et al. (Emir Coban et al., 2024) with slight modifications. A mucilage solution was prepared from extracted QSM and stirred for 15 min to obtain a homogeneous mixture. Glycerol (0.06 mL/100 mL) was added to this solution as a plasticizer, and the mixture was stirred on a magnetic stirrer without heating for 30 min. The homogenized solution was centrifuged at 3,000 rpm for 10 min to remove air bubbles. The resulting film-forming solutions were poured into Petri dishes (20 mL per dish) with dimensions of 120 mm × 17 mm and dried under controlled conditions at 35°C and 50% relative humidity (RH). The dried films were peeled from the plates and stored at 25°C and 50% RH for subsequent analysis. All films were prepared in duplicate.

3. Physiochemical, mechanical, and thermal properties of edible films

3.1. Thickness of edible films

Film thickness was measured at 5 random points using a digital micrometer with 0.01 mm accuracy (Emir Coban et al., 2024; Kashiri & Davtalab, 2023).

3.2. Contact angle

The contact angle of the prepared bio-based films was measured using the sessile drop method. Initially, quince film samples were cut into defined dimensions, and their surfaces were carefully cleaned and dried to ensure surface uniformity and the removal of any contaminants or lipid residues. Subsequently, the samples were placed on the instrument holder under controlled environmental conditions (25°C and constant relative humidity). To determine the contact angle, a 5–10 µL droplet of distilled water was gently deposited onto the film surface using a micropipette syringe. After droplet stabilization, the image was captured using a high-resolution camera. The contact angle was calculated using the dedicated image analysis software of the goniometer, defined as the angle between the tangent of the water

droplet and the film surface at the point of contact. To enhance accuracy, the test was repeated at six different locations on each sample, and the mean values were reported. This measurement provides an indicator of surface hydrophilicity or hydrophobicity, reflecting the impact of cold plasma treatment on improved wettability and surface polarity (Huhtamäki et al., 2018).

3.3. Water vapor permeability (WVP)

To evaluate the moisture barrier properties of edible films fabricated from QSM, WVP testing was performed using a gravimetric approach in accordance with ASTM E96 standard. In this method, laboratory vessels, typically small beakers or specialized permeation cells, were charged with either dried silica gel or a saturated salt solution to establish a controlled relative humidity environment inside each container. The mouth of each vessel was completely sealed with the test bio-based film, and the edges were secured using Parafilm or wax to prevent leakage and air exchange. The assembled vessels were then placed inside a chamber maintained at a defined temperature and relative humidity, specifically 25°C and 75% RH. The weight of the vessels was recorded at regular intervals (typically every 24 hours), and the rate of weight gain was determined as an indicator of the amount of moisture absorbed due to water vapor transmission across the film. WVP was subsequently calculated using standard equations, taking into account film thickness, effective permeation area, the slope of the water vapor pressure gradient, and the steady-state vapor transmission rate. This test reflects the film's capacity to impede moisture transfer, a critical factor in preserving food quality and extending product shelf life (Shahrbanoo Ahmadi Ledari et al., 2020).

3.4. Surface morphology

To examine surface alterations and assess the roughness and uniformity of bio-based films fabricated from QSM, Atomic Force Microscopy (AFM) was employed. Following complete drying, film specimens were cut into small pieces of uniform dimensions and mounted onto the sample holder without any coating or special preparation. Imaging was performed in contact mode under ambient temperature conditions. Specific areas of the film surface were selected with scan dimensions of 5 × 5 or 10 × 10 μm, and high-resolution three-dimensional topographical images were captured. Subsequently, parameters including average surface roughness (Ra) and root mean square roughness (Rq) were extracted from the obtained images (Bahrami et al., 2022).

3.5. FTIR

To analyze the chemical structure and investigate alterations in functional groups of bio-based films fabricated from QSM, Fourier transform infrared (FTIR) spectroscopy was employed. The film specimens were thoroughly dried and placed directly into the FTIR instrument without requiring any special preparation. Absorption spectra were recorded within the wavenumber range of 4000 to 600 cm^{-1} at a resolution of 4 cm^{-1}, using 45 consecutive scans per sample. The test was conducted in transmission mode, and the obtained spectra for each sample were compared against a control (untreated film) (Emir Coban et al., 2024).

3.6. Mechanical properties

To evaluate the mechanical properties of bio-based films fabricated from QSM, tensile strength and elongation at break tests were conducted in accordance with ASTM D882 standard using a universal santam machine. Initially, quince film specimens were cut into strips of uniform dimensions (typically 2 cm × 10 cm), and the thickness of each specimen was measured at five random points using a digital micrometer, after which the average value was calculated. The specimens were then mounted between two grips of the apparatus at a specified gauge length, ensuring that no folds or initial tension were present on the specimen surface. The crosshead speed was set to 50 mm/min, and the test was continued until complete specimen rupture. The recorded data acquired by the machine software included the applied force and the corresponding change in specimen length during the test, from which tensile strength (maximum tensile force divided by the initial cross-sectional area) and elongation at break (percentage increase in length relative to the initial specimen length) were calculated. The results obtained from these tests play a critical role in assessing the structural integrity and processability of the film for food packaging applications (Dong et al., 2020).

3.7. Thermal properties

The thermal properties of bio-based films derived from QSM were characterized using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA).

3.7.1. TGA

The thermal stability of the films was evaluated by thermogravimetric analysis using a Dama Pajouh Arvin Co. (Iran) thermal analyzer. Approximately 40 mg of each film sample was subjected to heating from ambient temperature to 600°C at a programmed heating rate of 10°C min^{-1} in an air environment.

3.7.2. DSC

This analytical technique was employed to determine the glass transition temperature (Tg), melting temperature (Tm), and overall thermal stability of the specimens. To begin with, the films were thoroughly dried, and a defined quantity (typically 5–10 mg) of each sample was accurately weighed and placed into standard aluminum DSC pans. Subsequently, the lids were hermetically sealed using a dedicated press to prevent moisture evaporation and contact with atmospheric air. All measurements were conducted under a nitrogen atmosphere (flow rate of approximately 20 mL/min) to suppress oxidative reactions during heating. The applied thermal program involved heating the samples from 25°C to 300°C at a constant ramp rate of 10°C per minute (Romani et al., 2019).

3.8. Statistical analysis

Statistical analysis was carried out using SPSS software (IBM SPSS Statistics 23). All data were expressed as mean ± standard deviation (SD). Comparisons among datasets were performed using to-way analysis of variance (ANOVA), and a probability value of $p < 0.05$ was considered statistically significant across all evaluations (Davachi et al., 2021).

4. Results and discussion

4.1. Thickness of edible films

Edible film thickness is primarily influenced by the type and concentration of ingredients, the base material composition and intermolecular interactions in the film matrix. Film-forming properties and processing conditions and method also play a key role in this manner (Esfandiari et al., 2025; Song et al., 2026). The thickness of films prepared from QSM was measured using a digital micrometer with an accuracy of 0.01 mm, taking readings from five different locations on each film. The average of these values was subsequently reported as the representative thickness for each film. The obtained results demonstrated that all films exhibited a uniform thickness of 0.70 mm, and cold plasma pretreatment of QSM exerted no significant effect on film thickness distribution ($p > 0.05$). Furthermore, no statistically significant differences in film thickness were observed between treated and untreated quince seed. In their investigation concerning plasma treatment of films based on wild almond protein isolate, Tahsiri et al. (Tahsiri et al., 2025) concluded that cold plasma exposure neither increased nor altered film thickness. Notably, these researchers, consistent with the present study, subjected the film-forming solutions to cold plasma treatment prior to film casting. Consequently, they suggested that the absence of thickness variation might be attributed to the fact that the plasma treatment was not applied directly to the already-formed films, which could otherwise influence thickness through modifications in surface roughness. This observation contrasts with findings from an earlier investigation by the same group, wherein films were exposed to cold plasma after preparation, and thickness alterations were reportedly observed (Tahsiri et al., 2023). Comparable outcomes, indicating no significant effect of cold plasma treatment on film thickness, were also documented by Ledari et al. (S. A. Ledari et al., 2020), who examined cold plasma treatment of gelatin-based emulsion films.

4.2. Contact angle

The contact angle represents the angle at which a liquid droplet meets a solid surface and is widely used to characterize the surface wettability and hydrophobic behavior of materials. In general, surfaces exhibiting contact angle values below 90° are considered hydrophilic, indicating a strong affinity for water and enhanced wetting capability (Esfandiari et al., 2025). The contact angle measurements demonstrated that CAP treatment significantly altered the surface free energy and wettability behavior of QSM films. The contact angle of polymeric materials is primarily governed by several surface-related factors, including surface heterogeneity, surface free energy, polymer crystallinity, chemical structure, and surface roughness (Davachi et al., 2021). The effect of CAP exposure time was more pronounced than that of the applied voltage. At all voltage levels (6, 7, and 8 kV), extending the treatment time from 1 to 3 min increased the contact angle, indicating enhanced surface hydrophobicity. However, further increasing the exposure time to 5 min generally reduced the contact angle, suggesting that CAP treatment for 5 min plasma treatment partially diminished the hydrophobic modification. In contrast, increasing the applied voltage produced a less consistent effect on contact angle, with the highest value being obtained at the 7 kV for 3 min treatment condition. The highest water contact angle was observed

for sample F6, whereas the lowest contact angle values were recorded for samples F1, F2, and F3. The films treated at 6 kV for 1 and 3 min exhibited no statistically significant differences in contact angle compared with the untreated control, suggesting that the initial plasma-induced surface oxidation and the simultaneous increase in surface roughness exerted competing effects on wettability. However, increasing either the treatment duration or the applied voltage resulted in a significant increase in contact angle, indicating a reduction in surface free energy and a concomitant enhancement in surface hydrophobicity. Similar observations were reported by Hashemi Gahruie et al. (Hashemi Gahruie et al., 2023), who found that extending the cold plasma treatment time to 30 min significantly increased the contact angle (θ = 75.13°) of basil seed gum-based films, thereby reducing their surface wettability. The authors attributed this behavior to plasma-induced cleavage of chemical bonds through various surface reactions, leading to modifications in the chemical architecture of the polymer network and consequently decreasing the affinity of the film surface toward water. In addition to chemical modifications, plasma-induced surface etching has been recognized as another important mechanism contributing to the enhanced hydrophobicity of biopolymer films. This phenomenon alters the surface topography while simultaneously modifying the density and distribution of polar functional groups, particularly hydroxyl and carboxyl moieties, thereby influencing the wetting characteristics of the material (Dimitrakellis & Gogolides, 2018). During cold plasma exposure, energetic plasma species continuously bombard the film surface, promoting localized etching and increasing surface roughness (Dong et al., 2018). Similar plasma-induced increases in surface hydrophobicity have also been reported for whey protein isolate films (Segat et al., 2015) and gum Arabic films (Amirabadi et al., 2020). Nevertheless, the influence of plasma treatment on wettability is not universal and strongly depends on the physicochemical characteristics of the polymer matrix. Moosavi et al. (Moosavi et al., 2020) reported that cold plasma treatment using either air or argon significantly reduced the contact angle of whey protein isolate films, indicating enhanced surface hydrophilicity. This behavior was attributed to the incorporation of oxygen-containing polar functional groups generated by plasma treatment. In contrast, the same study found no significant changes in the surface wettability of wheat gluten films, which was explained by the inherently hydrophilic nature of the gluten surface and its limited responsiveness to plasma treatment regardless of the discharge gas employed. Likewise, Ledari et al. (S. A. Ledari et al., 2020) observed an increase in the hydrophilicity of gelatin-based emulsion films following CAP treatment, which they associated with the enrichment of polar functional groups at the film surface. Collectively, these findings suggest that the effect of cold plasma on the wettability of biopolymer films is highly material-dependent and is largely governed by the distribution, density, accessibility, and spatial orientation of surface functional groups, all of which determine the resulting surface free energy and consequently the measured contact angle. Among all treatments, sample F6 exhibited the highest contact angle (74.34°), indicating the greatest degree of surface hydrophobicity. This behavior can be attributed to the combined effects of plasma-induced surface roughening, rearrangement of polysaccharide chains, reorientation of polar functional groups and surface anchors, and increased surface densification resulting from plasma-mediated physicochemical reactions (Amirabadi et al., 2020; Dimitrakellis & Gogolides, 2018; Dong et al., 2018).

4.3. WVP

Evaluating WVP is crucial importance when assessing the film suitability for food packaging applications as moisture exchange between the food product and its surrounding environment constitutes one of the most influential factors affecting food quality. Biopolymer-based packaging films typically exhibit higher WVP compared to their petrochemical-based counterparts. Consequently, to broaden the applicability of biodegradable biopolymers in food packaging, modifications aimed to controlling their barrier properties are essential (Tahsiri et al., 2025). Figure 1 illustrated the WVP changes in cold plasma-treated samples compare to untreated one. A consistent trend was observed in the WVP of the films across all plasma treatment conditions. At a constant applied voltage of 6 kV, increasing the CAP exposure time from 1 to 3 min resulted in a reduction in WVP, indicating an improvement in the barrier properties of the film. However, extending the treatment duration to 5 min (sample F4) caused WVP to increase markedly, exceeding even that of the untreated control. A similar response was observed at both 7 and 8 kV, suggesting that the effect of treatment duration followed the same pattern regardless of the applied voltage. These findings indicate that, irrespective of the plasma voltage, 5 min exposure to CAP exerts a detrimental effect on the film microstructure. The treatment condition of 5 min plasma treatment is likely to promote structural degradation through over-etching and disruption of the polymer network, leading to a reduction in matrix compactness and structural integrity. Consequently, the formation of additional diffusion pathways facilitates the transport of water vapor through the film, resulting in an increase in WVP. However, cold plasma treatment generally reduced permeability compared to control samples, particularly at 3 minutes, indicating its positive effect on improving water vapor barrier properties of treated films. Similar findings were reported by Dong et al. (Dong et al., 2018), who observed a 24.5% reduction in zein film WVP with atmospheric-pressure cold plasma treatment compared to control sample. Song et al. (Song et al., 2026) attributed this improvement to increased tortuosity of the water vapor path due to surface crosslinks and increased density. Mohammadi et al. (Mohammadi et al., 2026) also noted that cold plasma can enhance WVP through surface densification and oxidative crosslinking. However, they cautioned that suboptimal conditions can compromise barrier performance by inducing porosity or microcracking, a phenomenon also observed in this study where permeability increased with treatment time beyond 3 minutes despite an initial decrease.

4.4. Surface morphology

Cold plasma treatment is a versatile and environmentally friendly surface modification technology capable of altering the surface morphology and chemical composition of biodegradable films without significantly affecting their bulk properties. One of the most common phenomena occurring during cold plasma processing is surface roughening, which primarily results from the selective etching of amorphous regions by reactive oxygen and nitrogen species (RONS) generated within the plasma discharge (Mohammadi et al., 2026). AFM is recognized as an effective analytical technique for evaluating plasma-induced modifications in surface topography and roughness. In the present study, three-dimensional AFM topographic images and table of QSM films (Fig. 2 and **Table 3**) were employed to investigate changes in surface morphology following cold plasma exposure. Surface characteristics were quantified using three roughness parameters, including average roughness (Ra), root mean square roughness (Rq), and skewness (Ssk). The AFM results revealed that cold plasma treatment significantly

modified the surface morphology of QSM films. The untreated control sample (F1) exhibited a relatively smooth and homogeneous surface with the lowest roughness values. Plasma exposure under all treatment conditions initially increased surface roughness, indicating the occurrence of surface etching and localized degradation induced by plasma-generated reactive species. Plasma exposure time exerted a more pronounced influence on the surface topography of QSM films than the applied voltage. At all voltage levels, short plasma exposure (1 min) generally increased the mean surface height and surface roughness parameters (Rq and Ra), indicating the formation of a rougher film surface as a result of plasma-induced surface etching. However, extending the treatment duration to 5 min tended to reduce the surface roughness and produce a more compact and homogeneous surface morphology, suggesting that 5 min plasma exposure time promoted surface reorganization and structural densification. The effect of the applied voltage on the AFM parameters was less systematic than that of treatment time. The 7 kV plasma treatment generally produced the highest values of mean surface height and roughness parameters, whereas increasing the voltage to 8 kV did not further enhance surface roughness. These findings suggest that plasma exposure time is the dominant processing parameter governing the evolution of the surface microstructure of QSM films, while the influence of voltage is dependent on the treatment duration. Similar findings were reported by Pankaj et al., who observed that the surface roughness of zein-based films treated with DBD plasma (80 kV, 5 min) increased from 16.4 nm in the untreated sample to 132.9 nm after plasma treatment (Pankaj, Bueno-Ferrer, et al., 2014). Likewise, Ledari et al. demonstrated that cold plasma treatment using different process gases substantially altered the surface morphology of gelatin-based films and significantly enhanced their surface roughness (S. A. Ledari et al., 2020). The increase in surface roughness following plasma treatment can be attributed to the bombardment of the film surface by energetic plasma species, including ions, electrons, free radicals, and ultraviolet (UV) radiation generated during the discharge process (S. A. Ledari et al., 2020). At an applied voltage of 6 kV, the highest roughness was observed in sample F2 (1 min treatment), suggesting that surface erosion and etching mechanisms predominated under these conditions. However, extending the treatment duration led to a reduction in roughness, which may be associated with plasma-induced functionalization of polysaccharide chains, molecular rearrangement, and enhanced intermolecular interactions occurring simultaneously with the etching process. In addition, the reduction in roughness may be partially explained by the shadowing effect. In this phenomenon, low-energy plasma particles diffuse into surface grooves and depressions, progressively filling these irregularities and thereby decreasing the overall surface roughness of the polymeric matrix (Dong et al., 2018; Moosavi et al., 2020). This trend contrasts with the observations reported by Pankaj et al. for zein films, where increasing both treatment voltage and exposure time resulted in a continuous increase in surface roughness (Pankaj, Bueno-Ferrer, et al., 2014). These discrepancies may arise from differences in the molecular architecture and crystalline-amorphous organization of QSM and zein matrices. Variations in crystalline and amorphous regions can lead to heterogeneous sputtering rates during the initial stages of plasma exposure, producing distinct surface morphologies. Furthermore, reaccumulation and redeposition reactions occurring concurrently with plasma-induced corrosion may generate surfaces with different degrees of roughness and specific surface area under various plasma operating conditions (S. A. Ledari et al., 2020). Among the samples treated at 7 kV, sample F7 (5 min)

exhibited the lowest roughness value, suggesting the formation of a more compact and uniform surface structure. A similar decreasing trend in roughness with increasing treatment time was also observed at 8 kV, although the magnitude of the reduction was less pronounced than that recorded at 7 kV. Changes in the skewness parameter (Ssk) further indicated that plasma treatment altered the balance between surface peaks and valleys. Depending on the treatment conditions, the resulting surface topography could be dominated either by protrusions formed during surface restructuring or by depressions generated through plasma-induced etching processes.

4.5. FTIR

FTIR spectroscopy was employed to investigate the structural and chemical modifications induced by CAP treatment on QSM. The spectra of the control (F1) and plasma-treated samples (F2-F10) are presented in **Figs. 3**. The broad and intense band centered around 3200–3400 cm^{-1} corresponds to O–H stretching vibrations of hydroxyl groups involved in intra- and intermolecular hydrogen bonding. The peaks at approximately 2920 – 2880 cm^{-1} are attributed to C–H stretching vibrations of methylene and methyl groups. In the fingerprint region, the absorption bands between 1600 – 1400 cm^{-1} are related to asymmetric and symmetric stretching of carboxylate groups (COO^-), while the strong bands in the 1200 – 1000 cm^{-1} region are assigned to C–O–C glycosidic linkages and C–O stretching vibrations of pyranose rings, which constitute the backbone of the polysaccharide structure (Hashemi Gahruie et al., 2023; Mutlu, Palabiyik, et al., 2023; Tahsiri et al., 2025).

Upon CAP treatment, all spectra maintained the overall profile of the native mucilage, indicating that the primary chemical structure of the polysaccharide was largely preserved. However, systematic changes in peak intensity, width, and position were observed as a function of treatment voltage (6, 7, and 8 kV) and exposure time (1, 3, and 5 min). These alterations suggest surface modification, partial oxidation, and possible cross-linking without complete degradation of the polymer chains (Mutlu, Palabiyik, et al., 2023). Specifically, the O–H stretching band (≈ 3200–3400 cm^{-1}) showed a slight decrease in intensity and broadening in several treated samples, particularly at higher voltages and longer treatment durations (e.g., F7, F9, and F10). This observation can be attributed to the consumption of hydroxyl groups through plasma-induced oxidation or the formation of new intermolecular interactions. It is believed that the working gas determines whether cross-linking or oxidation occurs. Noble gases, particularly argon, form reactive species that induce cross-linking and create reactive sites for subsequent reactions, whereas air and oxygen gases oxidize the surface (Mutlu, Palabiyik, et al., 2023). The C–H stretching region (≈ 2920 – 2850 cm^{-1}) remained relatively stable across samples, indicating minimal disruption to the aliphatic chains. These bands are characteristic of polysaccharides, appearing in spectra of others like xylan and carrageenans (Emir Coban et al., 2024). More pronounced modifications occurred in the fingerprint region (1500 – 900 cm^{-1}). Variations in the intensity and resolution of bands around 1100 – 1020 cm^{-1} (C–O–C and C–O vibrations) were evident, with a general trend of increasing changes at higher plasma energies (7–8 kV and 5 min exposure). Some samples displayed shifts or intensity alterations in the carboxylate region (≈ 1600 – 1400 cm^{-1}), suggesting partial oxidation of primary hydroxyl groups to

carbonyl or carboxyl functionalities. No entirely new prominent peaks appeared, confirming that cold plasma treatment acts primarily as a surface modifier rather than causing bulk structural destruction.

4.6. Mechanical properties

Edible films' tensile strength indicates their load-bearing capacity, and their elongation at break shows their flexibility (Song et al., 2026). **Table 4** presents the tensile strength and elongation-at-break values for various edible films.

The mechanical performance of QSM films was markedly influenced by CAP treatment, although the extent and direction of the changes depended strongly on both the applied voltage and exposure time. Among all treatments, sample F2 (6 kV, 1 min) exhibited the highest tensile strength (9.35 MPa), representing an approximately 23% increase compared with the untreated film. Interestingly, this sample also showed the highest elongation at break (11.21%), indicating that the initial CAP treatment simultaneously improved both film strength and flexibility. Plasma exposure time exerted a greater influence on the mechanical properties of QSM films than the applied voltage. In general, short plasma exposure (1 min) resulted in the highest tensile strength and elongation at break, whereas prolonged treatment (5 min) tended to reduce both mechanical parameters. The influence of the applied voltage on the mechanical properties was less consistent than that of treatment time. Lower plasma intensity (6 kV) generally produced superior tensile properties, while increasing the voltage to 8 kV did not further improve the mechanical performance and, in some cases, resulted in a noticeable decline. Kargarzadeh et al. (Kargarzadeh et al., 2017) found similar results in goat milk casein-based composite films, noting that cold plasma treatment significantly improved tensile strength and elongation at break. Cold plasma modification improves the composite system's compatibility and structural stability, reducing stress concentration. This synergistically increases tensile strength and elongation at break (Kargarzadeh et al., 2017).

Similar findings have been reported by Tahsiri et al. (Tahsiri et al., 2025), who observed significant improvements in both tensile strength and elongation at break of wild almond protein isolate-based films following 10 min of cold plasma treatment compared with the untreated control. The authors attributed these enhancements to the generation of metastable reactive species, particularly oxygen- and nitrogen-derived radicals, which effectively promoted the formation of additional intermolecular crosslinks on the film surface. The enhancement in tensile strength can be primarily explained by plasma-induced crosslinking within the polymer network. During plasma exposure, energetic ions, electrons, and reactive species continuously bombard the film surface, resulting in the cleavage of C–H and C–C covalent bonds. The resulting free radicals subsequently undergo radical–radical recombination or participate in chain propagation reactions, leading to the formation of new intermolecular linkages that reinforce the structural integrity of the polymer matrix. Consequently, the continuity and cohesion of the biopolymer network are enhanced, resulting in improved tensile resistance (Tahsiri et al., 2025). In addition to promoting crosslink formation, cold plasma treatment may also increase the free volume between adjacent polymer chains, thereby modifying chain mobility and molecular packing. These structural rearrangements facilitate greater segmental motion of the polymer chains under tensile loading, which

contributes to improved flexibility and higher elongation at break (Nuanmano et al., 2015; Tahsiri et al., 2025). When the treatment duration was extended to 3 and 5 min at 6 kV (F3 and F4), the tensile strength gradually declined toward the control value. This observation indicates that 5 min plasma exposure progressively shifted the dominant mechanism from network reinforcement toward polymer degradation. A different trend was observed at 7 kV. Samples F5 and F6 exhibited reduced tensile strength compared with the control, suggesting that the higher plasma intensity accelerated chain scission and disrupted the continuity of the polysaccharide network. However, extending the treatment to 5 min (F7) restored the tensile strength to 8.76 MPa. This recovery implies that secondary structural rearrangements may occur during 5 min exposure time, allowing newly generated reactive sites to participate in additional intermolecular bonding and partial reconstruction of the polymer network. Such structural reorganization is also supported by the AFM observations, where F7 exhibited the lowest surface roughness among all plasma-treated samples, indicating the formation of a more compact and homogeneous surface morphology. At the highest discharge voltage (8 kV), the mechanical properties deteriorated considerably, particularly in sample F9, which exhibited the lowest tensile strength (2.75 MPa).

The initial structural characteristics of edible films play a crucial role in determining their response to CAP treatment. Differences in polymer composition, molecular architecture, and intermolecular interactions can markedly influence the extent of plasma-induced physicochemical modifications and, consequently, the resulting mechanical performance. In this regard, Moosavi et al. (Moosavi et al., 2020) investigated the effects of CAP on protein-based films and reported that plasma exposure for 5 and 10 min significantly improved the mechanical properties, particularly tensile strength. However, extending the treatment duration to 15 min caused a pronounced decline in tensile strength, indicating that 5 min plasma exposure time adversely affected the structural integrity of the polymer network. The authors proposed that plasma treatment simultaneously induces both physical and chemical etching mechanisms. During plasma exposure, energetic ions bombard the film surface, producing physical etching, while reactive species, particularly oxygen-derived radicals, are generated within the polymer matrix and subsequently participate in radical-mediated reactions, resulting in chemical etching. Under prolonged treatment conditions (5 min), these degradation processes become dominant, leading to excessive erosion of the polymer matrix, disruption of intermolecular cohesion, and deterioration of the film's mechanical strength. These findings further support the existence of an optimum plasma treatment window in which constructive processes, such as molecular activation and crosslinking, outweigh degradation reactions. 3 min exposure time of plasma treatment substantially enhanced film flexibility, whereas more severe plasma conditions like in 5 min, produced only slight improvements or values comparable to the control. The ductility observed in sample F2 further supports the hypothesis that moderate plasma activation (3 min) improves network homogeneity rather than inducing excessive rigidity in 5 min exposure time. In contrast, under higher plasma intensities, molecular degradation likely reduced the continuity of the polymer chains, limiting the ability of the films to undergo plastic deformation before fracture. Goiana et al. (Goiana et al., 2021) reported that cold plasma treatment of corn starch-based films resulted in an approximately 30% reduction in elongation at break compared

with the untreated films. The authors attributed this decrease in film flexibility to the formation of additional hydrogen bonds and the development of a more compact starch network during plasma exposure. These structural modifications restricted polymer chain mobility, thereby reducing the capacity of the films to undergo plastic deformation before fracture. Elongation at break is another critical mechanical parameter that is highly sensitive to plasma-induced structural modifications. Changes in film extensibility are governed by several concurrent mechanisms, including energy transfer from plasma to the polymer surface, interactions with reactive plasma species, surface etching, functionalization, polymer degradation, and intermolecular crosslink formation. The relative contribution of these competing processes determines the mobility of polymer chains and, ultimately, the ability of the film to undergo deformation before fracture (Moosavi et al., 2020). The mechanical results are also in good agreement with the AFM and contact angle analyses. Although plasma treatment significantly modified the surface topography, the mechanical behavior was not directly correlated with surface roughness alone. For example, sample F2 exhibited the highest roughness while simultaneously presenting the greatest tensile strength and elongation at break, whereas sample F9 displayed the lowest mechanical resistance. These findings indicate that the bulk architecture of the polymer matrix, including molecular weight distribution, crosslink density, and network integrity, plays a far more important role than surface morphology in determining the mechanical performance of cold plasma-treated films.

4.7. Thermal properties

The thermal behavior of QSM films was markedly influenced by CAP treatment, as evidenced by the DSC and TGA thermograms (Fig. 4).

4.7.1. TGA

Although all samples exhibited the characteristic multi-stage thermal degradation pattern commonly reported for polysaccharide-based films, the plasma treatment noticeably modified both the thermal transitions and degradation profiles, indicating significant changes in the molecular organization and physicochemical structure of the polymer matrix. The TGA curves revealed that all films underwent three major stages of mass loss. The initial weight reduction observed below approximately 120°C was attributed to the evaporation of physically adsorbed and weakly bound water molecules (Codina et al., 2024). Because QSM is a highly hydrophilic polysaccharide rich in hydroxyl groups, moisture evaporation represents the first thermal event in all samples. Codina et al. (Codina et al., 2024) reported that, in films prepared from QSM, the initial stage of weight loss, occurring within the temperature range of approximately 70–130°C, was predominantly associated with the evaporation of loosely bound water retained within the polysaccharide matrix. This mass loss was attributed to the release of physically adsorbed and weakly bound moisture interacting with the hydrophilic functional groups of the polymer network during thermal heating. The minor differences in plasma-treated films indicate that CAP modifies the polymer matrix by altering intermolecular hydrogen bonding.

The second degradation stage, occurring approximately between 180 and 350°C, corresponded to the principal decomposition of the polysaccharide network. This region is generally associated with

cleavage of glycosidic linkages, dehydration reactions, depolymerization, and decomposition of oxygen-containing functional groups (like hemicellulose, lignin, and cellulose) (Lu et al., 2022; Otoni et al., 2014). According to Codina et al. (Codina et al., 2024), the principal stage of thermal degradation of QSM-based films occurred at approximately 235°C, indicating the relatively high thermal stability of the film matrix. This degradation temperature is consistent with the characteristic thermal decomposition range reported for hemicellulosic polysaccharides (approximately 200–260°C), suggesting that hemicellulose-derived constituents are the dominant components governing the thermal behavior of the films. The authors further concluded that the major weight loss observed during this degradation stage was primarily associated with the decomposition of (4-O-methyl-D-glucurono)-D-xylan, which represents the principal water-soluble polysaccharide in QSM. Moreover, the relatively broad degradation interval was attributed to the presence of multiple chemical linkages and heterogeneous structural domains within the polysaccharide network, resulting in overlapping thermal degradation events. Plasma treatment noticeably affected both the onset and the slope of this degradation region. At 3 min plasma exposure time of treatment, the degradation profile became slightly broader and shifted toward higher temperatures, suggesting an improvement in thermal resistance. This behavior can be attributed to plasma-induced molecular activation followed by the formation of additional intermolecular interactions and limited crosslinking, which stabilized the polymer network against thermal decomposition.

Comparable findings were reported by Chen et al. (Chen et al., 2020) for zein-PLA composite films, where cold plasma treatment for 60 and 120s produced films with enhanced thermal stability. The authors attributed this improvement to the strengthening of intermolecular hydrogen bonding interactions between zein and PLA molecules induced by plasma exposure. Interestingly, they also observed that the greatest increase in thermal degradation temperature was achieved after 45 s of plasma treatment, whereas prolonged exposure resulted in a decline in the thermal stability of the films, suggesting that the 5 min plasma treatment may adversely affect the integrity of the polymer network. Similarly, Dong et al. (Dong et al., 2018) reported that atmospheric cold plasma treatment for 60 s promoted the cross-linking of polar functional groups generated on the surface of zein-based films. This plasma-induced surface cross-linking contributed to the formation of a more compact polymeric network, thereby improving the structural stability of the film matrix.

However, increasing the plasma intensity or treatment duration altered this trend. Several highly treated samples exhibited a steeper mass-loss profile during the principal degradation stage, indicating that 5 min plasma exposure time promoted chain scission and partial depolymerization of the mucilage molecules prior to thermal analysis. Pankaj et al. (Pankaj, Bueno-Ferrer, et al., 2014) demonstrated that DBD plasma treatment reduced the Tg of sodium caseinate films. They attributed this reduction to plasma-induced chemical etching, which involved the cleavage of chemical bonds, polymer chain scission, and partial degradation of the biopolymer matrix. These structural modifications increased chain mobility within the polymer network, ultimately leading to a lower Tg. Under these conditions, degradation processes induced by reactive oxygen and nitrogen species (RONS) became dominant over crosslinking reactions, resulting in a polymer matrix with lower molecular integrity and consequently reduced thermal stability (M. Hoque et al., 2022). The final degradation stage, extending above

approximately 350–400°C, was associated with carbonization and decomposition of the remaining carbonaceous residue. Although all samples eventually reached similar residual masses, slight differences in the final residue suggest that plasma treatment modified the carbonization behavior of the films, reflecting alterations in the molecular architecture generated during plasma exposure.

4.7.2. DSC

The DSC thermograms of QSM films exhibited a broad endothermic transition at approximately 70–110°C, which was attributed to the evaporation of physically adsorbed water and the disruption of weak hydrogen bonds within the hydrated polysaccharide network. The initial mass loss observed in QSM is primarily attributed to the evaporation of physically bound water associated with its hydrophilic functional groups. Owing to the abundance of polar moieties within the polysaccharide matrix, the mucilage exhibits a high water-binding capacity by retaining water molecules through weak non-covalent interactions. Upon heating within this temperature range, these loosely bound water molecules are progressively released from the polymeric network across all samples, resulting in the observed weight reduction (Emir Coban et al., 2024). A similar thermal behavior was reported by Davachi et al. (Davachi et al., 2021), who investigated the effect of probiotic incorporation on edible films formulated from quince seed, flaxseed, and basil seed mucilages. Their findings demonstrated that all film formulations exhibited a distinct endothermic peak at approximately 100°C, which was attributed to the loss of trapped moisture, or the heat and water-induced phase transitions within the film's gel structure. CAP-treated samples, particularly F2 and F6, showed a noticeable reduction in the intensity of this endothermic event, indicating a lower water-holding capacity and a denser polymer structure.

A baseline shift observed around 60–67°C was assigned to the glass transition region. The glass transition temperature (Tg) represents a critical thermal threshold that governs the mechanical performance of polymeric films. Below Tg, the polymer matrix remains in a rigid, glassy, and brittle state, whereas above Tg, enhanced molecular mobility transforms the material into a more flexible and rubbery state (Jouki et al., 2013). The Tg values of F2 and F6 appeared slightly higher than that of the control film, suggesting restricted molecular mobility due to plasma-induced intermolecular interactions and partial crosslinking. In contrast, F9 exhibited a lower Tg, indicating increased chain mobility resulting from plasma-induced chain scission and depolymerization. In the study conducted by Davachi et al. (Davachi et al., 2021), mucilage-based films exhibited a glass transition temperature (Tg) ranging from 67 to 74°C. The authors attributed such variations to the inherent compositional and structural diversity of different plant-derived mucilages. Since the physicochemical characteristics, molecular architecture, and polysaccharide composition of mucilages vary depending on their botanical origin, differences in their thermal transition behavior, including Tg, are expected among different film systems. The most significant thermal event was the major endothermic melting transition occurring at approximately 220–245°C. This thermal transition can be attributed to the initiation of combustion, sample decomposition, and glycosidic bond cleavage (Davachi et al., 2021). CAP treatment shifted the melting peak toward higher temperatures in F2, F6, and F7, reflecting enhanced molecular ordering, stronger intermolecular interactions, and increased structural cohesion. The highest melting temperature was observed for F6,

whereas F9 showed a clear shift toward lower temperatures, indicating reduced thermal stability and disruption of ordered domains within the polymer matrix. The observed reduction in the melting temperature may be attributed to a decrease in the number of hydroxyl (-OH) groups present in the QSM molecules. Since these functional groups play a critical role in establishing intermolecular hydrogen bonding between adjacent polysaccharide chains, their reduction weakens the polymeric network, thereby lowering the thermal energy required for the melting transition (Jouki et al., 2013). Additionally, weak exothermic features detected around 165–190°C in F2, F6, and F7 were attributed to structural relaxation and molecular rearrangement prior to melting. Ledari et al. (S. A. Ledari et al., 2020) reported that DBD cold plasma treatment using air as the working gas increased the melting temperature of gelatin emulsion-based films. The authors attributed this enhancement primarily to plasma-induced modifications in polymer chain mobility within the film matrix. Cold plasma generates highly reactive species and free radicals on the film surface, promoting surface cross-linking reactions that alter the film network and consequently influence its barrier properties (Oh et al., 2016). These structural modifications may also contribute to significant differences in the mass-loss behavior of the samples during the moisture evaporation stage of thermal analysis. Furthermore, Ledari et al. (S. A. Ledari et al., 2020) suggested that part of the observed variation in the melting temperature could be associated with the removal of water from the film matrix during the initial heating cycle. Since water acts as an effective plasticizer in hydrocolloid-based films, its presence enhances polymer chain mobility, whereas moisture loss during heating reduces chain flexibility and consequently shifts the thermal transition to higher temperatures. Overall, these findings demonstrate that CAP modifies the thermal performance of QSM films through two competing mechanisms. Under optimized treatment conditions, plasma-generated reactive species promote intermolecular crosslinking, molecular rearrangement, and increased structural cohesion, thereby enhancing thermal stability. However, 5 min plasma exposure time intensifies oxidative etching, chain scission, and depolymerization, leading to a progressive decline in the thermal resistance of the biopolymer matrix. The balance between these constructive and destructive processes ultimately determines the thermal behavior of plasma-treated QSM films.

5. Conclusion

Increasing concerns over the environmental and health impacts of petroleum-based plastics have driven the development of biodegradable biopolymer-based packaging. Among available surface modification techniques, cold atmospheric plasma (CAP) has emerged as an efficient and eco-friendly strategy for improving film performance. In the present study, extracted QSM solution was subjected to atmospheric CAP treatment prior to film formation. During plasma exposure, energetic reactive species continuously interacted with the biopolymer surface, inducing surface etching, increasing surface roughness, and modifying the surface chemistry of the polymer matrix. The results indicate that plasma exposure time plays a more decisive role than the applied voltage in modulating the structural and physicochemical properties of the films. CAP treatment for up to 3 min effectively enhanced the functional performance of QSM films, as evidenced by increased surface hydrophobicity, lower water vapor permeability, and improved mechanical and thermal properties compared with the untreated control. However, extending

the exposure time to 5 min adversely affected the barrier, mechanical, and thermal performance of the films, suggesting that excessive plasma treatment promotes structural degradation of the biopolymer network. The results further demonstrate that CAP modifies the physicochemical, barrier, mechanical, and thermal properties of QSM-based films through two competing mechanisms. Under optimized processing conditions (3 min exposure time), plasma-generated reactive species promote intermolecular cross-linking, molecular rearrangement, and structural densification, thereby reinforcing the polymer network and improving its thermal stability and mechanical integrity. Conversely, excessive plasma exposure time (5 min) intensifies oxidative etching, polymer chain scission, and depolymerization, ultimately compromising the barrier performance, tensile strength, and thermal resistance of the biopolymer matrix. Therefore, the final properties of plasma-treated QSM films are governed by the dynamic balance between these constructive and degradative processes. Furthermore, the present findings indicate that the effectiveness of CAP treatment is highly material-dependent and is strongly influenced by the intrinsic molecular architecture of the biopolymer. Specifically, the distribution, density, accessibility, and spatial orientation of surface functional groups largely determine the extent of plasma-induced modifications by regulating the resulting surface free energy and, consequently, the overall functional characteristics of the films. These findings provide valuable insight into the optimization of plasma processing conditions for the development of high-performance, biodegradable polysaccharide-based packaging materials with enhanced applicability in sustainable food packaging systems.

Declarations

Conflict of Interest

There is no conflict of interest.

Declaration of AI in Scientific Writing

ChatGPT was used exclusively to assist with language editing and to improve the clarity and readability of the manuscript. All AI-generated suggestions were critically reviewed, revised where necessary, and approved by the authors. The authors accept full responsibility for the accuracy, integrity, and scientific content of the final published manuscript.

Funding Declaration

The authors received no funding for this work.

Author Contribution

Javaneh Krimi: Investigation and experimentation, data collection.Sahand Sohrabi: Data analysis, writing – original draft preparation.Mojtaba Moezzi Rad & Mehdi Sharifian: Resources provision, experimental

support.Leila Zare: Writing – review & editing, final draft approval.Neda Mollakhalili Meybodi: Supervision, methodology validation, final manuscript approval.

Acknowledgements

The authors gratefully acknowledge the support provided by Shahid Sadoughi University of Medical Sciences, Yazd, Iran, particularly the Student Research Committee, as well as Shahid Beheshti University of Medical Sciences, Tehran, Iran, whose valuable assistance contributed to the successful completion of this original article.

Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information.

References

1. Ahmed, J., Ravichandran, S., Thakur, R., Mulla, M., & Sarkar, P. (2023). Thermo-mechanical, rheological, microstructural, and barrier properties of gum-based edible packaging: A review. *Food Packaging and Shelf Life*, *38*, 101117. https://doi.org/10.1016/j.fpsl.2023.101117
2. Amirabadi, S., Milani, J. M., & Sohbatzadeh, F. (2020). Application of dielectric barrier discharge plasma to hydrophobically modification of gum arabic with enhanced surface properties. *Food Hydrocolloids*, *104*, 105724.
3. Bahrami, R., Zibaei, R., Hashami, Z., Hasanvand, S., Garavand, F., Rouhi, M., Jafari, S. M., & Mohammadi, R. (2022). Modification and improvement of biodegradable packaging films by cold plasma; a critical review. *Crit Rev Food Sci Nutr*, *62*(7), 1936–1950. https://doi.org/10.1080/10408398.2020.1848790
4. Basak, S., & Annapure, U. S. (2023). Rheological performance of film-forming solutions and barrier properties of films fabricated from cold plasma-treated high methoxyl apple pectin and crosslinked by Ca2+: Impact of plasma treatment voltage [Article]. *Int J Biol Macromol*, *227*, 938–951. https://doi.org/10.1016/j.ijbiomac.2022.12.161
5. Chen, G., Chen, Y., Jin, N., Li, J., Dong, S., Li, S., Zhang, Z., & Chen, Y. (2020). Zein films with porous polylactic acid coatings via cold plasma pre-treatment. *Industrial Crops and Products*, *150*, 112382.
6. Cheng, J., Gao, R., Zhu, Y., & Lin, Q. (2024). Applications of biodegradable materials in food packaging: A review. *Alexandria Engineering Journal*, *91*, 70–83. https://doi.org/10.1016/j.aej.2024.01.080
7. Codina, M. C., González, E. J., Molina, A., Carmona, M., & Berruga, M. I. (2024). Bio-based films from quince by-products: A sustainable alternative for biodegradable food packaging. *Food Hydrocolloids*, *157*, 110395. https://doi.org/https://doi.org/10.1016/j.foodhyd.2024.110395

8. Dauwe, R., Roulard, R., Ramos, M., Thiombiano, B., Mesnard, F., Gontier, E., & Jamali, A. (2021). Etching of the seed cuticle by cold plasma shortens imbibitional leakage in Linum usitatissimum L. *Industrial Crops and Products*, *167*, 113536. https://doi.org/https://doi.org/10.1016/j.indcrop.2021.113536
9. Davachi, S. M., Pottackal, N., Torabi, H., & Abbaspourrad, A. (2021). Development and characterization of probiotic mucilage based edible films for the preservation of fruits and vegetables. *Scientific Reports*, *11*(1), 16608. https://doi.org/10.1038/s41598-021-95994-5
10. Dick, M., Costa, T. M. H., Gomaa, A., Subirade, M., Rios, A. d. O., & Flôres, S. H. (2015). Edible film production from chia seed mucilage: Effect of glycerol concentration on its physicochemical and mechanical properties. *Carbohydrate Polymers*, *130*, 198–205. https://doi.org/https://doi.org/10.1016/j.carbpol.2015.05.040
11. Dimitrakellis, P., & Gogolides, E. (2018). Hydrophobic and superhydrophobic surfaces fabricated using atmospheric pressure cold plasma technology: A review. *Adv Colloid Interface Sci*, *254*, 1–21. https://doi.org/10.1016/j.cis.2018.03.009
12. Dong, S., Guo, P., Chen, G.-y., Jin, N., & Chen, Y. (2020). Study on the atmospheric cold plasma (ACP) treatment of zein film: Surface properties and cytocompatibility. *Int J Biol Macromol*, *153*, 1319–1327.
13. Dong, S., Guo, P., Chen, Y., Chen, G.-y., Ji, H., Ran, Y., Li, S.-h., & Chen, Y. (2018). Surface modification via atmospheric cold plasma (ACP): Improved functional properties and characterization of zein film. *Industrial Crops and Products*, *115*, 124–133. https://doi.org/https://doi.org/10.1016/j.indcrop.2018.01.080
14. Emir Coban, O., Akat, Z., Karatepe, P., & Incili, G. K. (2024). In vitro bioactivity of biodegradable films based on chitosan/quince seed mucilage reinforced with ZnO-nanoparticle. *Journal of Food Measurement and Characterization*, *18*(7), 5450–5461. https://doi.org/10.1007/s11694-024-02579-7
15. Erkaya-Kotan, T., Gürbüz, Z., Dağdemir, E., & Şengül, M. (2023). Utilization of edible coating based on quince seed mucilage loaded with thyme essential oil: Shelf life, quality, and ACE-inhibitory activity efficiency in Kaşar cheese. *Food Bioscience*, *54*, 102895. https://doi.org/https://doi.org/10.1016/j.fbio.2023.102895
16. Esfandiari, Z., Hassani, B., Sani, I. K., Talebi, A., Mohammadi, F., Zomorodi, S., Kaveh, M., Assadpour, E., Khodaei, S. M., & Eghbaljoo, H. (2025). Characterization of edible films made with plant carbohydrates for food packaging: A comprehensive review. *Carbohydrate Polymer Technologies and Applications*, 100979.
17. Goiana, M. L., de Brito, E. S., Alves Filho, E. G., Miguel, E. D. C., Fernandes, F. A. N., Azeredo, H. M. C. D., & Rosa, M. D. F. (2021). Corn starch based films treated by dielectric barrier discharge plasma [Article]. *Int J Biol Macromol*, *183*, 2009–2016. https://doi.org/10.1016/j.ijbiomac.2021.05.210
18. Goksen, G., Demir, D., Dhama, K., Kumar, M., Shao, P., Xie, F., Echegaray, N., & Lorenzo, J. M. (2023). Mucilage polysaccharide as a plant secretion: Potential trends in food and biomedical applications. *Int J Biol Macromol*, *230*, 123146. https://doi.org/https://doi.org/10.1016/j.ijbiomac.2023.123146

19. Guillard, V., Gaucel, S., Fornaciari, C., Angellier-Coussy, H., Buche, P., & Gontard, N. (2018). The Next Generation of Sustainable Food Packaging to Preserve Our Environment in a Circular Economy Context. *Front Nutr*, *5*, 121. https://doi.org/10.3389/fnut.2018.00121
20. Hashemi Gahruie, H., Eskandari, M. H., Sadeghi, R., & Hosseini, S. M. H. (2023). Atmospheric Pressure Cold Plasma Modification of Basil Seed Gum for Fabrication of Edible Film Incorporated with Nanophytosomes of Vitamin D3 and Tannic Acid. *Foods*, *12*(1), 71. https://www.mdpi.com/2304-8158/12/1/71
21. Hoque, M., McDonagh, C., Tiwari, B. K., Kerry, J. P., & Pathania, S. (2022). Effect of Cold Plasma Treatment on the Packaging Properties of Biopolymer-Based Films: A Review. *Applied Sciences*, *12*(3), 1346. https://www.mdpi.com/2076-3417/12/3/1346
22. Hoque, M., McDonagh, C., Tiwari, B. K., Kerry, J. P., & Pathania, S. (2022). Effect of Cold Plasma Treatment on the Packaging Properties of Biopolymer-Based Films: A Review [Review]. *Applied Sciences (Switzerland)*, *12*(3), Article 1346. https://doi.org/10.3390/app12031346
23. Huhtamäki, T., Tian, X., Korhonen, J. T., & Ras, R. H. (2018). Surface-wetting characterization using contact-angle measurements. *Nature protocols*, *13*(7), 1521–1538.
24. Jouki, M., Tabatabaei Yazdi, F., Mortazavi, S. A., & Koocheki, A. (2013). Physical, barrier and antioxidant properties of a novel plasticized edible film from quince seed mucilage. *Int J Biol Macromol*, *62*, 500–507. https://doi.org/https://doi.org/10.1016/j.ijbiomac.2013.09.031
25. Kargarzadeh, H., Johar, N., & Ahmad, I. (2017). Starch biocomposite film reinforced by multiscale rice husk fiber. *Composites Science and Technology*, *151*, 147–155.
26. Kashiri, M., & Davtalab, M. (2023). Effect of sorbitol concentration on physical and mechanical properties of bio-based film of quince seed mucilage. *Journal of food science and technology(Iran)*, *19*(132), 199–210. https://doi.org/10.22034/fsct.19.132.199
27. Khan, A., Gallah, H., Riedl, B., Bouchard, J., Sáfrány, Á., & Lacroix, M. (2016). Genipin cross-linked antimicrobial nanocomposite films and gamma irradiation to prevent the surface growth of bacteria in fresh meats. *Innovative Food Science & Emerging Technologies*, *35*. https://doi.org/10.1016/j.ifset.2016.03.011
28. Kozlu, A., & Elmacı, Y. (2024). Utilization of Mucilage from Quince Fruit Seeds as an Edible Coating to Improve the Quality of Fresh Turkey Breast During Cold Storage. *Waste and Biomass Valorization*. https://doi.org/10.1007/s12649-024-02855-z
29. Kumari, S. V. G., Pakshirajan, K., & Pugazhenthi, G. (2022). Recent advances and future prospects of cellulose, starch, chitosan, polylactic acid and polyhydroxyalkanoates for sustainable food packaging applications. *Int J Biol Macromol*, *221*, 163–182. https://doi.org/10.1016/j.ijbiomac.2022.08.203
30. Ledari, S. A., Milani, J. M., & Lanbar, F. S. (2020). Improving gelatin-based emulsion films with cold plasma using different gases. *Food Sci Nutr*, *8*(12), 6487–6496. https://doi.org/10.1002/fsn3.1939
31. Ledari, S. A., Milani, J. M., & Lanbar, F. S. (2020). Improving gelatin-based emulsion films with cold plasma using different gases. *Food Science & Nutrition*, *8*(12), 6487–6496.

32. Li, Y., Huang, X., Yang, Y., Mulati, A., Hong, J., & Wang, J. (2025). The Effects of Cold-Plasma Technology on the Quality Properties of Fresh-Cut Produce: A Review. *Foods*, *14*(2), 149. https://www.mdpi.com/2304-8158/14/2/149
33. Lu, X., Chen, Z., Ma, Q., Mu, J., Li, X., & Liu, H. (2022). Preparation and Characterization of Yellow Peach Peel/Sodium Alginate/Glycerol Antioxidant Film Applicable for Oil Package. *Polymers*, *14*(9), 1693. https://www.mdpi.com/2073-4360/14/9/1693
34. Mohammadi, X., Matinfar, G., Hossain, A., & Pratap-Singh, A. (2026). Cold-plasma surface engineering induces multifunctional enhancements in biodegradable packaging films [Review]. *Trends in Food Science and Technology*, *167*, Article 105445. https://doi.org/10.1016/j.tifs.2025.105445
35. Moosavi, M. H., Khani, M. R., Shokri, B., Hosseini, S. M., Shojaee-Aliabadi, S., & Mirmoghtadaie, L. (2020). Modifications of protein-based films using cold plasma. *Int J Biol Macromol*, *142*, 769–777. https://doi.org/10.1016/j.ijbiomac.2019.10.017
36. Mutlu, S., Kopuk, B., & Palabiyik, I. (2023). Effect of Cold Atmospheric Pressure Argon Plasma Jet Treatment on the Freeze-Dried Mucilage of Chia Seeds (Salvia hispanica L.). *Foods*, *12*(8), 1563. https://www.mdpi.com/2304-8158/12/8/1563
37. Mutlu, S., Palabiyik, I., Kopuk, B., Gunes, R., Boluk, E., Bagcı, U., Özmen, D., Toker, O. S., & Konar, N. (2023). Modification of chia (Salvia hispanica L.) seed mucilage (a heteropolysaccharide) by atmospheric pressure cold plasma jet treatment. *Food Bioscience*, *56*, 103178. https://doi.org/https://doi.org/10.1016/j.fbio.2023.103178
38. Nuanmano, S., Prodpran, T., & Benjakul, S. (2015). Potential use of gelatin hydrolysate as plasticizer in fish myofibrillar protein film. *Food Hydrocolloids*, *47*, 61–68.
39. Oh, Y. A., Roh, S. H., & Min, S. C. (2016). Cold plasma treatments for improvement of the applicability of defatted soybean meal-based edible film in food packaging. *Food Hydrocolloids*, *58*, 150–159.
40. Otoni, C. G., de Moura, M. R., Aouada, F. A., Camilloto, G. P., Cruz, R. S., Lorevice, M. V., de FF Soares, N., & Mattoso, L. H. (2014). Antimicrobial and physical-mechanical properties of pectin/papaya puree/cinnamaldehyde nanoemulsion edible composite films. *Food Hydrocolloids*, *41*, 188–194.
41. Pankaj, S. K., Bueno-Ferrer, C., Misra, N., O'Neill, L., Tiwari, B., Bourke, P., & Cullen, P. (2014). Physicochemical characterization of plasma-treated sodium caseinate film. *Food Research International*, *66*, 438–444.
42. Pankaj, S. K., Bueno-Ferrer, C., Misra, N., Bourke, P., & Cullen, P. (2014). Zein film: Effects of dielectric barrier discharge atmospheric cold plasma. *Journal of Applied Polymer Science*, *131*(18).
43. Romani, V. P., Olsen, B., Collares, M. P., Oliveira, J. R. M., Prentice-Hernández, C., & Martins, V. G. (2019). Improvement of fish protein films properties for food packaging through glow discharge plasma application. *Food Hydrocolloids*, *87*, 970–976.
44. Sani, I. K., Aminoleslami, L., Mirtalebi, S. S., Sani, M. A., Mansouri, E., Eghbaljoo, H., Jalil, A. T., Thanoon, R. D., Khodaei, S. M., Mohammadi, F., & Kazemzadeh, B. (2023). Cold plasma technology:

Applications in improving edible films and food packaging. *Food Packaging and Shelf Life*, *37*, 101087. https://doi.org/https://doi.org/10.1016/j.fpsl.2023.101087

45. Segat, A., Misra, N., Cullen, P., & Innocente, N. (2015). Atmospheric pressure cold plasma (ACP) treatment of whey protein isolate model solution. *Innovative Food Science & Emerging Technologies*, *29*, 247–254.
46. Song, A. Y., Oh, Y. A., Roh, S. H., Kim, J. H., & Min, S. C. (2016). Cold Oxygen Plasma Treatments for the Improvement of the Physicochemical and Biodegradable Properties of Polylactic Acid Films for Food Packaging. *J Food Sci*, *81*(1), E86-96. https://doi.org/10.1111/1750-3841.13172
47. Song, S., Song, J., Liu, J., Lei, Q., Li, C., Ge, W., & Zhang, J. (2026). Cold plasma-modified goat milk casein/Chinese yam polysaccharide/chitosan composite films: Structural, functional, and preservative properties for fresh pork [Article]. *Food Chemistry*, *513*, Article 148874. https://doi.org/10.1016/j.foodchem.2026.148874
48. Tahsiri, Z., Hedayati, S., & Niakousari, M. (2023). Improving the functional properties of wild almond protein isolate films by Persian gum and cold plasma treatment [Article]. *Int J Biol Macromol*, *229*, 746–751. https://doi.org/10.1016/j.ijbiomac.2022.12.321
49. Tahsiri, Z., Hedayati, S., & Niakousari, M. (2025). Improving the techno-functionality of wild almond protein isolate-based films by its hydrolysates and cold plasma treatment [Article]. *Food Hydrocolloids for Health*, *7*, Article 100199. https://doi.org/10.1016/j.fhfh.2025.100199
50. Tosif, M. M., Najda, A., Bains, A., Kaushik, R., Dhull, S. B., Chawla, P., & Walasek-Janusz, M. (2021). A Comprehensive Review on Plant-Derived Mucilage: Characterization, Functional Properties, Applications, and Its Utilization for Nanocarrier Fabrication. *Polymers*, *13*(7), 1066. https://www.mdpi.com/2073-4360/13/7/1066
51. Urena-Saborio, H., Alfaro-Viquez, E., Esquivel-Alvarado, D., Madrigal-Carballo, S., & Gunasekaran, S. (2018). Electrospun plant mucilage nanofibers as biocompatible scaffolds for cell proliferation. *Int J Biol Macromol*, *115*, 1218–1224. https://doi.org/https://doi.org/10.1016/j.ijbiomac.2018.04.129

Figures

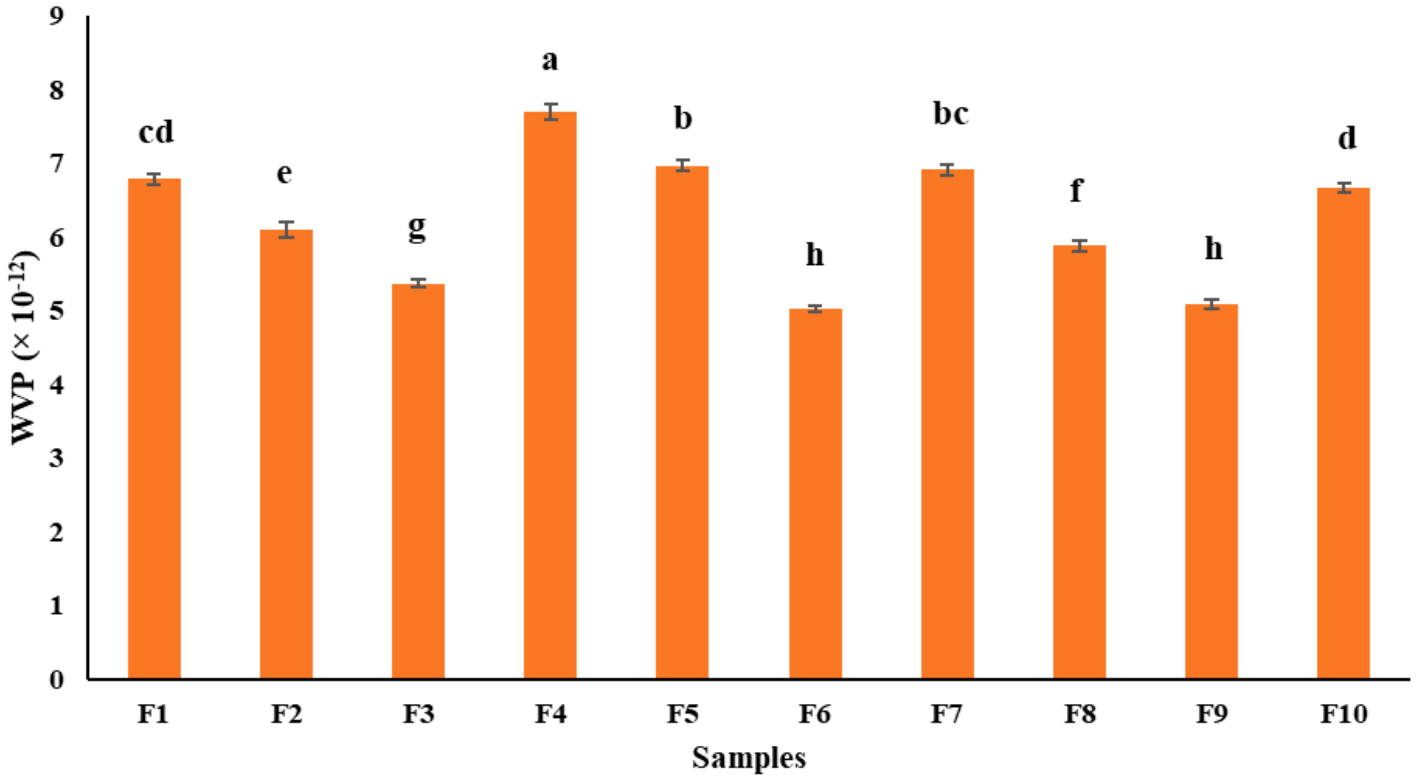


Figure 1

Effect of cold plasma treatment on WVP of Quince seed mucilage film.

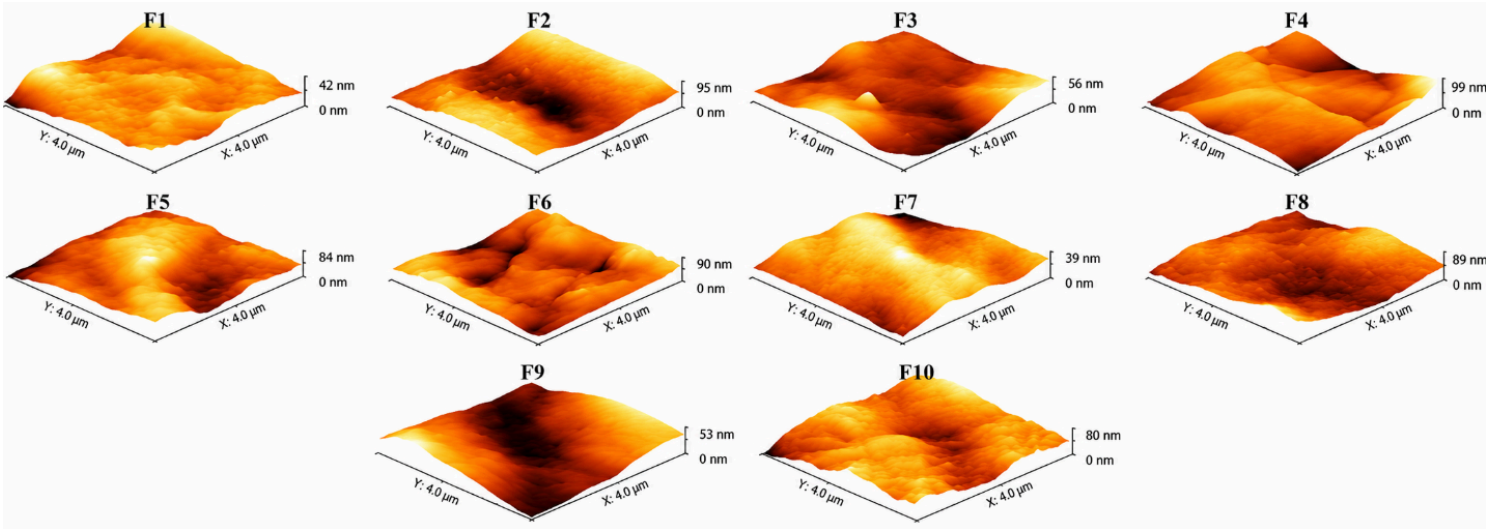


Figure 2

Three-dimensional AFM topographic images of cold plasma treated Quince seed mucilage film.

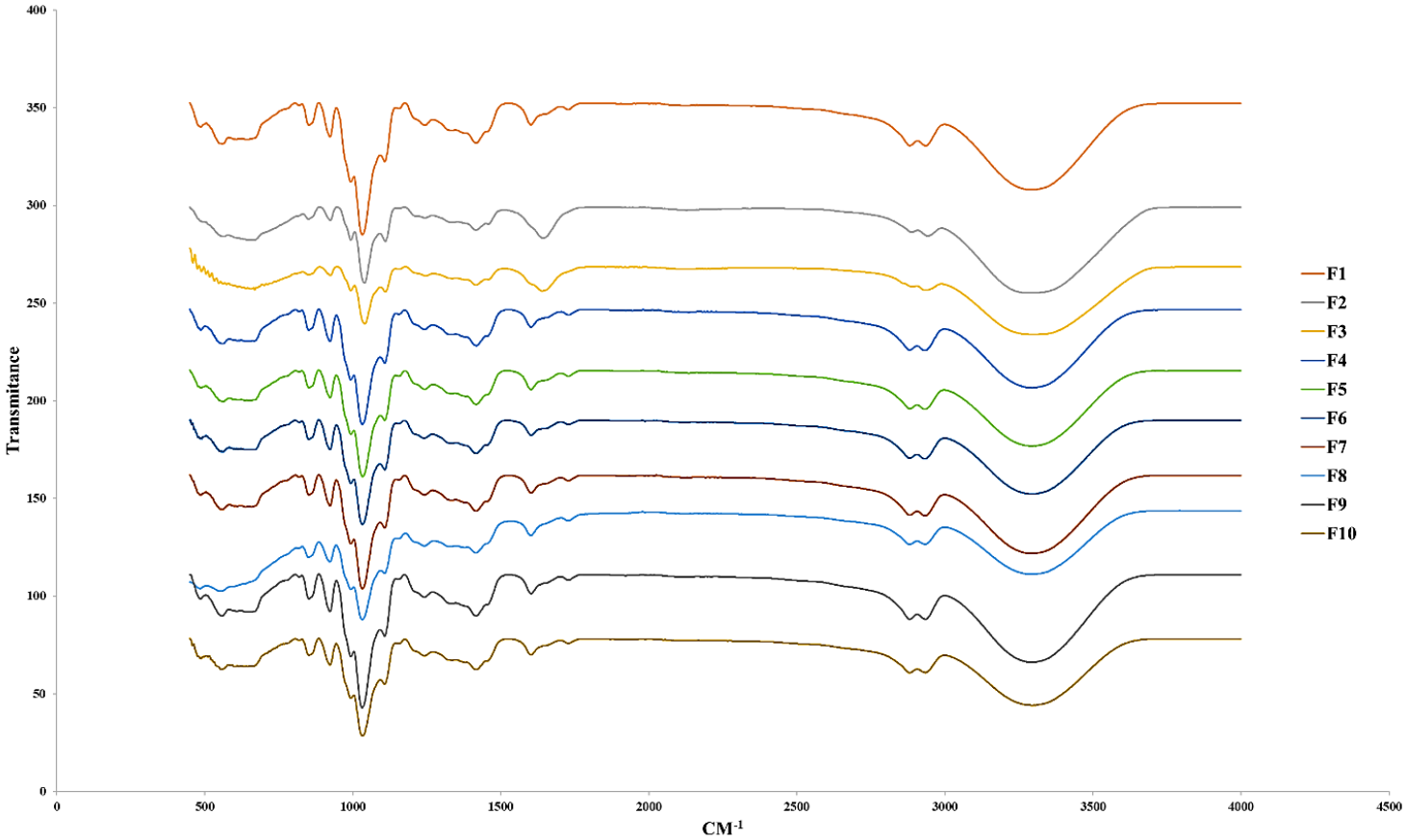
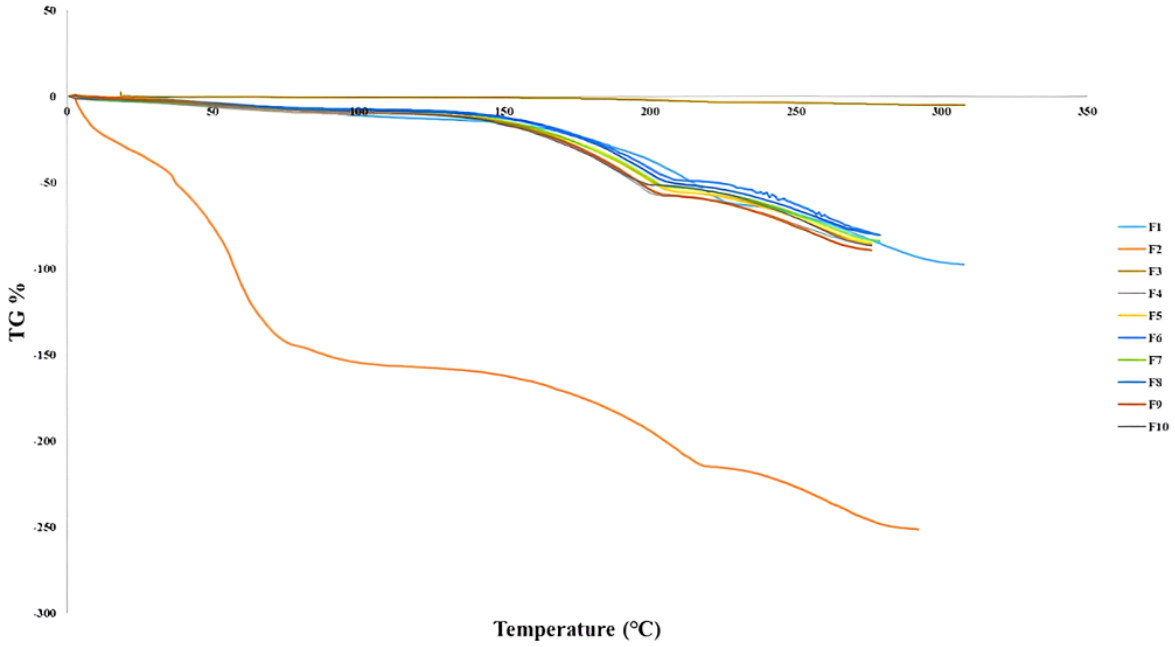
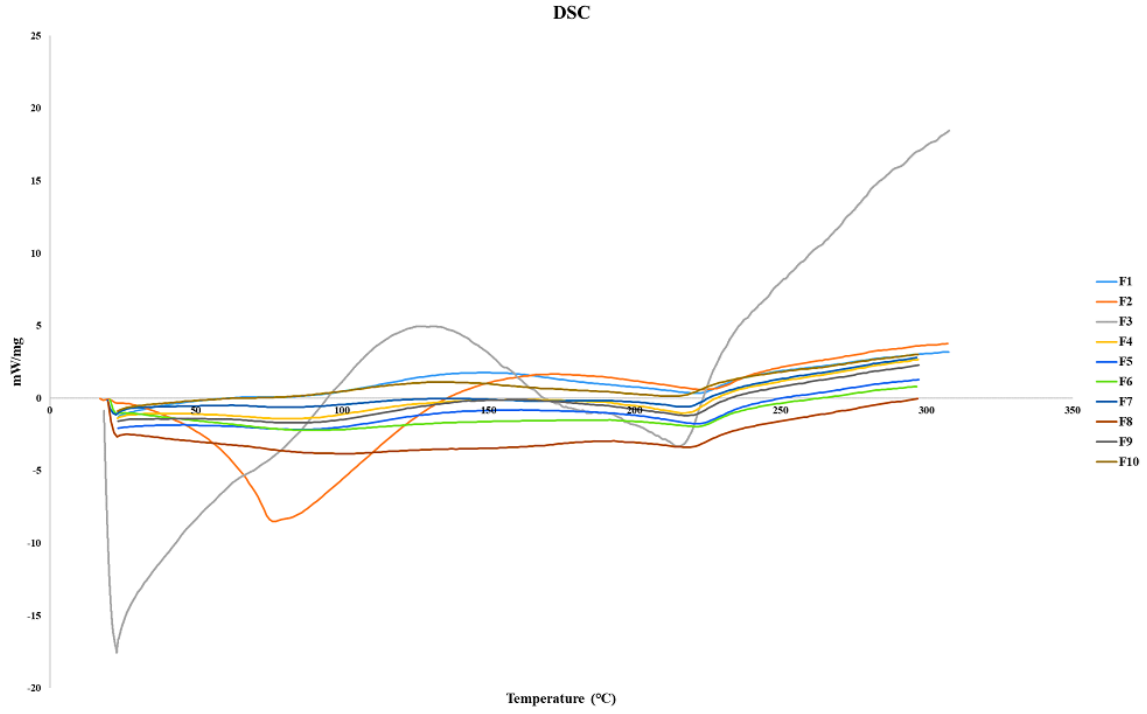


Figure 3

FTIR analysis of cold plasma treated Quince seed mucilage films.



A)



B)

Figure 4

Thermal behavior of QSM/CAP treatment films. **A)** TGA and **B)**DSC.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Graphicalabstract.pdf
- highlights.docx