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Research article

Structural, mechanical, barrier and antioxidant properties of pectin and xanthan gum edible films loaded with grapefruit essential oil

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ABSTRACT

This research focused on the development of films based on pectin and xanthan gum composite loaded with different concentrations of grapefruit essential oil (GFO). The fabricated films were characterized to assess the effect of GFO on the structural, mechanical, barrier, chemical, and antioxidant properties. The addition of GFO enhanced the functional properties of the films, as confirmed by FTIR analysis showing molecular interactions within the film matrix. SEM observations revealed that films with higher GFO content had a smoother, more compact structure with uniform oil distribution. Films loaded with oil demonstrated enhanced water resistance, as their decreased permeability ranged from 0.733 ± 0.009 to 0.561 ± 0.020 (g mm)/(m^2.h.kPa). Additionally, these films showed a notable increase in tensile strength, ranging from 2.91 ± 0.19 to 8.55 ± 0.62 MPa. However, the addition of oil led to a reduction in the elongation at break of the films, which decreased from 52.84 ± 3.41 % to 12.68 ± 1.52 %, and a decline in transparency from 87.57 ± 0.65 % to 76.18 ± 1.12 %. Fabricated films exhibited enhanced antioxidant properties, as evidenced by increased DPPH$^{\bullet}$ and ABTS$^{\bullet+}$ radical scavenging activities with the addition of GFO. The findings of the current study suggest that GFO is an effective natural additive for enhancing the physiochemical properties of pectin and xanthan gum-based films, making them more suitable for food packaging applications.

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1. Introduction

Biopolymer-based films have recently increased due to their non-toxic, biodegradable, eco-friendly, and edible nature. These films effectively prolong the shelf life of food products, enhance food quality, and shield against environmental factors like heat and humidity [1,2]. By incorporating bioactive components such as essential oils, the characteristics and quality of biopolymers can be improved. Biopolymers enriched with essential oils, also known as bioactive polymers, possess properties such as antimicrobial and antioxidant activity [3–5]. Grapefruit oil contains a high amount of phenolic acid, flavanones, and flavonoids and is characterized by a pleasant odor [6]. In addition, it exhibits favorable biological properties such as antibacterial and antioxidant effects [7]. Incorporating grapefruit oil as an active component in edible films can provide a useful approach to improve the safety and quality of products and boost their antioxidant properties.

A suitable biopolymer is important for developing effective edible films with desirable properties. Pectin is a naturally occurring polysaccharide in various vegetables and fruits, including citrus peel. Due to its unique physicochemical properties, it has been utilized in the food industry for food applications, primarily as a thickening, stabilizer, and gelling agent [8]. Pectin has been used to fabricate edible films for its various properties, such as improving product quality, making a barrier against carbon dioxide and oxygen, and good mechanical properties [9]. Xanthan gum, a polymer produced by *Xanthomonas campestris*, has shown great promise in various applications as an emulsifier, thickener, or stabilizer. Incorporating Xanthan gum into films has been demonstrated to improve the sensory and mechanical properties of the resulting films [10]. Lima et al. [10] proposed a study in which a film composed of xanthan gum, chitosan, and whitemouth croaker protein hydrolysate was prepared. The investigation revealed that incorporating xanthan gum significantly enhanced the film's mechanical properties [10]. Another study involved the development of a film composed of Arabic and xanthan gums, which was loaded with lemon grass oil. The study findings indicated that the film improved the overall quality of strawberries and enhanced antioxidant properties [11]. In a study by Fan et al. [12], an edible film composed of pectin, sodium alginate, and xanthan gum was developed and evaluated. The findings demonstrated that the composite film exhibited favorable properties, presenting a promising option for food packaging applications [12]. Studies have indicated that grapefruit essential oil (GFO) possesses an extensive spectrum of bioactive properties. Notably, it has demonstrated inhibitory effects on the proliferation of various food-borne spoilage bacteria and pathogenic microbial strains [13]. Additionally, GFO is known for its distinct aromatic profile, contributing a refreshing citrus flavor and aroma to various food products, thus augmenting their sensory appeal. Beyond its preservative and flavoring roles, GFO is also valued for its potential health benefits, including antioxidant properties, which align with the growing consumer demand for natural and health-promoting ingredients in foods [14]. The effects of GFO on the physicochemical characteristics of pectin (PC) and xanthan gum (XG) have not been studied. Therefore, this study focuses on fabricating and evaluating edible composite films made from PC and XG, incorporated with varying amounts of GFO.

2. Materials and methods

2.1. Chemicals

Pectin and xanthan gum were purchased from Sisco Research Laboratories Pvt Ltd. Mumbai, India. The Grapefruit essential oil (Batch no. NNIGFEO/107/0821) utilized in the study was provided by Nature Natural India. Glycerol was supplied by BDH Laboratory (London, England). In addition, other chemicals used in antioxidant studies were obtained from Sigma-Aldrich (St. Louis, MO, USA). All chemicals were of analytical grade.

2.2. Film formation

Edible films were prepared by casting method as mentioned in our previous study [15]. Both biopolymers, pectin, and xanthan gum, were mixed separately with distilled water to obtain the filmogenic solutions of 1.5 % (w/v). After mixing the two solutions, 0.3 % glycerol (v/v) as a plasticizer was added, and the resulting mixture was subjected to magnetic stirring for 3 h. Following a complete homogenization of the film-forming compounds, the solution was evenly distributed between four different beakers, each of which was subsequently named PG-1, PG-2, PG-3, and PG-4. Varying amounts 20 μL, 30 μL, and 40 μL of grapefruit essential oil (GFO) were added to PG-2, PG-3, and PG-4, respectively. PG-1 was selected as a blank and was not added with GFO. Afterward, 20 ml from each obtained solution was carefully distributed onto properly labeled Petri plated (90 × 14 mm) and left to dry under ambient conditions for 48 h. Visual analysis was performed for samples of edible films, and then the films were subjected to additional characterization.

2.3. Transparency and color analysis

The transparency of the PC-XG-based film samples loaded with varying amounts of GFO was evaluated utilizing a spectrophotometer, as per the methodology described by Zhao et al. [16]. The absorbance measurement for rectangular film samples was conducted by placing them into cuvettes and configuring the spectrophotometer to a wavelength of 550 nm.

The color assessment of the film samples was performed utilizing a Konica Minolta colorimeter from Tokyo, Japan. The a* (red-green) and b* (yellow-blue) values were assessed using a reference plate with an L* value of 100. The examination of color was conducted at multiple points on the films, and the results were computed by applying the given equation:

$$\Delta E* = \left[(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2\right]^{1/2} \quad (1)$$

ΔE^* represents the total color difference.

2.4. Thickness

To determine the thickness of the PC-XG-based film samples loaded with varying amounts of GFO, a digital micrometer (Yu-Su 150) acquired from China was utilized. The average thickness of the films was determined by measuring at five different points and then calculating the mean value.

2.5. Mechanical and barrier properties

D882To study the mechanical properties of the edible films, ASTM D882 was used. The test was conducted using a universal tester (TA. XT plus, Stable Micro Systems, UK). The mechanical properties of the films were determined via the following equations:

$$Tensile\ Strenght\ (TS) = \left(\frac{F}{A}\right) \quad (2)$$

The symbol F indicates the force, while A signifies the cross-sectional area of the film in the above equation:

$$Elongation\ at\ break\ (EAB)\ (\%) = \frac{Lf - Li}{Li} \times 100 \quad (3)$$

Li denotes the film's original length, while Lf represents the final length at the time of break.

A gravimetric method, as described by Erdem et al. [17], was used to determine the water vapor permeability (WVP) of the PC-XG-based film samples. The WVP of the edible films was calculated using following equation:

$$Water\ vapor\ permeability = \frac{\Delta m}{\Delta t \times \Delta P \times A} \times d \quad (4)$$

In this equation, (Δm/Δt) signifies moisture gain per unit of time in grams per day, the film area in square meters is denoted by (A), the difference in water vapor pressure across the two sides of the film in kilopascals is denoted by (ΔP), and the film thickness is represented by (d).

2.6. Moisture content

The gravimetric approach was utilized to ascertain the moisture percentage of the developed edible film samples. The weight of the films before and after drying was measured and recorded as W1 and W2, accordingly. The drying process was carried out at a temperature of 105 °C. The amount of moisture in the films was determined using the following formula:

$$Moisture\ content = \frac{W1 - W2}{W1} \times 100 \quad (5)$$

W1 is the initial film mass and W2 is the final mass.

2.7. Scanning Electron Microscopy (SEM)

Surface and cross-sectional micrographs of samples were obtained using a scanning electron microscope (JSM6510LA, Analytical SEM, Jeol, Japan). The samples were mounted on aluminum stubs and sputtered with gold to make the sample conductive. The SEM pictures were taken at an acceleration voltage of 20 kV.

2.8. Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR analysis was carried out to determine the interaction between the functional groups of various components in the edible film, including the polymeric matrix and oil. The analysis was conducted using InfraRed Bruker Tensor 37, Ettlingen, Germany, with an average of 32 scans performed at 25 °C. The range of wavenumbers used in the analysis was 500–4000 cm^{-1}.

2.9. X-RAY diffraction (XRD)

PC-XG-based film samples loaded with varying amounts of GFO were subjected to XRD analysis. The analysis was conducted using the XR-Diffractometer Bruker D8 Discover instrument, with a 2θ range of 5–50° at 40 kV.

2.10. Antioxidant activity

For the DPPH$^{\bullet}$ assay, 50 mg of film samples were analyzed according to the method described by Brand-Williams et al. [18]. The

ABTS$^{\bullet+}$ assay was conducted on 25 mg of film samples following the methodology of Re et al. [19]. The absorbance measurement was carried out for DPPH$^{\bullet}$ and ABTS$^{\bullet+}$, and the results were expressed as percentage inhibition.

2.11. Statistical analysis

All the measurements (except the mechanical testing) were performed in triplicates, and the averaged values were expressed as the mean ± standard deviation. To evaluate the significant differences in mean values, statistical software was used to perform a one-way analysis of variance, followed by Duncan's test at a significance level of 5 %.

3. Results and discussion

3.1. Visual characterization, transparency, and colour analysis

The sensory evaluation indicated that the films had a smooth and glossy surface and were easy to peel off, similar to the findings of Fan et al. [12]. The PE-XG composite films loaded with GFO demonstrated a uniform, homogenous, slightly yellow appearance (Fig. 1). The uniform distribution of GFO within the film matrix yielded a homogeneous structure of the edible film without any apparent oil droplets or agglomerates. The transparency of the films depends on the internal microstructure, the composition of the matrix, and the distribution of the components within the matrix. The transparency of the films decreased from 87.57 % to 76.18 % with increasing GFO content, as presented in Table 1. The films that contained GFO had greater opacity compared to the blank films. This is attributed to the dispersion of lipid droplets within the film network, which have a different refractive index and cause light scattering.

The transparency of the films exhibited a noticeable decrease from 87.57 % to 76.18 % as the GFO content increased, as detailed in Table 1. This shift in optical properties can be attributed to the dispersion of lipid droplets within the film network, introducing a distinct refractive index that induces light scattering. This phenomenon also could be a result of the interaction between the dispersed lipid droplets and the film matrix, influencing the overall optical characteristics. The intensity of light scattering increases with a higher concentration of droplets, which is also influenced by the size of the droplets [20]. Previous studies have also reported similar results [21,22]. Understanding these alterations in transparency is crucial for applications where optical clarity is a critical factor, such as in transparent packaging materials or films used for visual inspection of enclosed items.

Color is an important factor in determining the visual appeal of a food product. Edible films that are visually attractive are more likely to be perceived as desirable and appealing by consumers. As per colour analysis (Table 1), the oil incorporation slightly influenced L*, a*, b*, and difference of color (ΔE) values of the edible films. The colorimetric analysis of the films, specifically focusing on the b* coordinate (where positive values represent a yellow color), revealed an increasing trend from PG1 to PG4. The increase in the b* values across these films indicated a noticeable shift towards a light greenish-yellowish tone. This change was attributed to the incorporation of GFO, which not only affected the color but also introduced a yellowness tone. However, there was only minor fluctuation in the L, a*,b* and ΔE values of the blank film when compared to those containing various concentrations of GFO. Previous studies have shown that the incorporation of essential oils into polymer matrices can affect the color properties of the resulting

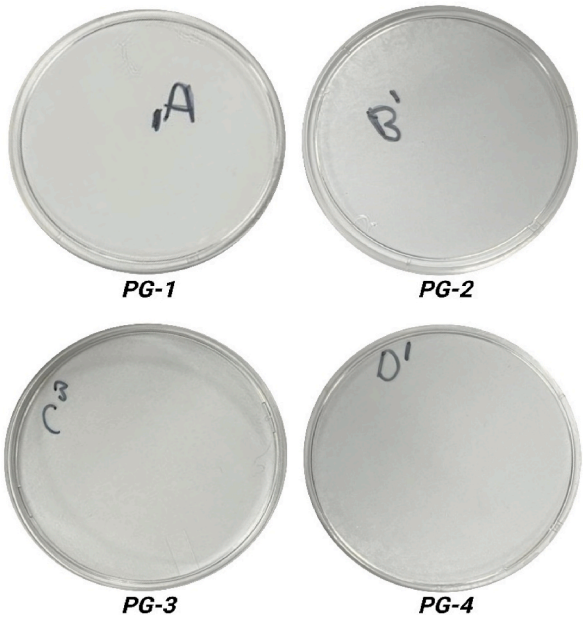

Fig. 1. Visual characterization of PC-XG-based composite blank and GFO loaded film samples.

Table 1
Thickness, transparency, and color analysis of PC-XG-based edible films.

Film Samples	Thickness (mm)	Transparency	L	a*	b*	ΔE*
PG-1	0.07 ± 0.01^{a}	87.57 ± 0.65^{a}	96.18 ± 0.03^{a}	-0.03 ± 0.02^{a}	0.82 ± 0.01^{a}	0.78 ± 0.02^{a}
PG-2	0.08 ± 0.01^{a}	83.88 ± 0.89^{b}	96.05 ± 0.02^{a}	-0.04 ± 0.03^{a}	0.86 ± 0.06^{a}	0.81 ± 0.02^{a}
PG-3	0.10 ± 0.01^{b}	78.83 ± 1.03^{c}	96.08 ± 0.02^{a}	0.00 ± 0.00^{a}	0.89 ± 0.03^{a}	0.81 ± 0.03^{a}
PG-4	0.11 ± 0.01^{b}	76.18 ± 1.12^{c}	96.09 ± 0.04^{a}	-0.01 ± 0.01^{a}	0.91 ± 0.07^{a}	0.84 ± 0.06^{a}

The values with different letters (a, b, c, and d) inside a column indicate significant differences ($p < 0.05$). L: lightness, a: green-red color, b*: blue-yellow color, ΔE*: overall color variation.

materials [23,24]. The obtained results regarding the colour and transparency were consistent with the visual observation of the prepared films.

3.2. Thickness

The edible films ranged in thickness from 0.07 to 0.11 mm, with the PG-4 sample containing 40 μL of GFO exhibited maximum thickness (Table 1). Such an increase in thickness could be attributed to the ability of essential oils to interact with the polymer matrix, possibly leading to changes in the film's structural integrity and swelling behavior. In the film matrix the GFO could distribute and insert between the polymer chains, increasing the volume, and eventually increasing the thickness of the edible film [25]. This phenomenon may have important implications over the functional properties of these films, such as their barrier properties and mechanical strength, which could be of interest for various applications, such as food packaging or pharmaceuticals. Zhou et al. [26] reported comparable results, indicating that the cinnamon essential oil enhanced the thickness of the cassava starch films.

3.3. Mechanical and barrier properties

The inclusion of GFO in the PC-XG composite edible films influenced both TS and EAB. Specifically, the TS increased while the EAB decreased with the addition of GFO in the films. The GFO-loaded films exhibited higher TS values than the control, as indicated in Table 2. The increase in the tensile strength of PC-XG films could be due to the crystallinity of the films [27]. This phenomenon indicates that elevated concentrations of in the film formulation play a pivotal role in fortifying and compacting the film network. The crystallinity of the films often influenced by the addition of additive such as oil, sometime resulting in the formation of more organized and closely arranged polymeric chains. This organized structure, in turn, enhances the mechanical strength of the film, making it more robust and resistant to deformation. The connection between GFO concentration and film tensile strength highlights the potential for tailoring the mechanical properties of films through controlled adjustments in ingredient concentrations, offering insights into optimizing film formulations for specific applications, such as packaging or coatings, where mechanical strength is crucial. In a previous study, the incorporation of corn oil was also found to increase the TS of gelatin-based films, as shown by Wang et al. [27].

The addition of GFO resulted in a reduction in the EAB of the film samples from 52.84 to 12.68 %. The PG-1/control had the highest value (52.84 %) for EAB compared to films loaded with GFO. This observation suggests that the inclusion of oil led to a more compact structure within the film matrix, potentially reducing the molecular mobility. The decreased EAB implies a shift toward reduced plasticity, indicating that the films become less stretchable before reaching the breaking point. The intricate interplay between GFO and the film matrix is crucial in understanding the mechanical properties. Yanwong and Threepopnatkul [28] also reported comparable outcomes, wherein the inclusion of citronella oils led to an increase in the TS but a decrease in the EAB of fish gelatin films.

If the film has high permeability, moisture can enter and create conditions that promote microbial growth, leading to spoilage and potentially harmful contamination of the packed food. The WVP of the edible film can also impact the texture and appearance of the food product. If the film has low permeability, it can trap moisture and lead to softening or sogginess of the packed food. Table 2 shows that the water vapor permeability value ranged from 0.73 to 0.56 (g mm)/(m^2.h.kPa). The incorporation of GFO resulted in a notable effect on the WVP of the PC-XG films. There was a consistent decrease in the WVP value as the concentration of GFO increased within the films. This observation implies that the introduction of GFO had a positive influence on the barrier properties of the films. Typically, a lower WVP value indicates improved resistance to water vapor transmission, suggesting enhanced moisture barrier characteristics in the presence of GFO. The reduction in WVP could be attributed to the structural changes induced by the addition of GFO. The compact structure formed within the film matrix due to the oil inclusion might contribute to a more effective barrier against the passage of water vapor. Furthermore, the hydrophobic nature of the GFO, results in a more water-resistant film with good barrier

Table 2
Mechanical attributes, water vapor permeability, and moisture percentage of film samples.

Film Samples	TS (Mpa)	EAB (%)	WVP ((g*mm)/(m^2*h*kPa))	Moisture (%)
PG-1	2.91 ± 0.19^{a}	52.84 ± 3.41^{a}	0.733 ± 0.009^{a}	26.69 ± 0.30^{a}
PG-2	3.26 ± 0.23^{ab}	47.72 ± 1.51^{a}	0.670 ± 0.028^{b}	25.36 ± 0.22^{b}
PG-3	3.77 ± 0.33^{b}	38.09 ± 2.66^{b}	0.617 ± 0.011^{c}	24.37 ± 0.08^{c}
PG-4	8.55 ± 0.62^{c}	12.68 ± 1.52^{c}	0.561 ± 0.020^{d}	24.30 ± 0.74^{c}

*The values with different letters (a, b, c, and d) inside a column indicate significant differences ($p < 0.05$).

properties. This effect aligns with the notion that the molecular interactions and arrangement within the film matrix play a crucial role in determining its barrier properties. Galus [21] also found that adding rapeseed oil reduced the WVP of the soy protein isolate films. Moreover, soybean oil in corn starch and methylcellulose films significantly reduced WVP [29].

3.4. Moisture content

In the analysis of the moisture content within the edible films, the PG-1/control sample exhibited the highest moisture content, reaching 26.69 %. Notably, the incorporation of GFO into the film matrix resulted in a substantial reduction in moisture content, with a notable decline to 24.30 %. Interestingly, the PG-4 sample, containing the highest concentration of GFO, demonstrated the lowest moisture content among the tested samples (Table 2). This observed reduction in moisture content is attributed to the inherently hydrophobic characteristics of GFO. The hydrophobic nature of GFO is known to impede the absorption and retention of moisture, thereby contributing to the overall reduction in the films' moisture content. This finding underscores the potential of GFO as an effective modifier in edible film formulations, offering improved moisture resistance and stability, crucial qualities for applications in food packaging and preservation. In the study conducted by Galus and Kadzińska [30], it was also observed that incorporating rapeseed oil in whey protein edible films resulted in a notable reduction in their moisture content. Several researchers have also documented reduced moisture levels of edible films when oil was incorporated [31,32]. By decreasing the moisture content, the films may also become more resistant to microbial growth and deterioration, which could have significant implications for preserving food products.

3.5. Microstructure of the films

Scanning Electron Microscopy (SEM) can be used to visualize the microstructure of the films, including the size and distribution of pores, cracks, and other surface features. This information is important for understanding various properties of the film, such as its strength, elasticity, and permeability. The fabricated composite film samples based on PC and XG were examined for their surface morphology and the obtained images are presented in Fig. 2. The control film sample, namely PG-1, exhibited a rough surface with

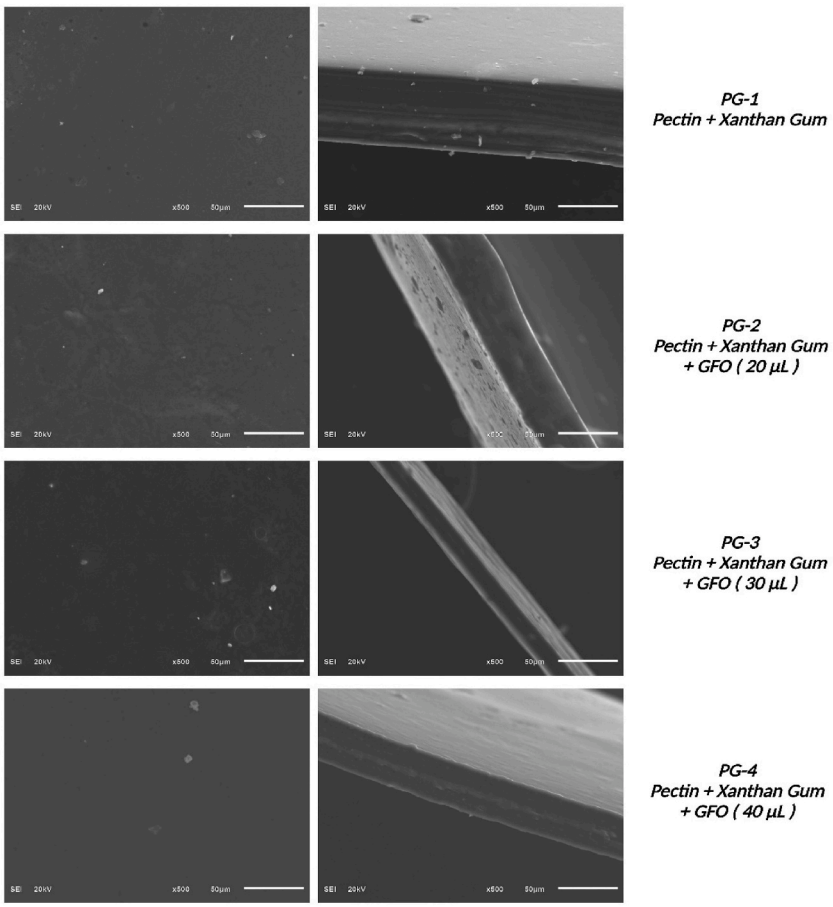

Fig. 2. SEM analysis of PC-XG-based composite blank and GFO loaded film samples.

several particles (Fig. 2) compared to films loaded with GFO comparable to the findings of Hosseini et al. [33]. When observed in cross-section, the oil-free film's structure revealed a continuous and homogenous phase, and a few particles were apparent on the film's surface. The film sample PG-2 loaded with 20 μL of GFO showed a similar surface appearance as the control but with some irregularities in the cross-sectional view, such as particles and pores. As the concentration of GFO increased from 20 to 30 μL in the PG-3 sample, noticeable oil droplets appeared on the film surface. This observation suggests a potential issue with the mixing process, leading to inadequate incorporation of the oil with the film-forming components. Consequently, small oil droplets became entrapped within the film matrix. In contrast, film sample PG-4, which contained the maximum GFO concentration of 40 μL, demonstrated improvement in the structural characteristic. It displayed a uniform, homogeneous, and compact composition with a well-distributed presence of oil within the film matrix. Unlike PG-3, the surface of PG-4 featured a reduced quantity of particles, and no visible spots or pores were evident. The uniform dispersion of GFO in PG-4 indicates the enhanced stability of the prepared film, and absence of oil droplet separation during the film formation process [26]. This underscores the importance of optimizing GFO concentrations to achieve a uniform and stable film structure in applications such as food packaging. Overall, the SEM analysis indicated good intermolecular interaction between the polymers and GFO, resulting in a uniform, homogeneous, and compact structure for potential applications in the food packaging industry.

3.6. X-ray diffraction analysis

X-ray diffraction (XRD) is an analytical technique that provides information about the degree of crystallinity and the presence of amorphous regions in a film matrix. Crystalline materials have a regular, ordered atomic arrangement, which results in sharp, well-defined diffraction peaks in the XRD pattern [34]. The XRD spectra of PC-XG composite film samples exhibited distinct characteristic peaks, and the diffraction peak intensity displayed a single main crystalline reflection within the range of (18.02–23.51°) in all the samples (Fig. 3). The samples containing GFO exhibited a prominent peak at $2\theta = 18.26°$, indicating the emergence of newly formed crystalline domains. The analysis revealed that PG-1, PG-2, PG-3, and PG-4 samples exhibited crystallinity percentages of 16.3 %, 19.1 %, 26.5 %, and 37.4 %, respectively. An increase in the concentration of GFO from 20 to 40 μL resulted in a corresponding elevate in the degree of crystallinity of the samples, as indicated by the results. Similar results were reported by Zhou et al. [26] demonstrated comparable findings, in which the incorporation of cinnamon essential oil increased the degree of crystallinity of cassava starch-based films. The obtained XRD pattern for the current study revealed that the PC, XG, and GFO exhibited compatibility and good intermolecular interaction, leading to the development of stable and compact films.

3.7. FTIR analysis

FTIR spectra of PC and XG-based composite films with and without GFO are depicted in Fig. 4. FTIR spectra of the composite films with and without GFO showed the same major peaks; however, differences in the amplitudes of the peak were found depending on the concentration of oil used. The significant stretching absorption associated with the hydroxyl groups (–OH) in the 3500–3000 cm^1 range was observed with the incorporation of oil. Compared to the blank, the absorption band at 3294 cm^{-1} was shifted to a higher wave number in the PG-2, PG-3, and PG-4 samples. The observed shift in the pattern may be linked to the hydrogen bonding and interactions between molecules among the film-forming components, which is an effect of the incorporation of GFO [35].

The characteristic bands of the pectin at approximately 1637 cm^{-1} and 1737 cm^{-1} are assigned to C═O stretching in the ester form [36]. The absorption peak at 1104 cm^{-1} represents the pure XG in the film matrix [37]. In addition, the peak observed at 2923 cm^{-1} corresponds to the C–H vibrations specific to the presence of glycerol [38]. The absorption peak at 1020 cm^{-1} indicates the stretching vibration of the C–O group, and the peak at 1230 cm^{-1} shows the C–N bond stretching vibrations [39]. In general, the FTIR analysis indicated the presence of intermolecular bonding between the film-forming constituents following the incorporation of GFO.

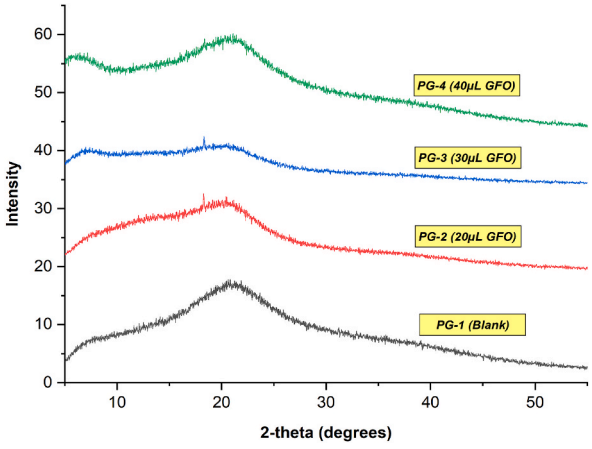

Fig. 3. XRD analysis of PC-XG-based composite blank and GFO loaded film samples.

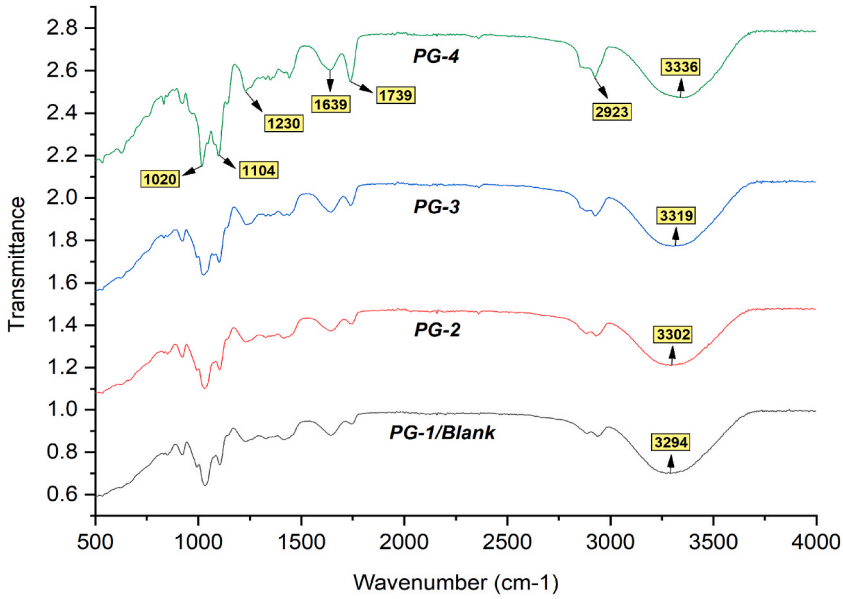

Fig. 4. FTIR analysis of the PC-XG-based composite blank and GFO loaded film samples

3.8. Antioxidant properties

The presence of antioxidants in edible films can aid in preventing and reducing oxidation in food products. Utilizing edible films with antioxidant activity can decrease the requirement for synthetic preservatives or antioxidants, which may have adverse health effects. The antioxidative activity of PC-XG composite films with and without GFO is shown in Fig. 5. Control or PG-1 film samples without adding GFO showed minimum (11.04 %) DPPH$^{\bullet}$ scavenging activity. It was observed from the results that the DPPH$^{\bullet}$ scavenging activity of PC-XG films increased from 15.38 % to 29.56 %, with an increase in the concentration of GFO from 20 to 40 μL. Antioxidant capacity detected by ABTS$^{\bullet+}$ assay has shown similar results where films incorporated with GFO indicated higher radical scavenging potential when compared to the control films (Fig. 5). It has been reported that grapefruit essential oil has antioxidant activity, which can be beneficial for food preservation and disease prevention [14,40]. Previous studies have also indicated that the antioxidant properties of edible films can be enhanced by adding essential oils. As per the findings of Dashipour et al. [41], the incorporation of 3 % clove essential oil in carboxymethyl cellulose films led to the achievement of the highest level of antioxidant activity, which was recorded at 71.76 %. Incorporating ginger essential oil enhanced the properties of chitosan-based edible films, as reported by Al-Harrasi et al. [40] in their study. The antioxidant efficacy of edible films depends upon various factors, such as the nature and proportion of the antioxidant used, how it interacts with other constituents, the film-forming substances, and the processing conditions. Careful consideration of these factors is necessary to optimize the antioxidant activity of edible films and improve the shelf life and quality of food products.

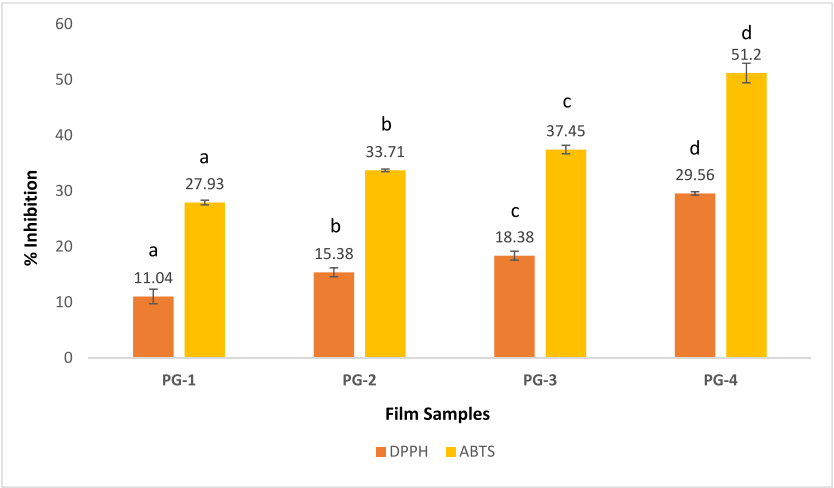

Fig. 5. Antioxidant properties of the PC-XG-based composite blank and GFO loaded film samples.

4. Conclusion

The current investigation involved the preparation of edible films based on PC-XG composite, followed by an evaluation of the impact of incorporating varying concentrations of GFO on the physicochemical and antioxidant characteristics of the films. Overall findings suggested essential oil incorporation improved the barrier, mechanical, and antioxidant properties of the PC-XG-based edible films. However, further studies on thermal stability and antimicrobial assessments of developed films against food-borne pathogenic microorganisms are also required to ensure their utilization as stable and active films for food packaging applications.

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Informed consent statement

Not applicable.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Saurabh Bhatia: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Ahmed Al-Harrasi:** Supervision. **Yasir Abbas Shah:** Writing – review & editing, Writing – original draft, Software, Methodology. **Aaisha Naseer Saif Alrasbi:** Software, Methodology. **Muhammad Jawad:** Validation. **Esra Koca:** Software, Methodology, Data curation. **Levent Yurdaer Aydemir:** Writing – review & editing, Methodology, Formal analysis. **Jawaher Abdullah Alamoudi:** Writing – review & editing, Validation. **Yosif Almoshari:** Validation, Formal analysis. **Syam Mohan:** Writing – review & editing, Formal analysis.

Declaration of competing interest

There is no conflict of interest among any of the authors whatsoever and all the authors have actively participated in the preparation of manuscript. There is no conflict of interest among any of the authors whatsoever and all the authors have actively participated in the preparation of manuscript.

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