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Exploring the impact of Galbanum on the functionality of gelatin-based packaging films

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Introduction: The current study was designed to investigate the effect of Galbanum absolute over the physico-chemical and antioxidant properties of gelatin films.
Methods: Traditional casting method was used to fabricated gelatin and galbanum absolute film samples. The developed films were further subjected to FTIR, XRD, SEM, and DSC analysis determine their physiochemical and structural properties.
Results: It was found that with an increase in the concentration of Galbanum absolute, film thickness (0.07 mm – 0.17 mm), thermal stability, and contact angle (51.53° – 80.14°) were increased whereas transmittance (63.44 – 90.32) and crystallinity of the samples decreased. Furthermore, the incorporation of Galbanum absolute significantly increased the antioxidant properties (from 39.44% to 61.99% for DPPH radical scavenging activity and 8.89% to 62.86% for ABTS radical scavenging activity) of gelatin films. However, micrographs of Galbanum absolute-loaded films showed an increase in roughness and cracks over the films with the addition of Galbanum absolute.
Discussion: Therefore, further optimization of the Galbanum absolute proportion in the biopolymer films can result in the development of stable active packaging. These findings highlight the potential applications of Galbanum absolute as a natural additive in biodegradable food packaging materials to enhance the thermal stability and antioxidant properties.

KEYWORDS

food packaging, biopolymer-based films, plant extract, active packaging, antioxidant

1 Introduction

Recent reports showed an increase in pollution due to the significant accumulation of plastic-based packaging especially flexible plastic packaging (Muncke, 2021). These flexible plastic sheets in the form of bags, pouches, laminates, adhesives, sealants, and wrappers once reach to waste stream, get contaminated (Hopewell et al., 2009; Cabrera et al., 2022). Sorting these challenges lead to the significant accumulation of these thin sheets in various environmental media, thereby increasing the carbon footprint (Ncube et al., 2020). Additionally, these contaminated and fragile films, when exposed to unfavorable environmental conditions such as high temperatures, become a significant source of microplastics (Sobhani et al., 2020; Versino et al., 2023). Recent literature showed that active packaging based on natural polymers and their composites could be suitable

and eco-friendly solution (Li et al., 2024). Gelatin is extensively used as a biopolymer to develop food packaging because of its non-toxicity, excellent film-forming properties, cost-effectiveness, readily available and biodegradability (Lu et al., 2022). It has certain limitation in food preservation applications due to poor moisture resistance, limited mechanical strength. These limitations can lead to microbial spoilage, reduced shelf-life, and restricted consumer acceptance (Reji et al., 2025). The addition of synthetic additives mainly endocrine disruptors such as bisphenols and phthalates in packaging have been highly criticized for their harmful effects recently (Paula and Alves, 2024). Thus, plant extracts offering good antioxidant and antimicrobial properties could be an excellent alternative to these synthetic preservatives (Beya et al., 2021).

Several studies showed that the incorporation of plant extracts such as oregano, grapefruit and rosemary extracts has enabled the development of biopolymer-based films with improved physical-chemical properties (Dutta and Sit, 2023). These extracts also act as natural plasticizers in food packaging material (Vieira et al., 2011). The plant-based extract also showed an adverse impact on the films in terms of developing heterogeneous materials, mainly due to the uneven distribution of extract in films (Moghadam et al., 2020; Hanani et al., 2019; Riaz et al., 2018; Lei et al., 2019; Du et al., 2021; Piñeros-Hernandez et al., 2017; Fabra et al., 2018; Hanani et al., 2018; Ooi et al., 2011; Ribeiro et al., 2020; Gasti et al., 2020). Several plant extracts cause precipitation, flocculation, and coalescence that disturb the morphology of the films. This may result in the development of defective morphology with holes, cavities, increased surface roughness, cracks, and spots over the surface of the films (Moghadam et al., 2020; Hanani et al., 2019; Riaz et al., 2018; Lei et al., 2019; Du et al., 2021; Piñeros-Hernandez et al., 2017; Fabra et al., 2018; Hanani et al., 2018; Ooi et al., 2011; Ribeiro et al., 2020; Gasti et al., 2020). This behavior could be due to the unsuitable environment (such as pH, temp, and interaction with other ingredients) of film forming solution that limits its solubility, resulting in the development of heterogeneous material (Moghadam et al., 2020; Hanani et al., 2019; Riaz et al., 2018; Lei et al., 2019; Du et al., 2021; Piñeros-Hernandez et al., 2017; Fabra et al., 2018; Hanani et al., 2018; Ooi et al., 2011; Ribeiro et al., 2020; Gasti et al., 2020). Although these extracts offer antimicrobial and antioxidant properties to the packaging, their addition sometimes demonstrated a negative impact on barrier, mechanical, optical, morphological, and thermal properties. Therefore, currently, researchers have been exploring new plant-based extracts in terms of their high potency (antioxidant and antimicrobial), cost-effectiveness, easy availability, and compatibility with films (solubility and uniform dispersion). Seididamyeh, Shi et al., 2024 studied the gum Arabic coatings loaded with extract. They observed that the extract loaded coating was suitable for postharvest treatment for frest-cut red capsicums as they strongly inhibited the soft-rot bacteria *P. viridiflava* (Seididamyeh et al., 2024). Woo et al., 2023 studied the effect of six natural extracts against *L. monocytogenes, C. perfringens, Salmonella spp.,* and *E. coli* on sausages. These natural extracts improved the quality and shelf-life of sausages by reducing the bacterial growth and lipid oxidation (Woo et al., 2023). Plant extracts exhibits strong antimicrobial activity on mesophilic bacteria, yeast-mold, and mesophilic/psychrophilic counts (Shi et al., 2024).

Galbanum is an aromatic oleo-gum resin mainly produced from medicinal plant, *Ferula galbaniflua* (synonym *F. gummosa*) is a north Persian plant and native to arid regions of Iran, Central Asia, and parts of the Middle East. Galbanum is used for several applications in medicine due to its therapeutic potential and in cosmetics, and textile industries. The FDA considers galbanum oil, resin, and related substances as natural flavoring agents that are generally recognized as safe (GRAS) for use in food under specific conditions. Furthermore, the galbanum (oil and resin) both have been approved for their use as flavor enhancer, flavoring agent or adjuvant (Ferula Galbaniflua Absolute, 2025; Ferula Galbaniflua, 2025; Galbanum, 2025). Galbanum gum is sticky, very bitter and possesses a strange odour (Hamedi et al., 2017). The potential effects of galbanum in biopolymer-based food packaging material remains unexplored. Thus, this is the first investigation evaluating the impact of varying concentrations of Galbanum absolute on the properties of gelatin-based films for potential use in active food packaging.

TABLE 1 Composition of gelatin films.

Sample code	Chemical composition
GG1	Gelatin (1.5%) + galbanum absolute (0%) + glycerol (1.5%)
GG2	Gelatin (1.5%) + galbanum absolute (0.5%) + glycerol (1.5%)
GG3	Gelatin (1.5%) + galbanum absolute (1%) + glycerol (1.5%)
GG4	Gelatin (1.5%) + galbanum absolute (1.5%) + glycerol (1.5%)

2 Material and methodology

2.1 Materials

Galbanum absolute was received as a gift sample from Fine Aromatics and Herbal Extract Pvt. Ltd (A subsidiary of Fine Fragrances Pvt. Ltd.), Umbergaon, India. *Ferula galbaniflua* resin (gum) was identified by Dr B S Kalakoti (Taxonomist), Head R&D, Fine Aromatics and Herbal Extract Pvt. Ltd. Gelatin was sourced from Sisco Research Laboratories Pvt Ltd. (Mumbai, India). Glycerol (99% pure) was purchased from BDH Laboratory Supplies (London, UK).

2.2 Extraction of galbanum absolute

The galbanum resin (1.0 Kg) was extracted with absolute ethanol (5.0 L) at 50 °C with continuous stirring for 3 h (3 times). At the end of each extraction, the solvent was filtered to get a clear solution. Finally, all three extractions were mixed and distilled out by a rotary evaporator under reduced pressure to get the thick sticky mass, i.e., Galbanum Absolute (500 g) (Groom, 2012).

2.3 Preparation of the films

Different samples of the gelatin films loaded with galbanum were prepared following the casting method (Bhatia et al., 2024). Gelatin solution (1.5%) was prepared by dissolving the biopolymer in 100 mL of distilled water following continuous stirring for 1 hour at room temperature. Subsequently, glycerol (1.5%) was introduced as a plasticizer (v/v) into the film-forming solution, which was then

continually mixed at room temperature for 30 min. Subsequently, the mixture was distributed into four beakers, the first beaker was treated as control and the galbanum was added to the remaining mixtures as detailed in Table 1. 20 mL of the solution from each beaker was transferred into plastic Petri plates, left to dry at room temperature for 24 h. Once fully dried, the film samples were carefully removed from the plates and prepared for further analysis.

2.4 Color analysis, light transmittance, and haze value

A spectrophotometer model CR-410 was used to determine the color attributed of fabricated films. The film samples were conditioned for 24 h at ambient laboratory conditions to ensure surface color stabilization and eliminate any transient moisture or thermal effects before analysis. L* denotes the lightness, a* represents red and green color, b* corresponds to yellow and blue color, and ΔE represents change in overall color of the fabricated films.

A Haze meter (model YH1200) manufactured by Guangdog Sanenshi Technology was used to determine the light transmittance and haze value of the fabricated films.

2.5 Antioxidant attributes of the films

The DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity of the fabricated films was determined by method described by Brand-Williams et al. (Brand-Williams et al., 1995). For ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) radical scavenging activity Re et al. (Re et al., 1999) method was used. 25 mg film sample was for DDPH measurement and 10 mg sample for ABTS measurement. Each sample was measured in triplicate. The inhibition activity was expressed in percentage (%). To determine the percentage inhibition (I) following Equation 1 was used:

$$I\ (\%) = \frac{Ao - Ai}{Ao} \times 100 \quad (1)$$

Where *Ao* is the absorbance of control and *Ai* is the absorbance of sample.

2.6 Water contact angle measurements

The surface properties (hydrophobicity or hydrophilicity) were determined by goniometer (OCA11, Data Physics Instruments) by measuring water contact angle. A film strip of (2 × 2 cm) was cut and placed on a flat surface and a 1 μL water droplet was dropped on the surface of the strip. The contact angle was determined by using dpiMAX software.

2.7 FTIR

The chemical interactions especially functional group interactions were determined by using FTIR (Fourier Transform Infrared) Spectroscopy. An InfraRed Bruker Tensor 37 Spectrometer from Ettlingen, Germany was used. The spectra were recorded from 400 cm^{-1} to 4,000 cm^{-1} with a resolution of 4 cm^{-1}.

2.8 XRD

A Bruker D8 Discover apparatus at 40 kV was used to determine the crystallinity of the fabricated films. Each sample was scanned over a 2θ range of 5°–55°. The scanning rate of 0.5°/point was used during the analysis. The source of radiation was copper (Kα) with a wavelength of 1.5418 Å.

2.9 Microstructural analysis of the films

Scanning Electron Microscope (SEM) model JSM6510LA bought from Jeol, Japan was used to determine the morphology of the fabricated samples. The system was set at ×400 magnification with a voltage of 10 kV. The small strips of the films mounted on aluminium stubs with double-sided tape were analyzed. To enhance surface visualization, a gold layer was applied using a sputter ion coater.

2.10 Thermal stability of the films

Thermogravimetric analysis (TGA) and Differential Scanning Calorimetry (DSC) of galbanum-loaded film samples were performed using a thermogravimetric analyzer (SDTQ600, TA Instruments, United States). About 10 mg of film samples were heated from 25 °C to 600 °C at a rate of 10 °C per minute under a continuous nitrogen flow.

2.11 Statistical analysis

Statistical analysis used mean values with standard error from three independent observations. A one-way ANOVA followed by Duncan's test determined significance at a 95% confidence level.

3 Results and discussion

3.1 Visual characteristics

Visual characterization of blank and films with extract are illustrated in Figure 1. Visual analysis showed that the incorporation of the extract resulted in an increase in brownishness in the films. The films with the highest concentration (1.5%) of GA showed more brownishness, surface roughness and fragility than other samples. The uneven distribution of colour at the highest concentration of GA indicates the non-uniform distribution of extract. However, films containing less concentration of GA showed uniform distribution of extract. This behavior could imbalance between hydrophobic and hydrophilic components, resulting in the development of heterogeneous materials. Visual analysis

FIGURE 1
Visual analysis of gelatin films with and without GA extract.

TABLE 2 Optical properties and thickness of fabricated films.

Sample code	L	a	b	ΔE	Transmittance	Haze	Thickness (mm)
GG1	87.42 ± 0.06[a]	1.48 ± 0.08[a]	−2.49 ± 0.24[b]	87.46 ± 0.06[a]	90.32 ± 0.020[a]	16.97 ± 0.015[b]	0.07 ± 0.01[c]
GG2	81.34 ± 0.88[b]	−0.2 ± 0.35[b]	10.10 ± 0.4[a]	81.99 ± 0.60[b]	63.44 ± 3.93[c]	73.14 ± 3.12[a]	0.17 ± 0.17[a]
GG3	82.00 ± 0.40[b]	−0.12 ± 0.09[b]	9.47 ± 0.54[a]	82.55 ± 0.37[b]	64.71 ± 0.625[c]	71.82 ± 2.01[a]	0.14 ± 0.14[ab]
GG4	81.40 ± 1.23[b]	−0.42 ± 0.11[b]	11.20 ± 1.59[a]	82.18 ± 1.07[b]	70.56 ± 1.75[b]	68.61 ± 4.35[a]	0.11 ± 0.02[b]

[a]Different letters such as a, b, c, and d represent significant differences ($p < 0.05$).

indicates that with an increase in concentration of GA, brownishness, surface roughness and fragility increased. This indicates the adverse effects of GA extract at higher concentrations.

3.2 Color analysis, light transmittance, and haze value

The color of food packaging materials often determines the consumer's acceptability of the food product (Adilah et al., 2018a). The color of packaging material is typically described using three parameters: L*, a*, and b*. The higher L* value determines the lightness, lower L* value determines darkness, negative a* value determines greenish hue, positive a* value determines reddish hue, negative b* value determines blue color, and positive b* value determines yellow color. The color characteristics of the film samples are often altered by the incorporation of plant extracts in their matrix. These changes are often determined by nature and concentration of extract used (Mir et al., 2018). The addition of GA extract into the polymer matrix resulted in a significant increase in positive b* value. This indicates that the GA led to increase the yellowish tint in the fabricated films. However, both L* value and a* value decreased significantly. This might be attributed to the

polyphenolic components and natural pigments available in GA. Similar findings have been documented in the previous studies (Du et al., 2021; Emam-Djomeh et al., 2015).

Table 2 demonstrates the light transmittance and haze value of the fabricated films. The light transmittance and haze value are an important characteristic of the packaging materials. These two parameters determine how much light can pass through the material and much clear an object is visible through it. The light transmittance of the fabricated films decreased significantly with the increase in concentration of GA in the polymer matrix. However, the haze value increased significantly. The control sample (GG1) demonstrated the highest light transmittance and lowest haze value. In contrast, the light transmittance from GG2 to GG4 increased, and haziness decreased with the increasing concentration of GA. This indicates that the film samples loaded with GA became more opaque. This might be attributed to the presence of phenolic compounds that can results in scattering of light and reduces the uniformity in the film matrix. Similar findings have been documented in the plant-extract loaded biopolymer films where the phenolic components and heterogenous dispersion of plant extract led to scattering of light which decreased the transmittance and increases the haziness (Qin et al., 2015; Gómez-Estaca et al., 2009a; Kumar and Pratibha, 2021).

3.3 Thickness of the films

Thickness of the packaging material is an important parameter that determines the mechanical properties and barrier properties (Sa and mi Rokayya, 2017; Sami and Khojah, 2019). The thickness of the biopolymer film is directly influenced by preparation method and the amount of solid content in the matrix (Siracusa et al., 2018). The thickness of the gelatin films increased with the increase in concentration of GA. This might be attributed to the increase in intermolecular spacing due to plasticizing effect of GA or might be due to the increase in solid content. Similar findings have been documented in the previous literature (Moghadam et al., 2020; Hanani et al., 2019; Hanani et al., 2018; Kumari et al., 2017).

3.4 Antioxidant properties of the films

The biopolymer films loaded with plants extract can reduce the oxidation of lipid and also prolongs the shelf-life of packaged food products (Manzoor et al., 2023). Figures 2a,b illustrates the antioxidant activity of the gelatin-based GA-loaded films. Figure 2a demonstrates the ABTS radical scavenging activity of the fabricated films. The radical scavenging activity of the fabricated films increased with the increase in concentration of GA in the films. The control sample (GG1) demonstrated the ABTS radical scavenging activity of 39.44%. The increase in concentration of GA resulted in significant increase in antioxidant activity. The GG4 sample loaded with the highest concentration of GA demonstrated 61.99% antioxidant activity. Furthermore, a 5-fold increase in ABTS scavenging activity was observed at higher GA concentrations (Asghari et al., 2022). Similarly, the addition of GA resulted in a 2-fold increase in DPPH scavenging activity (Figure 2b). The DPPH radical scavenging activity of the fabricated films increased from 8.89% to 62.86%. The strong antioxidant performance is largely attributed to the phenolic compounds present in GA. These phenolic compounds act as effective free radical scavengers (Wang et al., 2013). These findings indicate a positive correlation between the amount of polyphenol and antioxidant capacity, which is consistent with former results (Gómez-Estaca et al., 2009b). In a previous study Adilah, Adilah et al., 2018b observed that the incorporation of mango peel extract increased the antioxidant activity of the biopolymer films (Adilah et al., 2018b). Ali et al. (2023) observed that the addition of plant extract increased the antioxidant activity of the fabricated films (Ali et al., 2023). Another study showed an increased in antioxidant activity of biopolymer films loaded with red pickly pear (Aparicio-Fernández et al., 2018). The antioxidant activity of chitosan-based films improved with the addition of extracts of *Pistacia terebinthus* (Kaya et al., 2018). In another research study, the antioxidant activity of cassava starch-based rosemary extract-loaded sample improved (Piñeros-Hernandez et al., 2017). These trends are consistent with the role of phenolic compounds as hydrogen-donating radical scavengers. The higher concentration of plant extract increases the total phenolic content thus increasing the antioxidant activity (Cai et al., 2024; Zhang et al., 2020; Salah et al., 2024; Roufa et al., 2023) of biopolymer films (Adilah et al., 2018b; Nikmanesh et al., 2023; Last et al., 2025).

3.5 Water contact angle measurements

The film's surface hydrophobicity was determined by measuring the water contact angle by the sessile drop method. Usually, films with higher contact angle possess high surface hydrophobicity. Surfaces with a contact angle >65° are called hydrophobic whereas surfaces <65° are hydrophilic (Vogler, 1998). The water contact angle of all the films is demonstrated in Figure 3. In the present study blank gelatin film without GA extract possesses a contact angle of less than 65°, indicating the hydrophilic nature of the surface. However, gelatin films loaded with GA extract showed a contact angle >65° suggesting the hydrophobic nature of the films. The contact angle of GA-loaded films varied between 71.56° and 80.14°. These findings highlight the significant impact of GA extract on the surface properties of gelatin films, transforming them from hydrophilic to hydrophobic (Table 3; Figure 3).

3.6 FTIR

The Fourier Transform Infrared Spectroscopy (FTIR) spectra of the gelatin films with varying concentrations of GA show distinct features that highlight the interactions between the gelatin matrix and the GA (Figure 4). The spectra for GG1 (gelatin-only film) display characteristic peaks. The GG1 spectrum exhibited peaks typical of gelatin that corresponds to the protein backbone functional groups (such as amide and hydroxyl regions). As the concentration of GA increases in the films (GG2, GG3, and GG4), additional peaks and shifts become evident. The spectrum showed peaks at 3,288 cm^{-1}, 2,924 cm^{-1}, 1,635 cm^{-1}, 1,232 cm^{-1}, and 1,028 cm^{-1}. The peak at 3,288 cm^{-1} indicates the presence of O-H stretching,

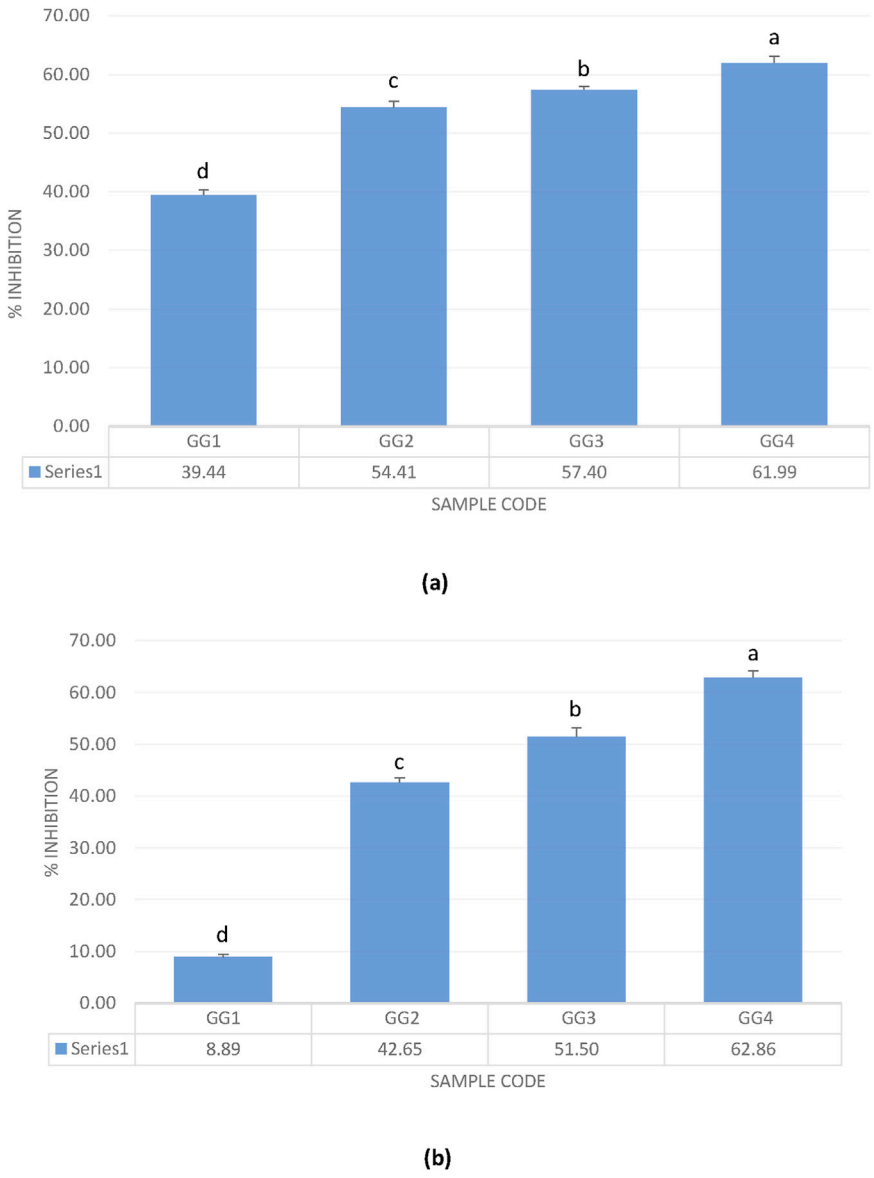

FIGURE 2
(a) ABTS radical scavenging activity of gelatin films with and without GA extract **(b)** DPPH radical scavenging activity of gelatin films with and without GA extract.

which is characteristic of hydroxyl groups. This might be due to the O-H stretching of glycerol (Łopusiewicz et al., 2018). The peak at 3,288 cm^{-1} in GG4 diminishes significantly, nearly disappearing, indicating a potential disruption in the hydrogen bonding network of the gelatin matrix at higher GA concentrations. This peak at 2,924 cm^{-1} corresponds to the C-H stretching vibrations. However, the band at 1,635 cm^{-1} is attributed to amide I (C=O stretching) which is the characteristic of peptide linkage (Piñeros-Hernandez et al., 2017). The peak 1,232 cm^{-1} is usually associated with the C-N stretching of the amide. Moreover, the peak at 1,028 cm^{-1} is generally associated with C-O stretching vibrations. The FTIR spectrum primarily reflects the chemical bonds and functional groups within a material. When GA is incorporated into the matrix, the slight shifts and variations in peak intensity suggest physical interactions, such as hydrogen bonding, or minor chemical interactions between GA and the matrix components. However, the absence of significant changes in the spectrum indicates that no new covalent bonds are formed, and the structural framework of the original matrix remains largely unchanged. Similar results were reported in previous studies where no clear chemical shift or intensity were observed in the FTIR spectrum due to the addition of different additives in films (Liu et al., 2020; Elshamy et al., 2021; Yu et al., 2022).

3.7 Crystallinity of the films

The diffractogram of the investigated samples (GG1-GG4) represents the two major peaks at around 5° and 21° of 2θ (Figure 5). After the addition of GA, a slight shift in the peak

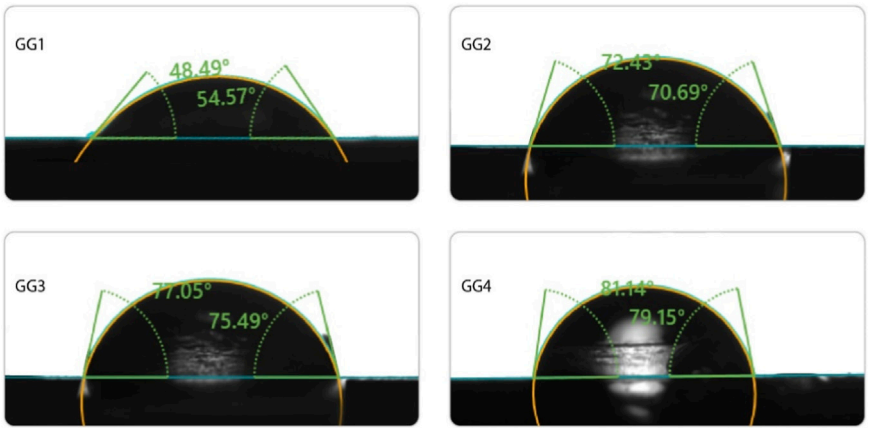

FIGURE 3
Contact angle of gelatin films with and without GA extract.

TABLE 3 Contact angle of fabricated film samples.

Sample code	Contact angle (˚)
GG1	51.53 ± 4.30[c]
GG2	71.56 ± 1.23[b]
GG3	76.27 ± 1.10[ab]
GG4	80.14 ± 1.41[a]

[a]Different values such as a, b, and c represent the significance difference ($p < 0.05$). higher concentrations.

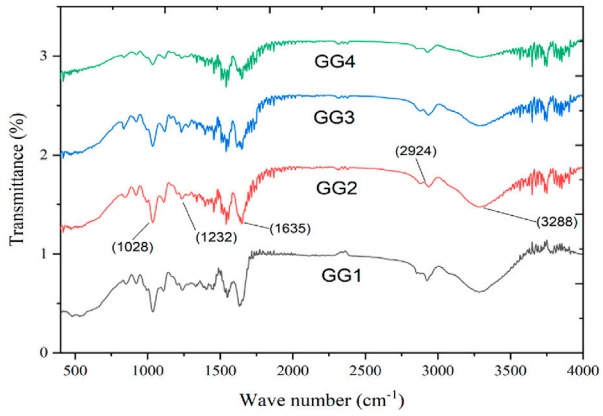

FIGURE 4
FTIR analysis of gelatin films with and without GA extract.

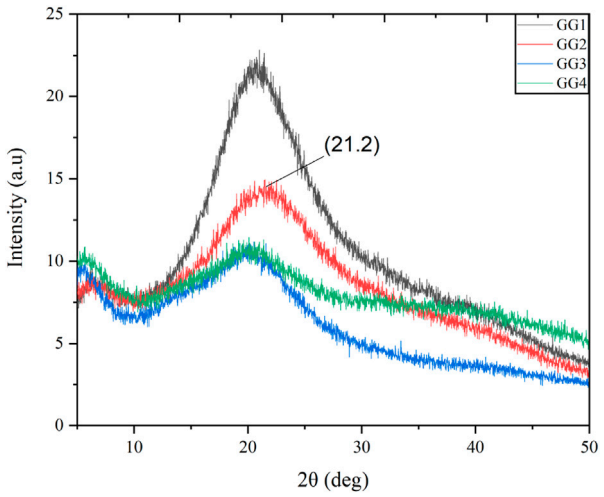

FIGURE 5
XRD analysis of gelatin films with and without GA extract.

around 5˚ was observed particularly in GG2 sample. This indicates the structural rearrangement and disruption of intermolecular hydrogen bonding between gelatin chains and GA components (Wang et al., 2017). The peak at ~8˚ could be related to the ordered region of the triple helix structure in gelatin polymer (Wang et al., 2017; Etxabide et al., 2022). It was found that the intensity of the characteristic peak at 21˚ of 2θ decreased with the addition of GA. The intensity of the prominent diffraction peak at 21.2˚ gradually decreases from GG1 to GG4. Furthermore, a progressive loss of crystallinity with the increase in GA content. This decrease in crystallinity could be due to the interference of phenolic and terpenoid constituents of galbanum absolute with gelatin. Thus, increasing the amorphous fraction of the film sample. Furthermore, the increase in the concentration of GA decreased the intensity of the developed films. However, different concentrations of the samples demonstrated different crystallinity. This could be related to the uneven distribution of GA and the development of insoluble gelatin particles in the matrix after the gelatinization and drying process, as confirmed by the SEM images (Figure 6), resulting in heterogeneous material with significant variation in the crystallinity at different concentrations. The incorporation of GA in the polymer matrix altered the crystalline and amorphous balance of gelatin matrix. This might be due to the interference of its polyphenolic compounds with the chains of gelatin

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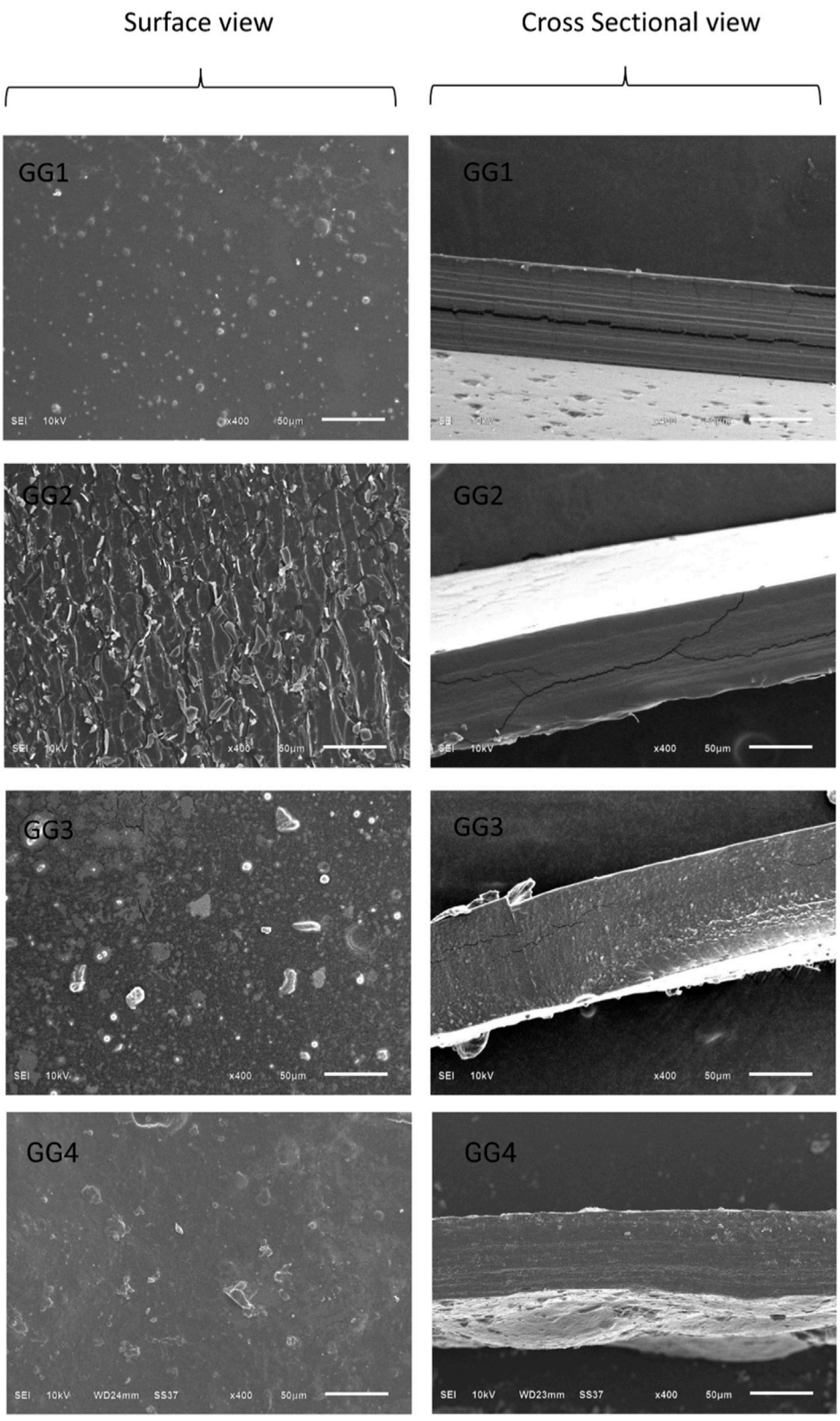

FIGURE 6
SEM analysis of gelatin films with and without GA extract.

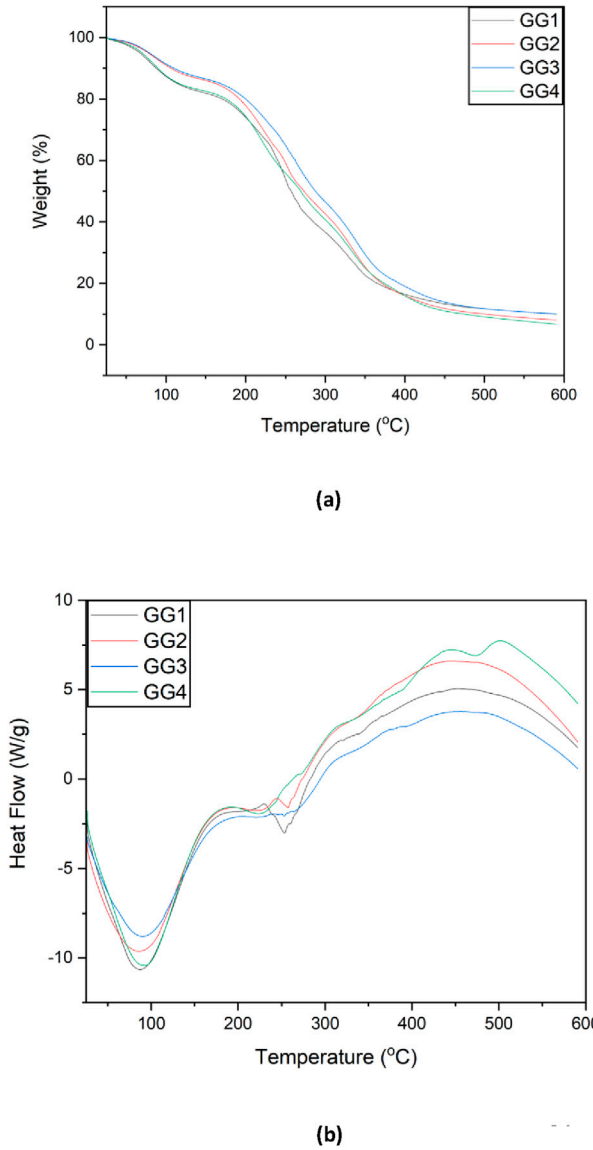

FIGURE 7
(a) TGA analysis of gelatin films with and without GA extract **(b)**: DSC analysis of gelatin films with and without GA extract.

(Wang et al., 2022). The plant derived extracts rich in secondary metabolites such as terpenes, flavonoids, and phenolic acids can disrupt the hydrogen bonding of crystalline domains with the polymer matrix. This results in broadening and reduction in the intensity of diffraction peaks. This structural modification enhances polymer flexibility and amorphous nature.

3.8 Microstructure analysis of the films

The surface and cross-sectional morphology of the GA-loaded gelatin-based films were determined to study the impact of the GA (0.5%–1.5%) over the developed films. Micrographs of the control and GA-loaded films demonstrated large particles, which could be due to the insoluble particles of the gelatin polymer and GA extract left after drying. This could be the reason behind the significant variation in crystallinity as demonstrated in the Figure 6. Surface roughness, particles and cracks increased with the increase in the concentration of GA, demonstrating the adverse effect of extract over the gelatin films. It was found that the addition of extract increased the surface roughness, particles, and cracks which is in line with the previous studies. The addition of plant extracts into the polymer matrix alters the morphology of biopolymer films. The plant extract loaded samples shows an increase in roughness and heterogenous structure. Several studies reported that the incorporation of plant-extract in the polymer matrix results in the aggregation of particles, pores, cracks, or irregular and brittles surface of the fabricated films (Moghadam et al., 2020; Hanani et al., 2019; Riaz et al., 2018; Lei et al., 2019; Du et al., 2021; Piñeros-Hernandez et al., 2017; Fabra et al., 2018; Hanani et al., 2018; Ooi et al., 2011; Ribeiro et al., 2020; Gasti et al., 2020; Azeredo et al., 2016; Norajit et al., 2010; Talón et al., 2017; Moura-Alves et al., 2023; Nguyen et al., 2020).

These defects are in the form of the formation of holes, cavities, particles, granules, cracks, increase in surface roughness resulting in the formation of heterogeneous structures (Moghadam et al., 2020; Hanani et al., 2019; Riaz et al., 2018; Lei et al., 2019; Du et al., 2021; Piñeros-Hernandez et al., 2017; Fabra et al., 2018; Hanani et al., 2018; Ooi et al., 2011; Ribeiro et al., 2020; Gasti et al., 2020).

3.9 Thermal analysis

TGA analysis was performed to study the effect of extract over the thermal stability of stability films. TGA thermogram showed three distinct phases of significant weight loss within the temperature range at 25 °C–150 °C, 150 °C–400 °C and 400 °C–600 °C (Figure 7a). The maximum weight losses were observed around 102 °C, 250 °C and 350 °C, respectively. The initial weight loss occurred between 25 °C and 150 °C. This could be due to the evaporation of loosely bound water and traces of residual solvent present in the film. The first evaporation cycle could also be attributed to the small molecule's volatilization (Riaz et al., 2018; Nguyen et al., 2020; Liu et al., 2016). The second stage of weight-loss cycle occurred between 150 °C and 400 °C. This could be due to the thermal decomposition of organic constituents such as glycerol and gelatin (Kaya et al., 2018; Ahmad et al., 2012). The third weight loss cycle ranged from 400 °C–600 °C. This could be mainly due to the further degradation and carbonization of polymer, GA and their end products produced during the first two stages. The interaction between the polyphenolic components and films resulted in an increase in thermal degradation temperature, suggesting stronger interactions between GA components and the film matrix. Furthermore, variation in thermal stability between GG2, GG3, and GG4 samples was also observed. This could be due to the uneven distribution of GA or increased hydrophilicity of the film at a higher concentration of GA (1%–1.5%) resulting in an increase of water content in the film, therefore, the thermal stability was found to be relatively less than that of other films (Du et al., 2021). The overall thermal behavior of gelatin film was influenced by the addition of GA. The weight loss rates of the pure gelatin films were faster than those of GA loaded. This could be due to phenol–gelatin interactions, in particular, covalent

cross-linking. This suggests an improvement in the thermal stability after the addition of GA (Munir et al., 2019). Our study was in line with the previous work where thermal stability was improved with the addition of rosemary extract in a concentration-dependent manner (Piñeros-Hernandez et al., 2017).

Differential scanning calorimetry was performed to determine the endothermic peak temperatures (Guerrero et al., 2011). Figure 7b demonstrates the DSC thermogram of films with and without GA extract. DSC thermogram demonstrated two endothermic peaks. Pure gelatin film showed two endothermic peaks at 85 °C and 250 °C (Nunes et al., 2021). The initial endothermic peak within the range of 80 °C–95 °C could be due to several possible factors such as evaporation, melting and recrystallization of small and/or imperfect gelatin crystallites (Denavi et al., 2009; Rivero et al., 2010). The second sharp peak in the range of 250 °C–275 °C could be related to the thermal degradation of the polymer. The incorporation of GA extract increased the endothermic temperature from 80 °C to 95 °C. It was found that after the addition of extract endothermic peaks have shifted to higher temperatures. This shift could be due to the crosslinking effect of polyphenolic components. This increase in melting and thermal degradation temperature might be due to the increase in hydrophobic content and potential crystallinity of the film samples. This enhanced chain ordering and restricted molecular mobility contribute to the thermal properties of the fabricated films.

4 Conclusion

In conclusion, the gelatin film sample loaded with Galbanum absolute (GA) were successfully prepared. This study demonstrated that the physicochemical, structural, and functional properties of the gelatin-based biopolymer films were significantly influenced by the addition of GA in gelatin-matrix. The thickness, surface hydrophobicity, and thermal stability of the fabricated films increased with the addition of GA. FTIR spectra revealed only minor shifts in functional groups were observed. Moreover, the light transmittance of plain gelatin film sample was highest compared to GA-loaded samples. However, the increase in concentration of GA resulted in decrease in light transmittance crystallinity. The SEM analysis revealed the GA-loaded samples increased surface roughness and microcracks. Overall, the findings highlight that the incorporation of GA can improve the stability and functional performance of gelatin films. This supports the potential application of GA as active and biodegradable packaging materials. Further research is required to evaluate the barrier properties, antimicrobial activity, and real-time food applications.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SB: Writing – review and editing, Writing – original draft, Project administration, Formal Analysis, Supervision. YS: Formal Analysis, Writing – review and editing, Data curation, Writing – original draft, Software. AA: Writing – review and editing, Formal Analysis, Data curation, Methodology, Software. TK: Software, Writing – review and editing, Writing – original draft, Formal Analysis, Data curation. MJ: Software, Formal Analysis, Data curation, Writing – review and editing. AA-H: Writing – review and editing, Supervision, Project administration. EK: Software, Data curation, Writing – review and editing, Formal Analysis. LA: Formal Analysis, Data curation, Writing – review and editing, Software. TA: Formal Analysis, Software, Writing – review and editing, Data curation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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