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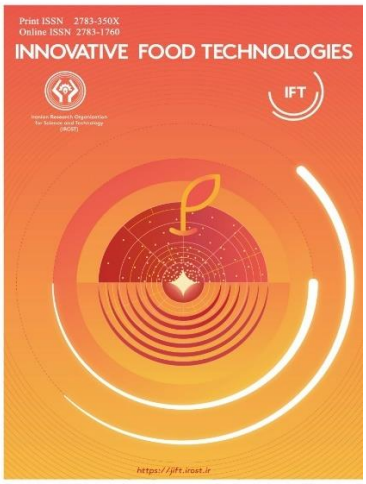

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DOI: https://doi.org/10.22104/ift.2026.8188.2284

To appear in: Innovative Food Technologies (IFT)

Received Date: 13 April 2026
Revised Date: 20 June 2026
Accepted Date: 11 July 2026

Please cite this article as: Roya Mehdizadeh, Babak Ghanbarzadeh, Nooshin Noshirvani, Fabrication and characterization of activated gelatin-inulin electrospun nanofibers loaded with savory extract, *Innovative Food Technologies (2026)*, doi: https://doi.org/10.22104/ift.2026.8188.2284

Fabrication and characterization of activated gelatin-inulin electrospun nanofibers loaded with savory extract

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Abstract
In the present study, electrospun gelatin/inulin nanofibers loaded with *Satureja hortensis* (savory) extract were successfully fabricated and characterized. Gelatin–inulin solutions with polymer ratios of 100:0, 90:10, 70:30, 60:40, and 50:50 were prepared for electrospinning, and the influence of key solution properties, including viscosity, electrical conductivity, and surface tension, on nanofiber morphology was systematically evaluated. The average diameter of the resulting fibers ranged from 0.219 to 0.553 μm, depending on the formulation. Fourier transform infrared (FTIR) spectroscopy confirmed the formation of hydrogen-bond interactions between gelatin and inulin and verified the successful incorporation of savory extract into the nanofiber matrix. Furthermore, the antioxidant activity of free and encapsulated extracts was monitored over a 21-day storage period. The encapsulated extract exhibited improved antioxidant stability compared with its free counterpart, demonstrating the protective effect of the nanofiber carrier system. Overall, the findings indicate that electrospun gelatin/inulin nanofibers represent a promising platform for the efficient encapsulation, protection, and delivery of savory bioactive compounds.

Keywords: Electrospinning, nanofiber, gelatin, inulin, savory extract

1 Introduction

Satureja hortensis L. (summer savory), a member of the Lamiaceae family, is an annual aromatic herb native to southern Europe and widely distributed in North America and parts of western and southern Asia, including Iran (Lincoln, 1976; Noshirvani & Fasihi, 2018). Owing to its rich phytochemical composition, this plant has attracted considerable attention in recent years. Several studies have reported a wide range of biological activities for *S. hortensis*, including antimicrobial, antioxidant, anti-inflammatory, and anticancer effects (Noshirvani, 2024). These functional properties are mainly attributed to its essential oil constituents, particularly carvacrol, thymol, p-cymene, γ-terpinene, and caryophyllene.

Despite their valuable biological activities, the active compounds present in plant extracts are often highly susceptible to environmental conditions. Many of these compounds exhibit poor water solubility, high volatility, and sensitivity to oxygen, light, temperature, pH fluctuations, and humidity. Consequently, substantial losses in bioactivity may occur during processing, storage, and application (Kfoury et al., 2019; Rezaei et al., 2019; Fasihi et al., 2017; Noshirvani & Abolghasemi Fakhri, 2024). Improving the stability and preserving the functionality of these compounds therefore remains a major challenge for their effective utilization in food, pharmaceutical, and nutraceutical products.

To address these limitations, various encapsulation and delivery systems have been developed to protect bioactive compounds and enhance their stability. Nanocarrier-based systems have received particular attention because they can improve the retention, controlled release, and bioavailability of encapsulated compounds (Patra et al., 2018; Fasihi et al., 2019; Fasihi et al.,

2023). Depending on the carrier design, the release of active compounds can be regulated through diffusion, swelling, degradation, or affinity-driven mechanisms (Luraghi et al., 2021). Among the different delivery platforms investigated to date, including liposomes, polymeric micelles, and inclusion complexes, nanofibrous systems have emerged as promising candidates due to their structural versatility and high loading capacity (Torres-Martínez et al., 2018).

Electrospinning, an electrohydrodynamic technique that employs an electric field to generate ultrafine fibers from polymer solutions, has become one of the most widely used approaches for fabricating nanofibrous delivery systems (Zare et al., 2021). The technique is relatively simple, cost-effective, and capable of producing fibers with diameters ranging from the nanometer to submicron scale. Electrospun fibers possess unique characteristics, including high surface area, interconnected porosity, and tunable morphology, which make them attractive matrices for the encapsulation of sensitive bioactive compounds (Min et al., 2004; López-Rubio et al., 2012; Neo et al., 2013; Unnithan et al., 2014). In addition, because electrospinning is generally performed at ambient temperature, thermal degradation of heat-sensitive compounds can be minimized during processing (Bumedi et al., 2023).

The selection of an appropriate carrier material plays a critical role in determining the performance of electrospun delivery systems. Inulin, a naturally occurring fructan, has been extensively used in food and pharmaceutical applications because of its biocompatibility, prebiotic properties, and stabilizing effects. Previous studies have shown that inulin can improve matrix stability, protect biological materials against dehydration stress, and contribute to the preservation of sensitive compounds during processing and storage (Mensink et al., 2015; Hirsch et al., 2021). Gelatin, another widely used biopolymer, is valued for its biodegradability, biocompatibility, and excellent film- and fiber-forming properties. Furthermore, gelatin can be electrospun using relatively mild solvent systems, making it suitable for the incorporation of delicate bioactive ingredients (Kanmani & Rhim, 2014; Mendes et al., 2017; Chen et al., 2009; Deng et al., 2017).

The combination of gelatin and inulin may offer additional advantages for the encapsulation of plant-derived bioactives. Gelatin is capable of forming a continuous fibrous network that physically entraps active compounds, whereas inulin may contribute to structural stabilization and protection against environmental stresses. Such a combination is expected to provide a favorable microenvironment for preserving the volatile and oxidation-sensitive constituents of *S. hortensis* extract. Nevertheless, information regarding the application of gelatin/inulin electrospun nanofibers as carriers for savory extract is still limited. In particular, the influence of gelatin-to-inulin ratio on solution properties, nanofiber formation, and the preservation of extract functionality has not been comprehensively investigated. The novelty of this work lies in the systematic investigation of gelatin–inulin interactions during electrospinning and their impact on nanofiber formation, providing new insights into the development of biopolymer-based nanocarriers for the protection and delivery of *S. hortensis* bioactive compounds.

Therefore, the objective of the present study was to develop electrospun gelatin/inulin nanofibers containing *S. hortensis* extract and to evaluate the effect of different gelatin/inulin ratios on the physicochemical properties of the spinning solutions, including viscosity, electrical conductivity, and surface tension, as well as on the morphology of the resulting nanofibers. The ability of the developed nanofibrous system to preserve the antioxidant activity of the encapsulated extract during storage was also assessed. This study provides further insight into the potential of gelatin–inulin electrospun matrices as natural carrier systems for enhancing the stability of bioactive plant extracts.

2. Materials and methods

2.1 Materials

Gelatin (180 bloom) was obtained from Sigma-Aldrich Co. (St. Louis, MO, USA). Inulin was purchased from Tokyo Industry Co. Japan. Acetic acid and ethanol were purchased from Merck Co., Germany. Tween-80 was supplied by Merck (Darmstadt, Germany). Deionized water was utilized as the solvent throughout the duration of the study.

2.2. Savory extract preparation

The maceration process involved grinding 80 g of dried savory leaves and extracting them with a 70% EtOH solution over a period of 100 hours. The resulting mixture was subsequently purified through filtration and centrifugation. Following purification, the solvent was evaporated to obtain a concentrated extract. This extract was then freeze-dried at -55°C under a pressure of 0.37 mbar, and the resulting dried material was stored at -4°C.

2.3. Preparation of electrospun solutions

Before the addition of biopolymers, the solvent was prepared using 42.1% ethanol, 35.65% acetic acid, and 22.25% distilled water. Afterwards, inulin (2% w/v) and gelatin (9% w/v) were individually added to the prepared solutions and stirred for 24 minutes and 30 minutes, respectively. Various ratios of the two polymer solutions were then prepared, specifically gelatin to inulin ratios of 100:0, 90:10, 70:30, 60:40, and 50:50. Following this, tween 80 was introduced as an emulsifier at 2% w/v, and finally, savory extract was incorporated into each biopolymer solution at a concentration of 5% v/v.

2.4. Electrospinning process

Nanofibers were fabricated using an electrospinning apparatus (ES-Lab RN/X, ANSTCO, Iran) configured in a horizontal orientation, operating at a voltage of 26 kV. The distance between the needle tip and the collector was maintained at 15 cm, with a rotation speed of 0.5 rpm. A 10 mL syringe equipped with a metallic needle (0.7 mm outer diameter) was utilized to electrospin gelatin/inulin solutions incorporating savory extract. The resulting fibers were collected on aluminum foil. The electrospinning process was conducted at ambient temperature, with each trial lasting 40 minutes.

2.5. Characterization of biopolymer solutions

2.5.1. Rheological properties

Rheological characterization of emulsions comprising inulin-gelatin and savory extract was conducted using a Paar Physica MCR 301 rheometer (Anton Paar GmbH, Austria) equipped with a cone-plate geometry, maintained at a constant temperature of 25 ºC. Shear stress and viscosity were measured as functions of shear rate to evaluate the flow behavior of the samples. Measurements were performed within the linear viscoelastic region, with the shear rate varying from 2 to 100 s^{-1} over a 10-minute duration. The stable shear flow test was performed on biopolymer solutions at shear speeds of 0.1 to 100/s and a temperature of 25 °C, and the values of apparent viscosity and shear stress were recorded according to the shear speed.

2.5.2. Electrical conductivity

The electrical conductivity of the solutions was determined using a conductivity meter (model 4510, Jenway, UK).

2.5.3. Surface tension

The surface tension of the samples was determined using the Wilhelmy plate method with a tensiometer (model DCAT 21, Data Physics, Germany). Calibration of the instrument was

performed using deionized water (72.52 mN/m). All measurements were conducted in triplicate to ensure reproducibility.

2.6. Electrospun nanofiber tests

All experiments were conducted under controlled laboratory conditions at a temperature of 25 ± 2 °C and a relative humidity of 45 ± 5%.

2.6.1. Scanning electron microscopy (SEM)

The morphology of electrospun inulin/gelatin nanofibers was investigated after drying all nanofiber samples at room temperature for 6 hours. Subsequently, each sample was sectioned into 1 × 1 cm pieces, which were then gold-coated prior to examination with a scanning electron microscope (Philips, model X130, Netherlands). Digimizer version 4.1.1.0 was used for obtaining the diameter distribution histogram. Specifically, the diameters of 100 fibers were randomly selected from multiple FESEM pictures for each sample.

2.6.2. Fourier transform infrared spectrometry (FT-IR) analysis

The chemical structures of the nanofibers based on inulin-gelatin containing savory extract were characterized using ATR-FTIR spectroscopy (TENSOR 37, Bruker, USA). Spectroscopy was performed in the range of 4000 and 400 cm^{-1} with a resolution of 2 cm^{-1} and 100 scans. Before the test, the samples were dried for 48 hours at 37°C.

2.6.3. Antioxidant activity

The antioxidant activities of the savory extract and nanofibers containing savory extract were evaluated using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay. For this assay, 5 mg of the fiber sample was combined with 3 mL of DPPH solution (0.1 mmol/L) and incubated in the dark at room temperature for 30 minutes. Following incubation, the absorbance of the solution was measured at 517 nm using UV-Vis NIR spectroscopy (Varian Cary 5000) (Wu et al., 2012). The antioxidant activity was calculated according to Eq. (1):

$$\text{Antioxidant activity (\%)} = \frac{A\ sample - A\ blank}{A\ blank} \times 100 \qquad \text{Eq. (1)}$$

2.7. Statistical Analysis

All experiments were conducted in triplicate, and the results are presented as mean values ± standard deviations. Significant differences among samples were assessed using one-way analysis of variance (ANOVA) followed by Duncan's multiple range test at a significance level of 5%, utilizing SPSS statistical software (IBM SPSS Statistics, Version 22, New York, USA).

3. Results and discussions

3.1. Properties of polymer solutions

Several critical parameters influence the electrospinning behavior of polymers, including viscosity, surface tension, and electrical conductivity (Moomand and Lim, 2015). Accordingly, biopolymeric solutions with varying gelatin-to-inulin ratios (100:0, 90:10, 70:30, 60:40, and 50:50), each containing 5% savory extract, were evaluated for their viscosities, surface tensions, and conductivities, as presented in Table 1. An increase in the gelatin content led to a significant rise ($P < 0.05$) in the electrical conductivity, surface tension, and viscosity of the polymer solutions. The observed increase in viscosity is attributed to the higher overall polymer concentration resulting from the increased gelatin ratio. A higher polymer concentration can promote greater chain entanglement, which enhances the solution's ability to retain water, thereby contributing to the observed increase in viscosity. The polymer concentration in a solution is a critical factor determining its suitability for electrospinning into nanofibers and significantly influences fiber morphology. A minimum polymer concentration is necessary to form fibers, while an optimal concentration is required to produce bead-free

fibers. Typically, increasing the solution concentration results in larger fiber diameters and improved uniformity. The electrospinning process relies on the transfer of electric charges from the electrode to the spinning droplet, making a minimum level of electrical conductivity essential for nanofiber formation. Solutions lacking electrical conductivity cannot be electrospun into nanofibers. Electrical conductivity is influenced by factors such as the type of polymer and solvent, polymer concentration, and temperature. When the polymer contains ionic functional groups, the solution's conductivity becomes dependent on its concentration (Okutan et al., 2014). The precursor solution conductivity of gelatin/inulin at 100:00 was the highest, but then reduced with the reduction of gelatin content. It corresponds to the nature of gelatin as a polyelectrolyte polymer which contains a lot of ionized groups, such as amine and carboxyl acids (Huanga et al., 2004; Zhang et al., 2005). The flow behavior in terms of shear stress-shear degree and viscosity-shear degree for different ratios of gelatin and inulin solutions are illustrated in Figure 1(a-b). Rheological properties, particularly viscosity, play a crucial role in the formation of nanofibers. Solutions with excessively high viscosity are unable to be ejected from the spinneret, whereas those with insufficient viscosity fail to form fibers (Bhardwaj and Kundu, 2010). The viscoelastic forces within the charged polymer jet counterbalance the Coulombic repulsion, which primarily drives the elongation of the jet beyond the apex of the Taylor cone (Okutan et al., 2014). According to the obtained results the gelatin and inulin solutions in ratios (50:50, 60:40, 70:30, and 90:10) showed Newtonian behavior. The R^2 for all solutions is one which confirms the Newtonian behavior. Surface tension, which depends on the solution composition, plays a pivotal role in the electrospinning process (Bhardwaj and Kundu, 2010). It acts as the primary force opposing the applied voltage during electrospinning and directly influences the processability of the solution. Solutions with low surface tension tend to produce bead-free fibers; however, a low surface tension alone does not guarantee successful electrospinning. The minimum voltage required to generate nanofibers generally increases with the solution's surface tension, although this relationship is not strictly linear. Surface tension of polymer solutions varies with changes in concentration, chemical composition, and temperature (Okutan et al., 2014). Successful initiation of electrospinning necessitates that the electrical forces overcome the solution's surface tension. According to Table 1, by increasing the ratio of gelatin in the gelatin-inulin solution from 50:50 to 100:00, the surface tension has increased from 30.91 mN/m to 34.043 mN/m.

Table 1. Physical properties of gelatin/inulin fibers and their precursor solutions

Sample number	Gelatin to inulin ratio	Conductivity [µS/ms]	Surface Tension (mN/m)	Average Diameter of Fibers [µm]
1	100:00	1309±0.115	34.043±0.071	0.553±0.137
2	90:10	1296.017±0.057****	33.71±0.23^{ns}	0.487±0.122**
3	70:30	1054.22±0.40****	31.29±0.75***	0.302±0.1****
4	60:40	961.11±0.26****	31.20±0.34***	0.295±0.069****
5	50:50	879.94±0.093****	30.91±0.95***	0.219±0.0635****

One-way analysis of variance (ANOVA) test was used as a statistical method to compare the different groups. Statistical significance was expressed using the following symbols: * for $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$, and **** for $p < 0.0001$

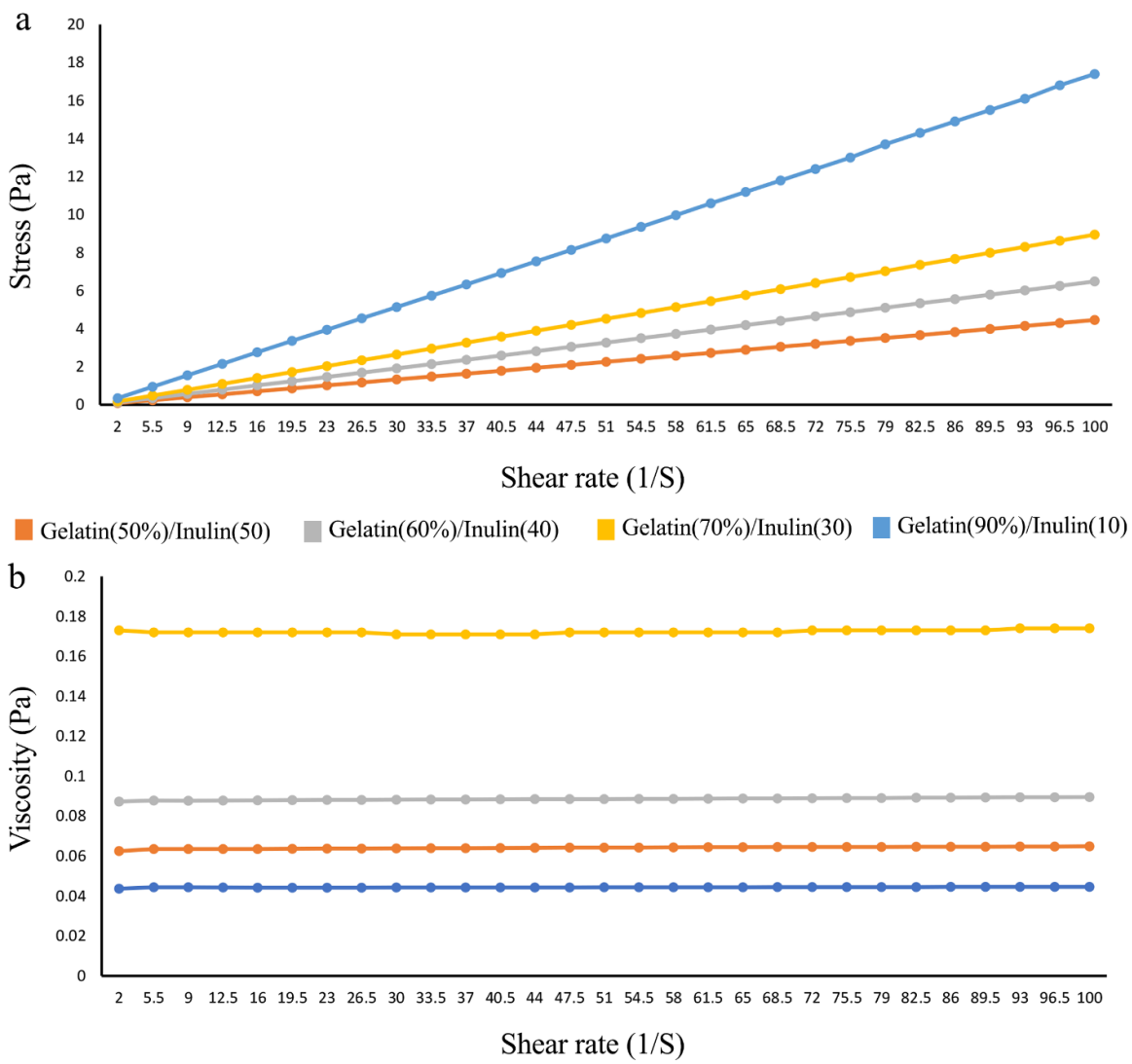

Figure 1. Rheological properties (a); and viscosity (b) of different ratios (50:50, 40:60, 70:30, 10:90) of gelatin/inulin

3.2. Morphology and size distribution of nanofibers

The morphology and size diameter distributions of gelatin-inulin fibers in different ratios (100:00,70:30, 60:40, and 50:50) including savory extract are shown in Figure. 2 (a-e), and 1 (f-j), respectively. Inulin solution alone was not able to electrospun. The electrospinning process relies on the transfer of electric charges from the electrode to the spinning droplet, making a minimum level of electrical conductivity essential for the successful formation of nanofibers. Solutions lacking electrical conductivity cannot be electrospun. Electrical conductivity is influenced by factors such as the type of polymer and solvent, polymer concentration, and temperature. Additionally, electrospinning parameters significantly impact fiber morphology. Among these, solution concentration is a key factor, as it affects viscosity, which in turn influences fiber shape and diameter. An increase in solution concentration typically results in greater fiber diameter, as illustrated in Figure 2.
The mean fiber diameter of gelatin/inulin mats with varying volume ratios (100:00 (a), 90:10 (b), 70:30 (c), 60:40 (d), and 50:50 (e)) and containing 5% savory ethanoic extract was

determined to be 0.55, 0.48, 0.32, 0.29, and 0.21 µm, respectively (Table 2). Our study elucidates that the incorporation of inulin into gelatin nanofiber groups leads to a reduction in the mean diameter of fibers. Similar results have also been reported in previous studies by other researchers (Yao et al., 2007; Torres-Giner et al., 2008; Neo et al., 2013). The observed increase in fiber diameter is likely attributed to the higher polymer concentration, which leads to increased viscosity. As a result, the charged jet formed from this more viscous solution exhibits greater resistance to elongation and thinning during the electrospinning process. As illustrated in Figure 2 (a–e), increasing the gelatin concentration in the solutions resulted in the formation of bead-free, smooth gelatin-inulin fibers with increased diameters. Several studies have demonstrated the influence of feed solution viscosity on fiber size, generally indicating that higher viscosity corresponds to larger fiber diameters and more uniform fiber morphology (Deitzel et al., 2001; Okutan et al., 2014). According to the SEM images two concentrations of 90:10 and 70:30 produced bead-free fibers. Since the volume ratio of inulin increased, the fiber diameter decreased. Viscosity plays a fundamental role in determining the morphology and diameter of electrospun nanofibers. Solutions exhibiting higher viscosity possess increased viscoelastic forces, which counteract axial elongation during electrospinning, thereby leading to an increase in fiber diameter and a reduction in bead formation (Gulzar et al., 2022). With the rise in polymer concentration and corresponding viscosity, the morphology of the beads transitions from spherical to spindle-shaped before ultimately disappearing (Ghorani, & Tucker, 2015). Conversely, several studies have demonstrated that lower polymer solution concentration or viscosity correlates with a higher incidence of bead formation and a reduction in the overall fiber diameter (Tan et al., 2005; Tang et al., 2010; Ramesh Kumar et al., 2012). Hani et al. (2017) conducted a study investigating the production of gelatin nanofibers via electrospinning at varying gelatin concentrations. Consistent with our results, they observed that an optimal gelatin concentration of 40% (w/v) yielded well-formed electrospun nanofibers. Additionally, at lower concentrations, bead formation was predominantly attributed to the predominance of surface tension forces over viscoelastic forces, which hindered sufficient polymer chain entanglement. Among the prepared formulations, the gelatin/inulin nanofiber containing a 70:30 ratio was selected for subsequent analyses because it exhibited a homogeneous fiber structure, an appropriate average fiber diameter, and no bead formation, indicating superior electrospinning performance and fiber quality compared with the other formulations.

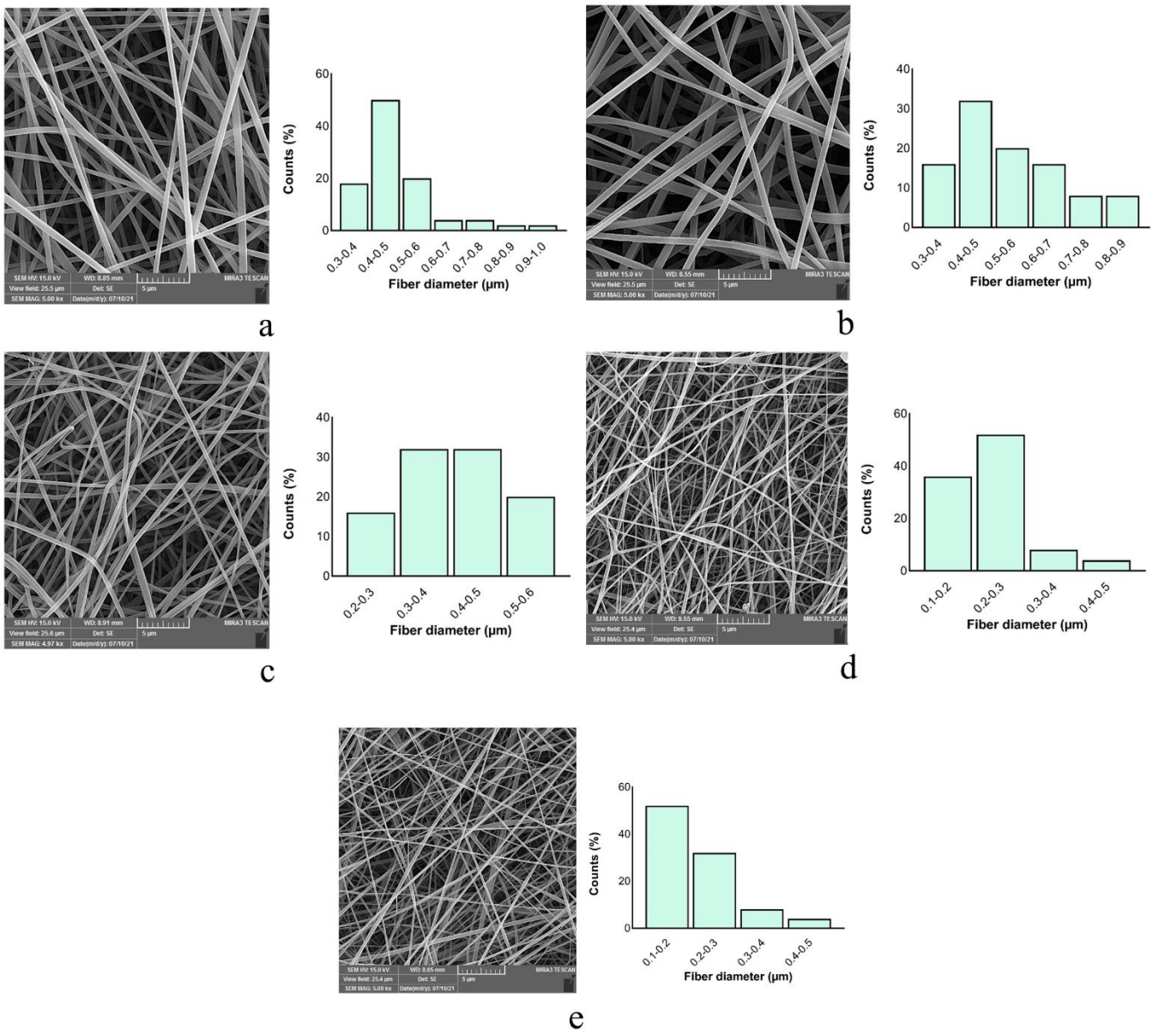

Figure 2. SEM images and distribution histograms of the electrospun gelatin/inulin nanofibers with different volume ratios (100:00 (a), 90:10 (b),70:30 (c), 60:40 (d) and 50:50 (e)) containing savory extract (%5).

Table 2. Morphological characteristics and mean fiber diameter of electrospun inulin/gelatin fibers at different inulin/gelatin ratios

Inulin/Gelatin Ratio	Mean Fiber Diameter (μm)	Morphology
100:0	0.553 ± 0.137	Bead-free microfibers
90:10	0.487 ± 0.122	Bead-free microfibers
70:30	0.302 ± 0.100	Microfibers with very few beads
60:40	0.295 ± 0.069	Microfibers with few beads

Inulin/Gelatin Ratio	Mean Fiber Diameter (μm)	Morphology
50:50	0.219 ± 0.0635	Microfibers with beads

3.3. FTIR analysis

FTIR spectra of different ingredients such as gelatin, inulin, savory, and gelatin/inulin (70:30) nanofibers are shown in Figure 3. According to the study of Pradini et al. (2018), there are four basic regions in the FTIR spectrum of gelatin that indicate the protein structure, including 3600-2300 cm^{-1} (amide A), 1644-1656 cm^{-1} (amide-I), 1335-1560 cm^{-1} (amide-II), and 670-1240 cm^{-1} (amide-III). The amide II peak is considered the most informative for FTIR analysis of protein secondary structures (Dulnik et al., 2018). A peak observed at 3573 cm^{-1} signifies the presence of hydrogen bonding between water molecules and the amide-A group. Characteristic peaks were identified at 1647 cm^{-1} (amide I), 1519 cm^{-1} (amide II), and 1234 cm^{-1} (amide III) within the FTIR spectrum. The spectral region between 1460 and 1380 cm^{-1} corresponds to symmetric and asymmetric bending vibrations of methyl groups (Das et al., 2017). In the spectrum of inulin, absorbance in the 400–800 cm^{-1} range is attributed to aliphatic C–H bending, while C–C stretching vibrations appear at approximately 1050 cm^{-1}. Inulin also exhibits two peaks within 3000–2800 cm^{-1} and a broad band around 3300 cm^{-1}, which are associated with C–H stretching and intermolecular H– and O–H stretching vibrations, respectively (Pourfarzad et al., 2015). The band at 3410 cm^{-1} corresponds to the stretching frequency of phenolic or alcoholic OH groups in savory extracts (Wu & Lee, 2000). A subsequent band near 2067 cm^{-1} is attributed to the stretching vibrations of C≡C and C≡N bonds found in aliphatic and aromatic compounds. Additionally, the spectral feature at 1641 cm^{-1} indicates the presence of C=C groups within aromatic structures. The C–O stretching vibrations of alcohols, ethers, carboxylic acids, esters, and ketones are observed in the 1000–1300 cm^{-1} range. Finally, a broad band near 667 cm^{-1} may be indicative of CH groups present in aromatic bicyclic monoterpenes found in savory extracts. The prominent peaks observed in the FTIR spectrum of the nanofiber are 3287, 2947, 1636, 1072, and 586 cm^{-1} (Ahmadi et al., 2021). According to the independent spectra of each substance, the formation of a new peak or significant chemical change was not observed in the gelatin/inulin/savory extract nanofiber group but slight changes in the position or intensity there was a courier. Minor changes in the FTIR pattern can be due to hydrogen bonding and other physical interactions with no change in the chemical structure.

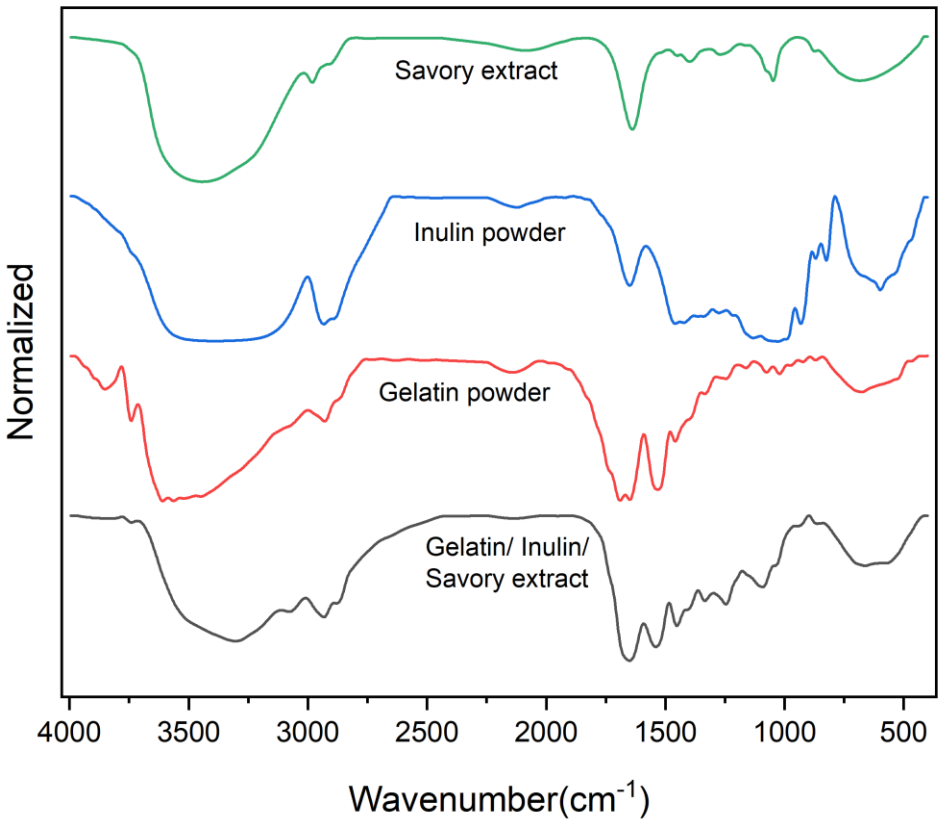

Figure 3. FTIR spectrum of gelatin powder, inulin powder, savory extract, and gelatin/inulin (70:30) nanofibers containing savory extract

3.4 Antioxidant activity

The antioxidant activity of free and encapsulated summer savory extracts was evaluated over a 21-day storage period using DPPH radical scavenging activity (Table 3). A significant decline in antioxidant activity was observed for both treatments throughout storage ($p < 0.05$), with the highest values recorded on Day 1 and the lowest values on Day 21. Although the free extract exhibited higher initial antioxidant activity (76.39%), the encapsulated extract retained its antioxidant capacity more effectively during storage, resulting in significantly ($p < 0.05$) higher antioxidant activity at the end of the storage period (29.84%) compared with the free extract (20.41%). This enhanced stability may be attributed to the protective effect of the nanofibrous matrix against degradation of phenolic compounds, indicating a slower degradation rate of active compounds. This behavior suggests that the gelatin–inulin nanofibrous matrix acted as a protective barrier, limiting the exposure of phenolic compounds to environmental factors such as oxygen, light, and moisture. Consequently, the encapsulation process contributed to improved stability of the bioactive compounds, which can be interpreted as a controlled release behavior, where the gradual diffusion of antioxidants from the fiber matrix helped sustain their activity over time. Although direct encapsulation efficiency and in vitro release kinetics were not quantified in this study, the observed time-dependent preservation of antioxidant activity indirectly supports the presence of a controlled release mechanism. The sustained antioxidant response in the encapsulated system compared to the rapid decline in the free extract indicates

that the nanofibrous structure modulated the availability of active compounds rather than allowing an immediate loss of activity. Previous studies have similarly reported that nanofibrous structures, owing to their high surface area and efficient entrapment of bioactive compounds, can improve the preservation of antioxidant properties. Furthermore, the observed free-radical scavenging activity may be associated with the synergistic effects of phenolic constituents present in summer savory (Exarchou et al., 2002) and the antioxidant potential of inulin (Shang et al., 2018). Comparable findings have been reported for summer savory essential oil encapsulated in chitosan nanoparticles, which exhibited antioxidant activities ranging from 43.66% to 56.99% (Feyzioglu et al., 2016).

Table 3. The antioxidant activity (%) of free and encapsulate extract of summer savory via DPPH radical scavenging method over 21 days

Treatment	Day 1	Day 7	Day 14	Day 21
Free extract	76.39 ± 0.35^{a}	60.41 ± 0.42^{c}	38.47 ± 0.46^{e}	20.41 ± 0.39^{g}
Encapsulated extract (70:30)	68.20 ± 0.30^{b}	56.27 ± 0.79^{d}	43.50 ± 0.47^{f}	29.84 ± 0.15^{h}

Different letters in each column indicate statistically significant differences between the mean values ($p < 0.05$).

4. Conclusion

The findings confirmed the successful encapsulation of savory extract within electrospun gelatin–inulin fibers through the electrospinning technique. SEM images revealed the formation of uniform, bead-free nanofibers from gelatin and inulin solutions containing savory extract at ratios of 90:10 and 70:30. The antioxidant activity of the encapsulated savory extract (70:30) was higher compared to its non-encapsulated (free) form. Given these results, electrospun gelatin–inulin fibers exhibit significant potential for application in the food industry. Consequently, future research will focus on their use in food packaging and the encapsulation of bioactive food components. Future studies should investigate the encapsulation efficiency and release kinetics of the bioactive compounds from the electrospun inulin/gelatin fibers to provide a more comprehensive assessment of their potential as a controlled delivery system.

Data Availability Statement: Data sharing not applicable.

Funding: This research was funded by the Drug Applied Research Center at Tabriz University of Medical Sciences and the Biophysics Laboratory within the Department of Food Science and Technology at Tabriz University. The authors also acknowledge the financial support provided by the Iran Nanotechnology Innovation Council.

Declarations competing interests: The author declares no competing interests.

Author contribution:

Roya Mahdizadeh; Writing - Original Draft, Conceptualization, Methodology, Formal analysis, Investigation,

Babak Ghanbarzadeh: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Review & Editing, Supervision, Project administration, Validation

Nooshin Noshirvani: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Review & Editing, Supervision, Project administration, Validation

References:

Ahmadi, S., Fazilati, M., Nazem, H., Mousavi, SM. (2021). Green synthesis of magnetic nanoparticles using *Satureja hortensis* essential oil toward superior antibacterial/fungal and anticancer performance. *BioMed Resarch International*. 1, 8822645.

Bhardwaj, N. and Kundu, S. C. (2010). Electrospinning: A fascinating fiber fabrication technique. *Biotechnology Advances*, 28, 325-347.

Bumedi, F., Aran, M., Miri, M. A., & Seyedabadi, E. (2023). Preparation and characterization of zein electrospun fibers loaded with savory essential oil for fruit preservation. *Industrial Crops and Products*, 203, 117121.

Chen, H. C., Jao, W. C., & Yang, M. C. (2009). Characterization of gelatin nanofibers electrospun using ethanol/formic acid/water as a solvent. *Polymers for Advanced Technologies*, 20(2), 98–103.

Das, MP., R. SP, Prasad, K., & Jv V, M R. (2017). Extraction and characterization of gelatin: a functional biopolymer. *International Journal of Pharmaceticy and Pharmaceutical Sciences*, 9(9), 239.

Deitzel, J. M., Kleinmeyer, J., Harris, D., & Beck Tan, N. C. (2001). The effect of processing variables on the morphology of electrospun nanofibers and textiles. *Polymer*, 42(1), 261- 272.

Deng, L., Kang, X., Liu, Y., Feng, F., & Zhang, H. (2017). Effects of surfactants on the formation of gelatin nanofibres for controlled release of curcumin. *Food Chemistry*, 231, 70–77.

Dulnik, J., Kołbuk, D., Denis, P., & Sajkiewicz, P. (2018). The effect of a solvent on cellular response to PCL/gelatin and PCL/collagen electrospun nanofibres. *European Polymer Journal*, 104,147–156.

Exarchou, V., Nenadis, N., Tsimidou, M., Gerothanassis, I.P., Troganis, A., Boskou, D. (2002). Antioxidant activities and phenolic composition of extracts from Greek oregano, Greek sage, and summer savory. *Journal of Agriculture Food Chemistry*. 1, 50(19), 5294–5299.

Fasihi, H., Fazilati, M., Hashemi, M., & Noshirvani, N. (2017). Novel carboxymethyl cellulose-polyvinyl alcohol blend films stabilized by Pickering emulsion incorporation method. *Carbohydrate Polymers*, *167*, 79-89.

Fasihi, H., Noshirvani, N., Hashemi, M., Fazilati, M., Salavati, H., & Coma, V. (2019). Antioxidant and antimicrobial properties of carbohydrate-based films enriched with cinnamon essential oil by Pickering emulsion method. *Food Packaging and Shelf Life*, *19*, 147-154.

Fasihi, H., Noshirvani, N., & Hashemi, M. (2023). Novel bioactive films integrated with Pickering emulsion of ginger essential oil for food packaging application. *Food Bioscience*, *51*, 102269.

Feyzioglu, GC., Tornuk, F. (2016). Development of chitosan nanoparticles loaded with summer savory (*Satureja hortensis* L.) essential oil for antimicrobial and antioxidant delivery applications. *LWT-Food Science and Technology*. 70, 104–110.

Ghorani, B., Tucker, N. (2015). Fundamentals of electrospinning as a novel delivery vehicle for bioactive compounds in food nanotechnology. *Food Hydrocolloids*, 51, 227–240.

Gulzar, S., Tagrida, M., Nilsuwan, K., Prodpran, T., Benjakul, S. (2022). Electrospinning of gelatin/chitosan nanofibers incorporated with tannic acid and chitooligosaccharides on polylactic acid film: Characteristics and bioactivities. *Food Hydrocolloids*, 133, 107916.

Hani, N. M., Torkamani, A. E., Azarian, M. H., Mahmood, K.W., Ngalim, S. H. (2017). Characterisation of electrospun gelatine nanofibres encapsulated with *Moringa oleifera* bioactive extract. *Journal of Science and Food Agriculture*, 97, 3348–3358.

Hirsch, E., Pantea, E., Vass, P., Domján, J., Molnár, M., Suhajda, Á., Andersen, S.K., Vigh, T., Verreck, G., Marosi, G.J., Nagy, Z.K. (2021). Probiotic bacteria stabilized in orally dissolving nanofibers prepared by high-speed electrospinning. *Food and Bioproducts Processing*, 1(128), 84-94.

Huanga, Z., Zhang, S., Ramakrishna, C., Lim, T. (2004). Electrospinning and mechanical characterization of gelatin nanofibers. *Polymer*, 15, 5361–5368.

Kanmani, P., & Rhim, J. W. (2014). Physicochemical properties of gelatin/silver nanoparticle antimicrobial composite films. *Food Chemistry*, 148, 162–169.

Kfoury, M., Auezova, L., Greige-Gerges, H., & Fourmentin, S. (2019). Encapsulation in cyclodextrins to widen the applications of essential oils. *Environmental Chemistry Letters*, 17(1), 129–143.

López-Rubio, A., Sanchez, E., Wilkanowicz, S., Sanz, Y., & Lagaron, J. M. (2012). Electrospinning as a useful technique for the encapsulation of living bifidobacteria in food hydrocolloids. *Food Hydrocolloids*, 28(1), 159–167.

Lincoln, D.E., Langenheim, J.H. (1976). Geographic patterns of monoterpenoid composition in *Satureja douglasii*, *Biochemical Systematics and Ecology* 4, 4, 237–248.

Luraghi, A., Peri, F., Moroni, L. (2021). Electrospinning for drug delivery applications: A review. *Journal of Controlled Release, 334*, 463–484.

Mendes, A. C., Stephansen, K., & Chronakis, I. S. (2017). Electrospinning of food proteins and polysaccharides. *Food Hydrocolloids*, 68, 53–68.

Mensink, M. A., Frijlink, H. W., van der Voort Maarschalk, K., Hinrichs, W. L. (2015). Inulin, a flexible oligosaccharide. II: Review of its pharmaceutical applications. *Carbohydrate polymers*, 10(134), 418-428.

Min, B.-M., Lee, G., Kim, S. H., Nam, Y. S., Lee, T. S., & Park, W. H. (2004). Electrospinning of silk fibroin nanofibers and its effect on the adhesion and spreading of normal human keratinocytes and fibroblasts in vitro. *Biomaterials*, 25(7–8), 1289–1297.

Moomand, K., Lim, L. T. (2015). Effects of solvent and n-3 rich fish oil on physicochemical properties of electrospun zein fibres. *Food Hydrocolloids*, 46, 191-200.

Neo, Y. P., Swift, S., Ray, S., Gizdavic-Nikolaidis, M., Jin, J., & Perera, C. O. (2013). Evaluation of gallic acid loaded zein sub-micron electrospun fibre mats as novel active packaging materials. *Food Chemistry*, 141(3), 3192–3200.

Neo, Y. P., Ray, S., Jin, J., Gizdavic-Nikolaidis, M., Nieuwoudt, M. K., Liu, D., and Quek, S. Y. (2013). Encapsulation of food grade antioxidant in natural biopolymer by electrospinning technique: A physicochemical study based on zein–gallic acid system. *Food Chemistry*, 136(2), 1013–1021.

Noshirvani, N., & Fasihi, H. (2018). Control of *Aspergilus niger* in vitro and in vivo by three Iranian essential oils. *International Food Research Journal, 25*(4), 1745-1752.

Noshirvani, N. (2024). Essential oils as natural food preservatives: special emphasis on antimicrobial and antioxidant activities. *Journal of Food Quality*, 1, 5807281.

Noshirvani, N., & Abolghasemi Fakhri, L. (2025). Advances in extending the microbial shelf-life of bread and bakery products using different technologies: A Review. *Food Reviews International*, 1-26.

Okutan, N., Terzi, P., & Altay, F. (2014). Affecting parameters on electrospinning process and characterization of electrospun gelatin nanofibers. *Food Hydrocolloids*, 39, 19–26.

Patra, J.K., Das, G., Fraceto, L.F. *et al.* (2018). Nano based drug delivery systems: recent developments and future prospects. *Journal of Nanobiotechnology*, 16(1), 71.

Pradini, D., Juwono, H., Madurani, K.A., Kurniawan, F. (2018). A preliminary study of identification halal gelatin using Quartz Crystal Microbalance (QCM) sensor. *Malaysian Journal of Fundamental Applied Sciences*, 14(3).

Pourfarzad, A., Habibi Najafi, M. B., Haddad Khodaparast, M. H., & Khayyat, M. H. (2015). Serish inulin and wheat biopolymers interactions in model systems as a basis for understanding the impact of inulin on bread properties: a FTIR investigation. *Journal of Food Science and Technology*, 52(12).

Ramesh Kumar, P., Khan, N., Vivekanandhan, S., Satyanarayana, N., Mohanty, A., Misra, M. (2012). Nanofibers: effective generation by electrospinning and their applications. *Journal of Nanoscience and Nanotechnology*, 12, 1-25.

Rezaei, A., Fathi, M., & Jafari, S. M. (2019). Nanoencapsulation of hydrophobic and low-soluble food bioactive compounds within different nanocarriers. *Food Hydrocolloids*, 88, 146–162.

Shang, H. M., Zhou, H. Z., Yang, J. Y., Li, R., Song, H., Wu, H. X. (2018). In vitro and in vivo antioxidant activities of inulin. *PLoS One*. 13(2), e0192273.

Tan, S., Inai, R., Kotaki, M., Ramakrishna, S. (2005). Systematic parameter study for ultra-fine fiber fabrication via electrospinning process. *Polymer*, 46, 6128- 6134.

Tang, S., Zeng, Y., Wang, X. (2010). Splashing needleless electrospinning of nanofibers. *Polymer Engineering & Science*, 50, 2252-2257.

Torres-Giner, S., Gimenez, E. & Lagaron, J. M. (2008). Characterization of the morphology and thermal properties of zein prolamine nanostructures obtained by electrospinning. *Food Hydrocolloids*, 22, 601-614.

Torres-Martínez, E. J., Cornejo Bravo, J. M., Serrano Medina, A., Pérez González, G. L., Villarreal Gómez, L. J. (2018). A summary of electrospun nanofibers as drug delivery system: Drugs loaded and biopolymers used as matrices. *Current drug delivery*, 15(10),1360-1374.

Unnithan, A. R., Gnanasekaran, G., Sathishkumar, Y., Lee, Y. S., & Kim, C. S. (2014). Electrospun antibacterial polyurethane–cellulose acetate–zein composite mats for wound dressing. *Carbohydrate Polymers*, 102, 884–892.

Wu, X. Y., & Lee, P. I. (2000). Preparation and characterization of inulin ester microspheres as drug carriers. *Journal of Appllied Polymer Science*, 77(4), 833-840.

Wu, Y., Luo, Y., Wang, Q. (2012). Antioxidant and antimicrobial properties of essential oils encapsulated in zein nanoparticles prepared by liquid–liquid dispersion method. *LWT-Food Science and Technology*, 48, 283-290.

Yao, C., Li, X., & Song, T. (2007). Electrospinning and crosslinking of zein nanofiber mats. *Journal of Applied Polymer Science*, 103(1), 380-385.

Zare M, Dziemidowicz K, Williams GR, Ramakrishna S. (2021). Encapsulation of pharmaceutical and nutraceutical active ingredients using electrospinning processes. *Nanomaterials*, 11(8),1968.

Zhang, Y., Ouyang, H., Lim, C. T., Ramakrishna, S., & Huang, Z. M. (2005). Electrospinning of gelatin fibers and gelatin/PCL composite fibrous scaffolds. *Journal of Biomedical Materials Research Part B: Applied Biomaterials: An Official Journal of the Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials*, *72*(1), 156-165.