PREPARATION AND COMPREHENSIVE CHARACTERIZATION OF CHITOSAN-BASED FILMS ENHANCED WITH FERULIC ACID

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Abstract

This study explores the development and detailed characterization of chitosan-based films enhanced with ferulic acid to improve their properties for biomedical, environmental, and packaging applications. Chitosan, a biopolymer derived from chitin, exhibits valuable attributes such as biocompatibility, biodegradability, and antimicrobial properties. However, it requires modifications to overcome limitations in mechanical strength, water permeability, and antioxidant properties. Ferulic acid, a phenolic compound, was incorporated into chitosan films at varying concentrations (1%, 2%, 5%, and 10%) to investigate its influence on film properties. The films were characterized through FTIR to confirm interactions between ferulic acid and chitosan, resulting in enhanced mechanical flexibility, thermal stability, and water resistance. Mechanical tests indicated that ferulic acid improved film flexibility while maintaining tensile strength, making it suitable for flexible packaging and wound dressings. Additionally, water vapour permeability and swelling tests suggested potential improvements in moisture control. Optical assessments showed increased whiteness and reduced colour variability, highlighting the aesthetic and protective advantages of ferulic acid-enriched films. These findings suggest that ferulic acid-modified chitosan films can serve as multifunctional biomaterials, addressing the growing demand for sustainable, high-performance materials in various industries. Further research on biological properties is recommended to fully establish their applicability in biomedicine and environmentally sensitive applications.

Keywords: *chitosan, ferulic acid, thin films, phenolic acid*

Introduction

Chitosan, a biopolymer derived from chitin, has garnered substantial attention in material science due to its remarkable biocompatibility, biodegradability, and inherent antimicrobial properties, making it an excellent candidate for biomedical and environmental applications [1]. Various methods have been developed to prepare chitosan-based materials, including solution casting, electrospinning, and freeze-drying, allowing the formation of films, scaffolds, and fibers [2]. Furthermore, crosslinking agents such as glutaraldehyde, genipin, and phenolic acids (for example, ferulic acid) are commonly used to enhance the mechanical stability and functional properties of these materials [3-5]. Among its various uses, chitosan-based films have been explored for applications in wound dressings, food packaging, and tissue engineering, where material performance and bioactivity are crucial. However, pure chitosan films often have limitations in mechanical strength, water permeability, and antioxidant properties, which necessitate enhancements to meet the demands of various applications [6].

In recent years, considerable research has focused on improving the properties of chitosan-based materials by incorporating bioactive compounds. Phenolic acids, such as ferulic acid, provide an intriguing modification strategy, as they offer not only antioxidant and antimicrobial benefits, but also act as crosslinking agents [7,8]. Ferulic acid, in particular, contains a phenolic ring and carboxylic groups capable of forming hydrogen bonds or covalent interactions with amino groups in chitosan [9]. These interactions can improve the mechanical strength, flexibility, and water resistance of the resulting films, making them more resilient and adaptable to diverse conditions. Additionally, ferulic acid's antioxidant properties offer protection against oxidative degradation, potentially extending the shelf life and functional stability of chitosan films in packaging and medical applications [10].

Specific examples highlight the versatility of chitosan films. In tissue engineering, these films serve as scaffolds for cell growth due to their biocompatibility, porosity, and ease of functionalization, enabling the repair of soft tissues and wound healing [11,12]. In the pharmaceutical sector, chitosan-based films have been utilized as drug delivery systems, where their controlled degradation and ability to encapsulate active compounds enhance therapeutic efficacy [13]. In cosmetics, such films are applied as facial masks or skin patches, leveraging their moisturizing and antimicrobial properties [14]. Furthermore, in the food industry, these films act as biodegradable packaging materials with excellent oxygen and water vapour barrier properties, prolonging the shelf life of perishable products such as fruits and meats [15].

This study aims to develop and characterize chitosan-based films enhanced with varying concentrations of ferulic acid, focusing on how this addition impacts the mechanical, thermal, and physicochemical properties of the films. By assessing parameters such as tensile strength, water vapour permeability, swelling, and colour properties, this research provides a comprehensive evaluation of the material's suitability for practical applications. For instance, tensile strength and flexibility are critical for wound dressings to conform to various body contours, while water resistance and barrier properties are paramount for food packaging to protect contents from external moisture and contaminants. Similarly, antioxidant capacity is essential for pharmaceutical and food applications to ensure the stability of sensitive compounds. Through this investigation, we seek to contribute to the development of multifunctional, biopolymer-based materials with the potential to address the increasing demand for sustainable and high-performance biomaterials in medical, food packaging, and other environmentally sensitive applications.

[Engineering of Biomaterials 172 (2024) 08]

doi:10.34821/eng.biomat.172.2024.08

Submitted: 2024-08-25, Accepted: 2024-09-19, Published: 2024-09-23

Materials and Methods

Chemicals

Chitosan (CTS, M_v = 1.8 × 10^6 g/mol, DD = 78%) and acetic acid were purchased from Pol-Aura (Zawroty, Poland). Ferulic acid (FE, M_W = 194.19 g/mol) was purchased from Carl Roth (Karlsruhe, Germany).

Films preparation

The preparation of chitosan-based (CTS) films started by dissolving chitosan in a 1% acetic acid solution at a concentration of 3%. Ferulic acid (FE) was simultaneously dissolved in 0.1M acetic acid at a 1% concentration. The two solutions were then mixed in four different ratios: 1% FE, 2% FE, 5% FE, and 10% FE relative to the chitosan solution. These mixtures were stirred continuously for one hour using a magnetic stirrer. Afterwards, the mixtures were poured into plastic moulds (40 mL per 10 cm x 10 cm), where thin films formed as the solvent evaporated.

Fourier Transform Infrared Spectroscopy-Attenuated Total Reflectance (FTIR–ATR)

FTIR-ATR was used to analyze the samples. Spectra were recorded in the range of 4000–500 cm^{-1} with a resolution of 4 cm^{-1}, and 64 scans using spectrometer Nicolet iS10 (Thermo Fisher Scientific Inc., Waltham, MA, USA), equipped with a germanium crystal in absorbance mode.

Atomic Force Microscopy (AFM)

The analysis of surface roughness was performed at room temperature in ambient air using a NanoScope IIIa MultiMode Scanning Probe Microscope (Veeco Metrology, Inc., Santa Barbara, CA, USA) operating in tapping mode. The Nanoscope Analysis v6.11 software (Bruker Optoc GmbH, Ettlingen, Germany) was utilized to calculate the root-mean-square roughness (Rq) and the mean arithmetic roughness (Ra).

Mechanical testing

The mechanical properties of the films were tested using a Shimadzu EZ-Test EZ-SX machine (Kyoto, Japan). The films were clamped and stretched at a speed of 5 mm/min. Young's modulus (E_{mod}), maximum tensile strength (σ_{max}) and elongation at break (dl) were calculated from the slope of the stress-strain curve in the linear region, between 0.3-1.5 N, using Trapezium X Texture software (Kyoto, Japan).

Water Vapour Permeation Rate (WVPR)

The water vapor permeation rate of the films was determined by measuring the weight change of anhydrous calcium chloride (m_0), used as a desiccant, placed inside a container with a 5 cm diameter. The containers were sealed with the films and kept at room temperature for 24 h. The weight change of calcium chloride, calculated as the difference between the initial weight (m_0) and the weight after 24 h (m_t), was used to calculate WVPR in units of g/cm²/h based on the absorbed water vapor.

$$\text{The percentage weight gain of } CaCl_2 = \frac{m_t - m_0}{m_0} \times 100\% \quad (1)$$

Swelling

Dry films with a known starting weight (m_s) were immersed in distilled water. After 1, 2, 3, 4, and 5 h of incubation, the samples were removed, gently dried with tissue paper, and weighed (m_{in}). The percentage of weight change was calculated using the appropriate formula:

$$\text{swelling [\%]} = \frac{m_{in} - m_s}{m_s} \times 100\% \quad (2)$$

Water content

The water content of the films was determined by drying the samples at 105°C until a constant weight was reached. The results were expressed as grams of water per 100 g of dry sample (n = 5).

Differences in colour and whiteness index

The colour properties of the films were measured using a Corneometer CL 400 colorimeter (Courage+Khazaka electronic GmbH, Cologne, Germany). The parameters measured included L (lightness), a (green to red spectrum), and b (blue to yellow spectrum). From these measurements, the total colour difference (ΔE) and whiteness index (WI) were calculated using standard formulas [16-17].

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{0.5} \quad (3)$$

$$WI = 100 - ((100 - L)^2 + a^2 + b^2)^{0.5} \quad (4)$$

where:

$\Delta L = L - L_0$; $\Delta a = a - a_0$; $\Delta b = b - b_0$;

L - the component describing lightness;

a - represents the colour ranging from green (−a) to red (+a);

b - represents the colour ranging from blue (−b) to yellow (+b);

L_0; a_0; b_0 - colour values for the white background, L_0 (lightness), a_0 (redness/greenness), and b_0 (yellowness/blueness).

Statistical analysis

Data collected during the study were analyzed using specialized software (SigmaPlot 14.0, Systat Software, San Jose, CA, USA). The Shapiro-Wilk test was applied to assess the normality of the data distribution. Results are presented as mean values ± standard deviation (SD). Differences between groups were analyzed using one-way analysis of variance (ANOVA), and multiple comparisons with the control group were conducted using the Bonferroni t-test, with the statistical significance set at $p < 0.05$.

Results and Discussions

Fourier Transform Infrared Spectroscopy–Attenuated Total Reflectance (FTIR–ATR)

The FTIR spectra of all films display characteristic peaks associated with chitosan (FIG. 1). The prominent peaks in the range of 3000–3500 cm^{-1} are attributed to the stretching vibrations of O-H and N-H bonds, which are typical for polysaccharide structures like chitosan [18]. Peaks around 1650 cm^{-1} correspond to the amide I region [19], which reflects the C=O stretching of the amide bonds in chitosan, while peaks near 1550 cm^{-1} can be assigned to the amide II band, associated with N-H bending and C-N stretching. Upon the addition of ferulic acid, changes are noticeable, particularly in the region between 1600–1700 cm^{-1}, which corresponds to the C=O stretching vibrations. These shifts indicate the formation of interactions between the carboxyl groups of ferulic acid and the amine groups of chitosan, likely forming hydrogen bonds or even covalent interactions [20]. Additionally, the presence of ferulic acid is also evident from peaks around 1500–1600 cm^{-1}, which correspond to the aromatic C=C stretching of the phenolic ring structure in ferulic acid. These peaks become more pronounced as the concentration of FE increases, signifying stronger contributions from the ferulic acid structure.

Atomic Force Microscopy (AFM)

The study of chitosan (CTS) films modified with ferulic acid (FE) revealed a significant impact of this additive on the surface properties of the material (TABLE 1). Ferulic acid, well-known for its antioxidant properties and ability to interact with polymers, was found to influence the microstructure of chitosan by altering its surface roughness.

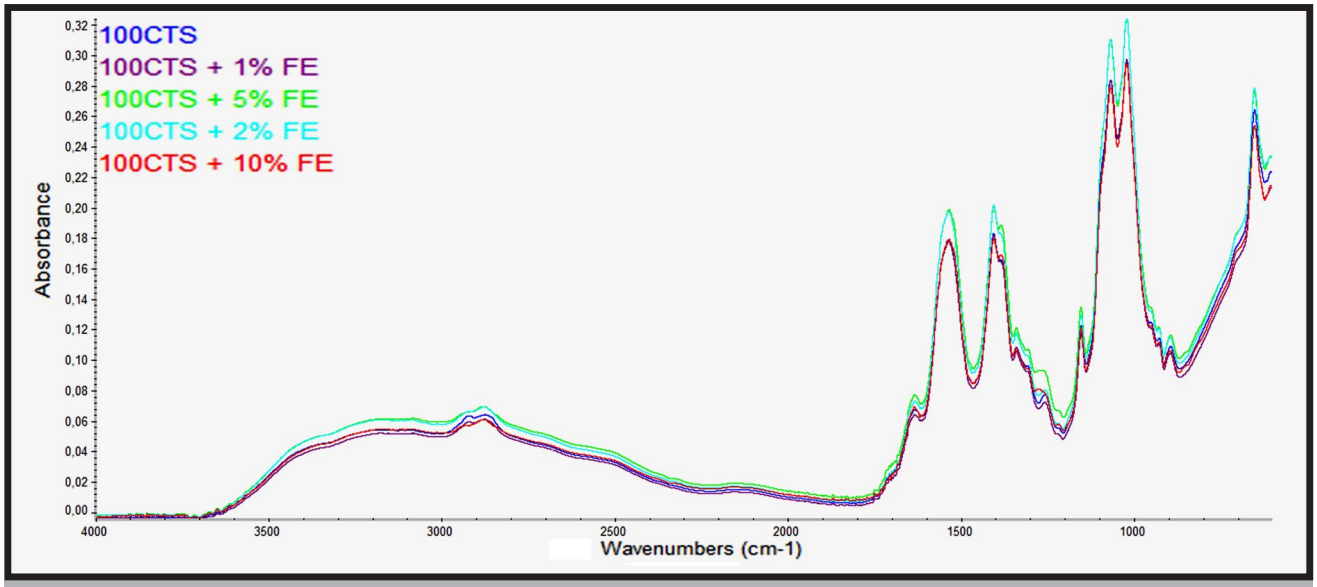

FIG. 1. FTIR spectra of all studied samples.

TABLE 1. The roughness parameters for all studied films (n = 5; no significantly different from 100CTS (p<0.05).

Specimen	Ra [nm]	Rq [nm]
100 CTS	1.55 ± 0.15	1.94 ± 0.24
100 CTS + 1% FE	1.37 ± 0.12	1.74 ± 0.15
100 CTS + 2% FE	1.28 ± 0.17	1.66 ± 0.18
100 CTS + 5% FE	1.37 ± 0.17	1.76 ± 0.24
100 CTS + 10% FE	1.24 ± 0.07	1.56 ± 0.10

Pure chitosan films (100 CTS) exhibited a smooth surface, characteristic of unmodified chitosan structures that form relatively uniform matrices (FIG. 2A). The introduction of FE resulted in a decrease in surface roughness, suggesting that this additive contributes to the smoothing of the film structure [5]. For instance, films containing 1% FE displayed a reduced roughness, with an Ra value of 1.37 ± 0.12 nm compared to 1.55 ± 0.15 nm for pure chitosan (FIG. 2B). Increasing the FE concentration to 2% further decreased the roughness to 1.28 ± 0.17 nm (FIG. 2C). This effect may stem from interactions between the hydroxyl and carboxyl groups of ferulic acid and the chitosan polymer network, leading to improved molecular organization and reduced surface irregularities. At higher concentrations of FE, such as 5% (FIG. 2D) and 10% (FIG. 2E), the Ra values were measured at 1.37 ± 0.17 nm and 1.24 ± 0.07 nm, respectively, highlighting a trend towards surface homogenization.

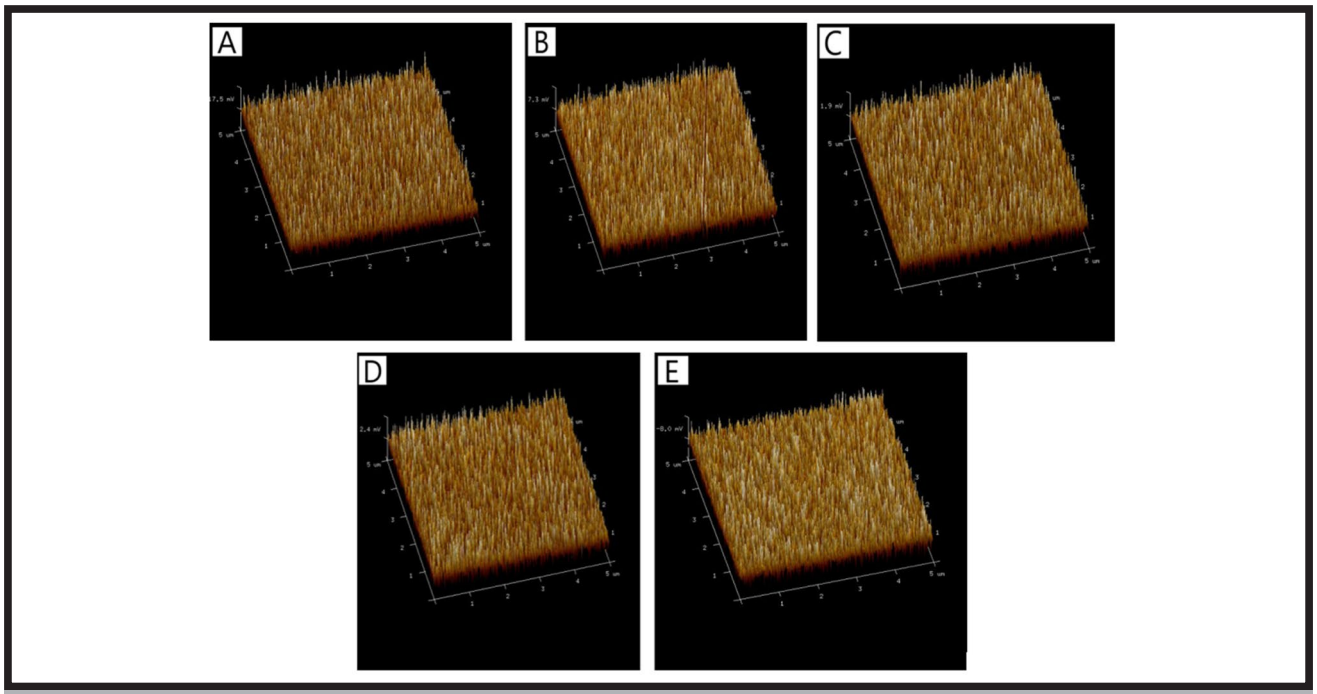

FIG. 2. The 3D images of surfaces of films: A) 100CTS; B) 100CTS + 1%FE; C) 100CTS + 2%FE; D) 100CTS + 5%FE; E) 100CTS + 10%FE.

The observed changes could be attributed to both the plasticizing effect of FE and its ability to modify the polymer network. The chemical properties of ferulic acid, including its capacity to form hydrogen bonds, might limit the tendency of chitosan to develop micro-protrusions and depressions, resulting in a more homogeneous surface [21].

Furthermore, the stability of measurement results across different samples containing FE indicates the repeatability of its modifying effect, which is promising for potential applications in biomaterials. The ability of ferulic acid to control surface properties may be particularly valuable in contexts requiring precise regulation of interactions with cells, proteins, or other biological components [22,23].

Mechanical testing

Young's modulus, which reflects the stiffness of the films, showed a noticeable decrease as the concentration of ferulic acid increased (FIG. 3). The pure chitosan film demonstrated the highest stiffness, while the addition of FE led to a reduction in modulus. This suggests that ferulic acid incorporation makes the films more flexible. Films with 1% and 2% FE maintained relatively high stiffness compared to higher concentrations, indicating that moderate amounts of FE preserve some of the structural integrity provided by the chitosan matrix. However, at 5% and 10% FE, the films exhibited lower stiffness, implying that higher FE concentrations reduce the material's resistance to deformation. This trend may be attributed to the interaction between ferulic acid and chitosan, which could disrupt the chitosan network and create a more elastic or less tightly bound matrix.

The maximum tensile strength which is responsible for the films' strength before breaking, was relatively stable across all formulations, indicating that the addition of ferulic acid does not drastically alter the tensile strength of the films (FIG. 3). While the pure chitosan film and the ones with lower concentrations of FE (1% and 2%) displayed slightly higher maximum stress, the differences were not significant enough to suggest that the films became weaker or stronger with FE incorporation. This consistency in strength suggests that while the films became more flexible with increased FE, their ability to withstand stress before breaking remained intact, which could be advantageous for applications requiring both flexibility and strength.

Elongation at break, which is responsible for the films' ability to stretch before breaking, showed a slight decrease as the concentration of ferulic acid increased (FIG. 3). The pure chitosan film exhibited the highest elongation, implying greater ductility, while films with added FE were less ductile. The reduction in elongation with higher FE concentrations suggests that while FE enhances flexibility in terms of stiffness, it simultaneously reduces the films' capacity to stretch before failure. This trade-off between flexibility and elongation might be due to the interaction between chitosan and FE, which likely creates a denser network that is less prone to stretching but still more pliable in terms of deformation.

Research on the effects of ferulic acid (FA) on the mechanical properties of various materials demonstrates that its impact is strongly dependent on both concentration and the type of matrix. For example, Kaczmarek et al. [24] showed that higher FA concentrations (10%) in collagen films lead to improved mechanical properties, including increased tensile strength and elongation at break, suggesting that FA may reinforce collagen structure. Conversely, Lim et al. [25] found that in Gelidium corneum films, the optimal FA concentration is 10 mg/100 mL, with higher levels reducing tensile strength, which indicates potential destabilization of the material's structure at elevated FA doses. Similar patterns are evident in the present findings for chitosan films: increasing FA concentration lowers Young's modulus, making the films more flexible while having only a minor effect on maximum tensile strength. The observed decrease in elongation at break at higher FA concentrations may result from a denser chitosan network, which becomes less prone to stretching yet remains more flexible under deformation. This aligns with previous observations of Kaczmarek or Lim [24,25]. These findings highlight the importance of precisely adjusting FA concentration to optimize mechanical properties based on specific application requirements.

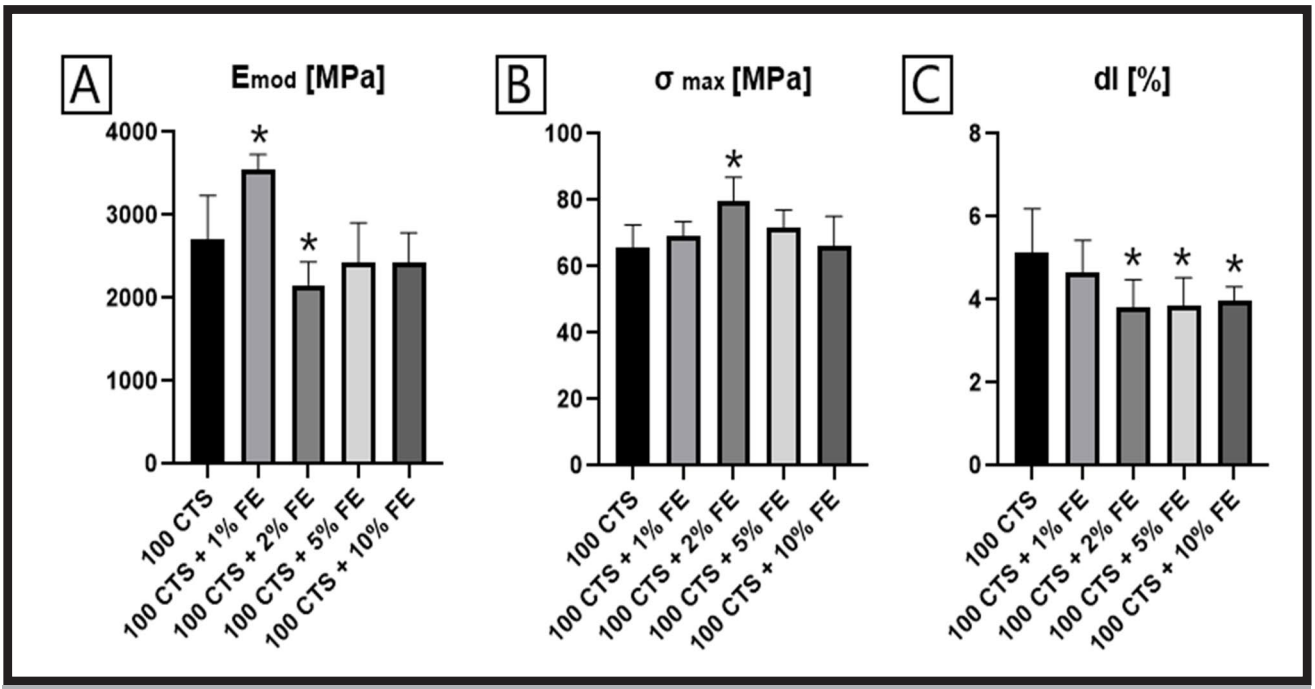

FIG. 3. A) The Young Modulus (E_{mod}), (B) maximum tensile strength (σ_{max}) and (C) elongation at break (dl) determined for films based on 100 CTS, 100CTS + 1%FE, 100CTS + 2%FE, 100CTS + 5%FE and 100CTS + 10%FE. (n = 10; significant differences from 100CTS ($p<0.05$).

Water Vapour Permeation Rate (WVPR)

The analysis of the WVPR across different formulations of CTS and FE revealed that the permeability of the films to water vapour remained relatively stable, regardless of the concentration of FE added (TABLE 2). This suggests that the barrier properties of the films were not significantly affected by the incorporation of ferulic acid [26,27]. The likely explanation is that ferulic acid contains numerous hydroxyl groups, which can bind with water, resulting in no apparent change in the WVPR. The film with 5% FE showed slightly better performance in reducing water vapour permeability, indicating that this concentration might enhance the film's moisture resistance. This stability in WVPR across formulations demonstrates the films' robustness, making them potentially suitable for applications requiring moisture control, such as food packaging or wound dressings.

Incorporating ferulic acid (FA) into biopolymer films notably affects their properties, enhancing performance in specific applications. Studies show that FA addition to chitosan films reduces moisture content and water vapour permeability while boosting mechanical resistance [28]. Similar benefits have been observed in bitter vetch protein and chitosan-fish gelatin films, where FA reduced permeability [29,30]. In our study, water vapour permeability (WVPR) across different FA concentrations remained stable, suggesting FA's hydroxyl groups likely bind water without significantly altering barrier properties. The 5% FA film showed a slight improvement in moisture resistance, supporting FA's role in enhancing stability in moisture-sensitive applications, such as food packaging and wound dressings.

TABLE 2. The WVPR of films of CTS with 1, 2, 5 and 10% of ferulic acid addition (n = 5; no significant differences from 100CTS (p<0.05).

Specimen	WVPR [g/cm²/h]
100CTS	0.0401 ± 0.0037
100CTS + 1%FE	0.0404 ± 0.0061
100CTS + 2%FE	0.0397 ± 0.0024
100CTS + 5%FE	0.0394 ± 0.0037
100CTS + 10%FE	0.0401 ± 0.0037

Swelling

The addition of FE to the CTS matrix influenced the swelling behaviour, with higher FE concentrations leading to increased water absorption (TABLE 3, FIG. 4). Films with 2%, 5%, and 10% FE showed a more pronounced swelling effect compared to the pure CTS and 1% FE films. The increase in swelling could be attributed to the hydrophilic nature of ferulic acid, which facilitates water uptake by creating additional sites for hydrogen bonding [31,32]. The 10% FE film, in particular, exhibited the highest swelling capacity, indicating that the incorporation of FE enhances the film's ability to absorb water, likely by loosening the chitosan network and increasing its porosity [33].

Over the first hour of immersion, films with higher FE concentrations swelled more rapidly than the pure CTS film. This suggests that the presence of FE disrupts the tight chitosan structure, allowing water molecules to penetrate more easily. The differences became more pronounced over time, with the 5% and 10% FE films absorbing significantly more water than the other formulations after 240 min. This time-dependent behaviour highlights the role of FE in modifying the film's structural properties, particularly its ability to retain and absorb water over extended periods.

TABLE 3. The swelling of films of CTS with 1, 2, 5 and 10% of ferulic acid addition (n = 5; * significantly different from 100CTS (p<0.05).

Specimen	Film weight gain [%]					
	15 min	30 min	45 min	60 min	120 min	240 min
100CTS	1050 ± 91	1120 ± 38	1150 ± 33	1237 ± 60	1361 ± 61	1408 ± 51
100CTS + 1%FE	1028 ± 31	1126 ± 44	1170 ± 60	1201 ± 11	1287 ± 32	1326 ± 41
100CTS + 2%FE	1151 ± 61	1297 ± 79*	1389 ± 54*	1520 ± 82*	1616 ± 38*	1719 ± 75*
100CTS + 5%FE	1080 ± 85	1199 ± 87	1274 ± 95	1409 ± 22*	1573 ± 87*	1713 ± 52*
100CTS + 10%FE	1082 ± 83	1229 ± 86	1329 ± 38*	1406 ± 45*	1548 ± 83*	1776 ± 73*

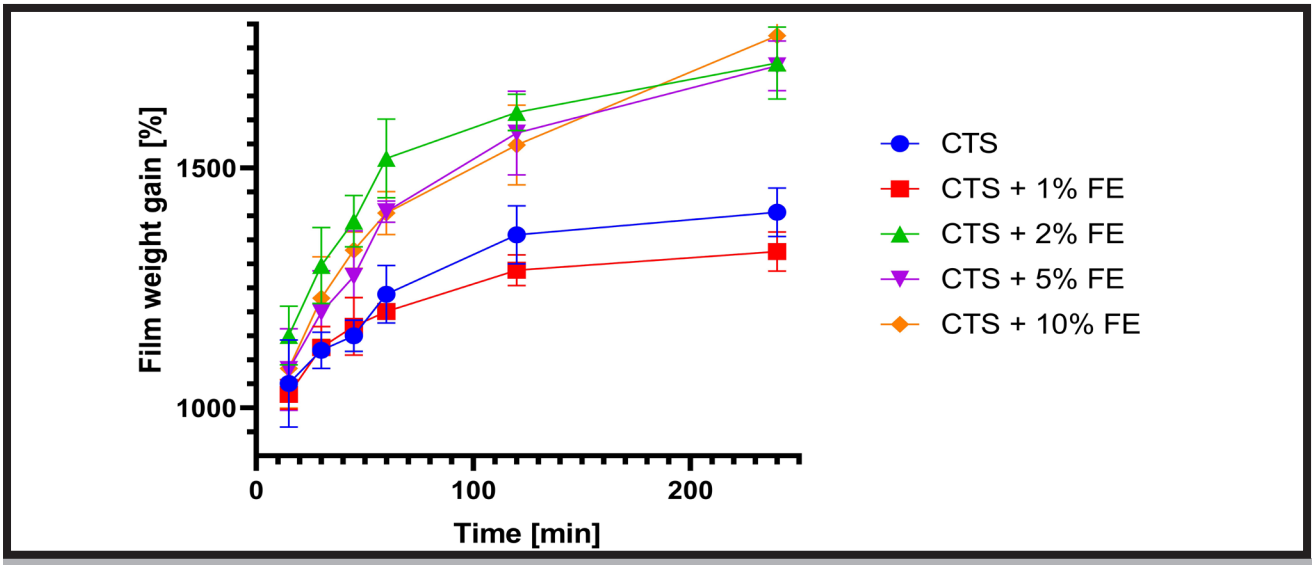

FIG. 4. The swelling of films of CTS with 1, 2, 5 and 10% of ferulic acid addition.

The swelling behaviour also indicates that higher concentrations of ferulic acid (FE) in chitosan (CTS) films accelerate material degradation, as evidenced by the complete disintegration of the material after 240 min, preventing further swelling analysis and highlighting the loss of structural integrity.

Chitosan films with added ferulic acid (FA) demonstrate reduced moisture content, lower water vapour permeability, and improved resistance, as shown by Rivero et al. [29]. The swelling of FA-functionalized hydrogels also varies with substitution degree and ionic strength, indicating FA's adaptability in enhancing material properties [36]. These modifications make FA-modified biopolymers promising for applications in food packaging, pharmaceuticals, and cosmetics. In our study, higher FA concentrations (2%, 5%, 10%) significantly increased water absorption in chitosan films, likely due to FA's hydrophilic nature, which enables more hydrogen bonding and loosens the chitosan network. Notably, the 10% FA film absorbed the most water and swelled rapidly in the first hour, highlighting FA's role in altering structural and water retention properties over time, consistent with Dulong et al.'s findings [32].

Water content

The water content of the films increased with the addition of lower concentrations of FE (TABLE 4). To support the observed increase in water content at lower FE concentrations, Aljawish [34] noted that chitosan films exhibit high moisture content due to strong hydrogen bonding between water molecules and chitosan's functional groups, such as hydroxyl and amino groups. The hydrophilic nature of ferulic acid likely intensifies these interactions at lower concentrations, promoting water retention within the film matrix. However, as FE concentration rises, water content reaches a plateau, possibly due to saturation of hydrophilic sites, as seen in similar films studied by Rivero [35]. Thus, films with lower FE concentrations, which exhibit higher water content, their suitability for applications where controlled water absorption or retention is important, such as in wound dressings.

Differences in colour and whiteness index

The addition of FE impacted the optical properties of the films, particularly their colour and whiteness (TABLE 5). Films with higher concentrations of FE exhibited improved whiteness, making them appear brighter and more visually appealing and may enhance properties like UV protection [36]. In contrast, films with lower concentrations of FE showed greater colour variation, likely due to the interaction between FE and the chitosan matrix. The formulation containing the highest concentration of FE demonstrated the best results in terms of whiteness, suggesting that FE can be used to enhance the aesthetic properties of chitosan-based films. These improvements in optical properties make films with higher FE concentrations ideal for applications where visual clarity and brightness are important, such as in packaging materials or wound dressing.

Ferulic acid (FA) is recognized for its potential as a whitening agent, which has led to its incorporation into a range of cosmetic and food products [37]. Its ability to synergize with other ingredients, such as Waltheria indica extract, in whitening complexes enhances its inhibitory effect on tyrosinase and provides mild exfoliation, making it a versatile and effective choice for promoting skin brightening and antioxidant effects [38]. Our study supports these findings, particularly regarding FA's influence on the optical properties of chitosan films, where higher concentrations significantly enhanced whiteness and brightness. This effect likely arises from FA's interaction within the chitosan matrix, creating films with greater visual appeal.

TABLE 4. The water content of films of CTS with 1, 2, 5 and 10% of ferulic acid addition (n = 5; no significant differences from 100CTS (p<0.05).

Specimen	Water content [g/100 g]
100CTS	15.18 ± 1.70
100CTS + 1%FE	16.61 ± 1.65
100CTS + 2%FE	16.94 ± 1.02
100CTS + 5%FE	15.32 ± 1.37
100CTS + 10%FE	15.18 ± 1.13

TABLE 5. The total difference of colour value (ΔE), and whiteness index (WI) of films chitosan modified by 1, 2, 5 and 10% of ferulic acid addition (no significant differences from 100CTS (p<0.05).

Specimen	ΔE	WI
100CTS	6.73 ± 0.75	93.39 ± 0.47
100CTS + 1%FE	7.36 ± 0.88	92.33 ± 0.85
100CTS + 2%FE	6.97 ± 0.55	92.26 ± 0.74
100CTS + 5%FE	6.45 ± 0.54	92.54 ± 1.25
100CTS + 10%FE	6.13 ± 0.62	94.93 ± 1.10

As a result, FA-enriched films hold promise for applications that benefit from improved aesthetic properties, such as skincare, wound dressings, and packaging. Furthermore, these enhanced optical qualities align with FA's known photoprotective and anti-aging benefits in cosmetic products, as it not only improves film appearance but also contributes functional advantages like UV protection [39].

Conclusions

The addition of ferulic acid (FE) to chitosan films introduces significant changes to their structural, mechanical, and functional properties, with these effects becoming more pronounced at higher FE concentrations. Increasing the FE content from 2% to 5% and 10% results in smoother surfaces, enhanced flexibility, and greater water absorption. These changes are attributed to interactions between FE and the chitosan matrix, including hydrogen bonding, which improves molecular organization and disrupts the rigid polymer network. Films with lower FE concentrations, such as 2% and 5%, maintain a balance between flexibility and mechanical strength, along with moderate water absorption. These properties make them particularly suitable for biomedical applications, such as wound dressings or drug delivery systems, where controlled flexibility and swelling are essential for functionality and biocompatibility. The smooth surface texture further enhances their potential for interactions with biological tissues. At 10% FE, the films exhibit the highest flexibility and water absorption capacity, making them more suited for environmental applications like biodegradable packaging or moisture regulation systems. However, this concentration also results in reduced mechanical strength, which may limit its use in applications requiring high durability.

Among the tested formulations, 5% FE emerges as the optimal concentration, offering the best balance of surface smoothness, mechanical flexibility, and water absorption. This concentration allows for versatility, enabling the films to meet the requirements of both biomedical and environmental applications. Tailoring the concentration of FE in chitosan films provides a pathway to customize their properties for specific uses, enhancing their potential as multifunctional, sustainable materials.

Further studies should investigate the biological properties of the studied films, including their potential biocompatibility, antimicrobial activity, and effects in different environmental conditions, to fully understand their applicability in biomedical and environmental contexts.

Acknowledgements

The present study was supported in some part by the Nicolaus Copernicus University in Torun (Torun, Poland) to maintain research potential, by the Excellence Initiative Research University competition for scientific groups—BIOdegradablePACKaging materials research group (4101.00000085).

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