Macromolecular Materials and Engineering

Macromolecular Materials and Engineering Open Access

www.mame-journal.de

RESEARCH ARTICLE OPEN ACCESS

Electrospun Composite *Lavandula Angustifolia* Mill. Extract/PVP Nanofibers

Nan Yang[1] | Gareth. R. Williams[1] | Banaz Jalil[1] | Olha Mykhailenko[1,2]

[1]UCL School of Pharmacy, University College London, London, UK | [2]Pharmaceutical Chemistry Department, National University of Pharmacy, Kharkiv, Ukraine

Correspondence: Olha Mykhailenko (o.mykhailenko@ucl.ac.uk)

Received: 3 September 2025 | **Revised:** 8 December 2025 | **Accepted:** 18 December 2025

Keywords: drug delivery | electrospinning | lavender | nanofibers | polyphenols

ABSTRACT

Background: *Lavandula angustifolia* Mill. is widely used for its potential health benefits. It has antimicrobial, anti-inflammatory, and wound-healing properties due to the presence of both terpenoids and phenolic compounds. Novel formulations for both oral and topical usage could extend the range of applications.

Methods: In this study, electrospun nanofibers incorporating dry extract of lavender (at 9.09%, 16.67%, and 24.98% w/w) were prepared using polyvinylpyrrolidone (PVP) as a polymer matrix, with the aim of creating fast-dissolving systems.

Results: Fibers produced at 10 kV exhibited uniform morphology, with the 9.09% w/w lavender extract ratio showing the optimum morphology (average diameters: 0.70–1.49 μm). The obtained fibers were smooth, uniform, free of beads, and comprised amorphous solid dispersions. All the fiber formulations rapidly disintegrated and accelerated the dissolution of lavender extract.

Conclusions: These findings highlight the potential of lavender extract-loaded nanofibers as fast-acting delivery systems. This work provides a novel approach for formulating medicinal plant-loaded nanofibers, especially for active ingredients with low solubility, and offers a potential therapy for wound healing.

1 | Introduction

Several *Lavandula* species are important medicinal and aromatic plants with wide applications in several industries, such as perfumery, food, cosmetics, and medicine [1, 2]. *Lavandula angustifolia* Mill. (commonly known as lavender) is widely investigated for its biological and clinical activities [3, 4]. The aerial parts of the plant are a source of flavonoids, phenolic acids, and triterpenoids [5], known for their antioxidant, antimicrobial, anti-inflammatory, and neuroprotective properties [6]. Lavender extract and essential oil are classified as GRAS by the US Food & Drug Administration and can be consumed in oral dosage or topical forms without any significant adverse reports in the literature [1, 3]. The growing demand for medicinal plant-derived metabolites, together with the broader pursuit of sustainable development, has stimulated research into new delivery systems of natural products in the biomedical and pharmaceutical fields.

Topical formulations of lavender extracts, including creams, ointments, gels, and balms, are commonly used for skin ailments due to their ease of use and direct delivery to the treatment site [7]. For example, creams and gels offer a cooling effect and rapid relief, whereas ointments and balms form a protective barrier that shields the wound and supports healing. Although effective, these dosage forms have limitations such as limited control of drug release, poor adherence, and inconsistent moisture retention [8]. Recent research has therefore explored nano-based strategies for wound-healing applications [9, 10]. Among these systems, electrospun nanofibers can maintain a moist environment, ensure adequate oxygen and water permeability, protect wounds from bacterial invasion, and enable controlled release of therapeutic agents [11]. Lavender extract is a suitable functional ingredient for incorporation into nanofibers due to its biocompatibility, low immunogenicity, and antimicrobial and anti-inflammatory properties [10].

Electrospinning, a technique based on electrohydrodynamic processes, enables the fabrication of nanostructured fiber mats that mimic the natural extracellular matrix architecture [12]. This technique avoids harsh processing conditions such as high temperature or pressure, thereby preserving thermolabile bioactives like phenolic compounds [13]. Electrospun nanofibers (ENs) can function as encapsulating carriers and as controlled-release platforms. For example, ENs loaded with *Matricaria chamomilla* L. extract have been prepared using polycaprolactone, carboxyethyl chitosan, and poly(vinyl alcohol) [14]. These formulations exhibited antioxidant and antibacterial properties alongside sustained release, making them promising candidates for wound dressing applications. Similarly, polyvinylpyrrolidone (PVP)-based electrospun mats loaded with *Isatis tinctoria* L. root extract demonstrated strong antibacterial activity and nearly complete wound closure after 11 days in experimental models [15].

Research on ENs has advanced along two main directions: (1) technological improvements (coaxial [16], side-by-side [17], and triaxial [18] electrospinning) and (2) functionalization of nanofibers through incorporation of active ingredients. This study follows the latter approach by incorporating *L. angustifolia* extract into PVP nanofibers, combining rapid dissolution with the bioactivity of the phenolic-rich crude extract [19–22].

PVP is a non-toxic, hydrophilic, and biocompatible polymer widely used in wound healing applications due to its mucoadhesive properties and ability to enhance the dissolution of poorly water-soluble drugs through solid dispersion formulations [23]. Its effectiveness as a drug carrier is well documented in electrospun systems designed for rapid release [24, 25]. PVP has been successfully combined with a range of bioactive agents—including curcumin, equisetin, propolis, aloe vera, and green tea extract—demonstrating its versatility in supporting hemostasis, antimicrobial activity, and antioxidant preservation [26, 27]. These properties make PVP a suitable matrix for developing lavender extract-loaded nanofibers intended for wound care.

The primary objective of this study was to develop fast-dissolving electrospun nanofibers containing lavender extract as a potential topical wound dressing. The rationale lies in the need for dressings that rapidly deliver bioactive compounds upon contact with wound exudate. The approach involves electrospinning PVP solutions loaded with lavender extract, followed by physicochemical characterization and assessment of disintegration time and dissolution behavior. To the best of our knowledge, crude lavender extract has not previously been incorporated into electrospun PVP nanofibers, making this work the first attempt to exploit its phenolic-rich profile for rapid-release woundcare and healing applications.

2 | Material and Methods

2.1 | Extraction and Processing of Lavender Plant Materials

Lavandula angustifolia Mill. was harvested during the mass flowering stage in 2021 at Ksaverivka village, Vinnytsia region, Ukraine. The plant material, including leaves, flowers, and inflorescence stems, was air-dried and ground prior to analysis. Approximately 200–300 g of the ground plant material was extracted using water (500 mL) at 40°C; this process was repeated three times. A rotary evaporator was subsequently used to concentrate and filter the water extract solution (operating under decreased pressure and at a temperature below 50°C). After being dried to leave a solid residue, the extract was kept at −20°C in a tightly sealed glass container until it was used for formulation. The resulting crude extract, a brown powder with a pleasant floral scent, was stored at room temperature and used in this study. Polyvinylpyrrolidone (average Mw = 360 000 Da, CAS No.9003-39-8) was sourced from Sigma-Aldrich (UK). All other chemicals were of analytical grade and used as provided.

2.2 | Electropsinning

Anhydrous ethanol was selected as the spinning solvent since it is an excellent solvent for both lavender extract and PVP. The base solution was prepared by dissolving lavender extract in ethanol at three concentrations of 1%, 2%, and 3.33% w/v. PVP was dissolved in this base solution or pure ethanol to prepare four formulations: a blank PVP control (F0, 0% extract), and lavender-extract-loaded fibers containing 9.09% (F1), 16.67% (F2), and 24.98% w/w (F3) lavender extract, with detailed compositions summarized in Table 1. All solutions were magnetically stirred overnight at room temperature to ensure complete dissolution before electrospinning.

The spinning solution was loaded into a 1 mL plastic syringe (Terumo, UK) fitted with a 21G metal spinneret (0.51 mm inner diameter, Nordson EFD, UK). Electrospinning was performed using a high-voltage DC power supply (HCP35-35 000, FuG Elektronik, Germany), with the positive electrode connected to the spinneret and the grounded electrode attached to an aluminum foil-covered static metal collector (14.7 × 20 cm). Through initial optimization studies, the processing parameters were established as follows: applied voltage of 10 kV, a constant flow rate of 0.5 mL h^{-1} maintained by a syringe pump (78-9100C, Cole-Parmer, UK), and a fixed spinneret-to-collector distance of 15 cm. All electrospinning processes were conducted under ambient laboratory conditions (temperature 19–23°C, relative humidity 30%–50%).

2.3 | Chemical Characterization and Pharmaceutical Performance Tests

2.3.1 | Optical Microscopy

An Invitrogen AMF4300 EVOS fluorescent microscope (Thermo Fisher Scientific, USA) was used to examine the morphology of lavender extract. The sample was placed on a slide, dispersed in an aliquot of water, and covered with a square coverslip. Images were captured at 400x magnification using the transmitted light channel.

2.3.2 | Scanning Electron Microscopy

A bench-top Phenom Pro scanning electron microscope (SEM; Thermo Fisher Scientific, USA) was utilized to examine the

TABLE 1 | Compositions of the electrospinning solutions and fibers.

Concentration	Formulation			
	F0	**F1**	**F2**	**F3**
Electrospinning solutions (% w/v)				
Lavender extract	0	1	2	3.33
PVP	10	10	10	10
Electrospun fibers (% w/w)				
Lavender extract	0	9.09	16.67	24.98
PVP	100	90.91	83.33	75.02

morphology of the electrospun fibers. Samples were cut from the mat, and gold sputter-coated to ensure electrical conductivity. Images were acquired at an excitation voltage of 5 kV. The average fiber diameter was calculated by measuring 100 points in the SEM images using the ImageJ software [28] (version 13.0.6, National Institutes of Health, USA), with the results reported as mean ± standard deviation (SD).

2.3.3 | X-ray Diffraction

A MiniFlex 600 diffractometer (Rigaku, Japan) was used to obtain X-ray diffraction (XRD) patterns with Cu Kα radiation ($\lambda = 1.5148$ Å; 40 kV, 15 mA) over a 2θ range of 3–50°, with a step size of 0.010° and a scan speed of 3.000° min^{-1}.

2.3.4 | Thermogravimetric Analysis

A Discovery Series thermogravimetric analyzer (TA Instruments, USA) was used to analyze the thermal stability of lavender extract, PVP and fiber samples. Approximately 5 mg of each sample was placed in TGA 952018.906 aluminum pans (TA Instruments, USA) and heated from 40°C to 500°C at a rate of 10°C min^{-1}, with continuous nitrogen purging at a flow rate of 50 mL min^{-1} throughout the measurement.

2.3.5 | Differential Scanning Calorimetry

A Q2000 calorimeter (TA Instruments, USA) was used to conduct differential scanning calorimetry (DSC) measurements. Samples weighing 3–7 mg were accurately measured and sealed in Tzero aluminium pans with pinholed Tzero lids (TA Instruments, USA). The samples were then heated from 25°C to 300°C at a rate of 10°C min^{-1}, with continuous nitrogen purging at a flow rate of 50 mL min^{-1} throughout the measurement.

2.3.6 | Fourier Transform Infrared Spectroscopy

A Spectrum 100 spectrometer (PerkinElmer, USA) was used to perform Fourier transform infrared (FTIR)—attenuated total reflectance (ATR) spectroscopy. Samples were introduced to the infrared beam using an ATR attachment with a sampling plate fitted with a synthetic diamond crystal. The scanning range was set from 4000 to 650 cm^{-1}, with a resolution of 4 cm^{-1}, and data were collected over 8 scans.

2.3.7 | Disintegration Tests

Fiber samples, approximately 5 mg each, were prepared and placed in a Petri dish containing 10 mL of pre-warmed phosphate buffer solution (PBS, pH∼7.4) at 37°C. The disintegration process was recorded using the slow-motion feature on an iPhone (Apple, USA), positioned to capture the entire Petri dish. Each fiber sample was gently placed into the PBS, and recording continued until complete dissolution occurred. 5 mg of lavender extract was weighed and subjected to disintegration tests under the same conditions. The disintegration time was measured using timestamps from the slow-motion footage, starting from the moment the fiber contacted the PBS until it fully disintegrated, with the results reported as mean ± SD from three measurements.

2.3.8 | Dissolution Tests

A SpectraMax M2e microplate reader (Molecular Devices, USA) was used to analyse release aliquots. Fiber samples, approximately 5 mg each, were immersed in 10 mL of PBS at 37.0 ± 0.5°C in a Petri dish. At 30 s intervals over a 5-min period, aliquots (0.1 mL) were collected from the release media and transferred to a 96-well transparent plate, with each aliquot replaced by an equal volume of prewarmed PBS. A calibration curve of known lavender-extract concentrations was used to quantify the amount of extract released from the electrospun nanofibers at a λ_{max} of 316 nm. From these values, the cumulative percentage of extract release was calculated.

3 | Results and Discussion

In this study, a crude water extract was prepared from air-dried lavender herb (leaves, flowers, and inflorescence stems) sourced from the Vinnytsia region of Ukraine. The plant material was extracted three times in a water bath, followed by filtration, combination of extracts, and evaporation, yielding a dry brown powder with a characteristic floral scent. Previous

studies of lavender crude extract have confirmed a high content of phenolic compounds, including flavonoids, hydroxycinnamic acids, and tannins [19, 20]. Consistent with these data, analysis of our extract by Thin-Layer Chromatography (TLC) revealed the presence of non-polar constituents such as linalool, linalyl acetate, and 1,8-cineole (Supplementary Information, Figure S1). High-performance thin layer chromatography (HPTLC) and High performance liquid chromatography-pulsed amperometric detection (HPLC-PAD) further confirmed and quantified key phenolic compounds, including caffeic, chlorogenic, and rosmarinic acids (Figure S2, Table S1). The obtained analytical results were used to verify the chemical profile of the starting material. Given that the chemical composition of the extract had previously been established and described [19, 20], the present study focused on the development, fabrication, and evaluation of the technological characteristics of electrospun fibers with added lavender extract.

3.1 | Morphology: Optical Microscopy

Morphological analysis of the lavender extract by optical microscopy revealed diagnostic features (epidermal cells with sinuous walls containing prismatic crystals of calcium oxalate) consistent with *L. angustifolia* (Figure S3), in agreement with literature data [29, 30].

3.2 | Morphology: Scanning Electron Microscopy

Electrospinning at 10 kV yielded largely linear, bead-free, fibers. SEM images of the polymer fibers containing lavender extract are presented in Figure 1. The fibers are randomly oriented and cylindrical in shape. F1 produced fibers with similar diameter and morphology compared to the placebo (F0). In contrast, F2 shows some curvature and particulate matter, which could be indicative of extract precipitation. F3 exhibits even more pronounced particulate presence, along with two distinct fiber populations that are markedly different in diameter. This bimodal distribution is likely indicative of jet splitting [31].

The mean diameters of the fibers (Figure 2) were as follows: 0.70 ± 0.20 μm (F1); 0.77 ± 0.16 μm (F2); 1.49 ± 0.44 μm (F3, thick); 0.73 ± 0.16 μm (F3, thin); and 0.61 ± 0.10 μm (F0). Histograms of the diameter distributions are shown in Figure S4. The data suggest that as the ratio of polymer to extract decreases, the diameter of the fibers increases, likely due to a higher amount of solute being dispensed per unit of time [32, 33]. With a greater amount of extract present, there is likely to be less effective polymer chain entanglement, and as a result spinning becomes more difficult, leading to curvature and the presence of particles in the high drug-loaded fibers.

3.3 | X-Ray Diffraction

In Figure 3a, XRD patterns of the raw materials reveal both lavender extract and PVP to be amorphous, as evidenced by the absence of sharp Bragg reflections in their diffraction patterns. These data align with the established literature [34, 35]. All the fibers are also amorphous with no visible Bragg reflections in their XRD patterns, as shown in Figure 3b. The XRD patterns of the electrospun fibers displayed only broad humps at around 5°, 11°, and 22°.

3.4 | Thermal Analysis

As illustrated in Figure 4, all fiber samples and pure PVP underwent complete degradation around 470°C. In contrast, the lavender extract exhibited a total mass loss of only 55.2% at 500°C, with gradual decomposition initiating near 300°C. Based on these observations, a temperature range of 25°C–300°C was selected for subsequent differential scanning calorimetry (DSC) measurements to avoid thermal decomposition and ensure the reliability of thermal transition data.

The electrospun fibers showed minimal mass loss at low temperatures, mirroring the behavior of PVP (Figure 4b). Both the fibers and PVP displayed a single main degradation profile featuring two distinct stages: an initial weight loss of about 10 – 16% up to 200°C, attributed primarily to moisture evaporation, followed by major decomposition starting around 280°C. The overall mass loss reached approximately 98%, leaving a small residual mass of 2-3% at 500°C [36].

In comparison, the lavender extract exhibited a multi-stage degradation process (Figure 4a). The first stage, between 40°C–200°C, involved a 15.5% mass loss due to evaporation of absorbed water. The second stage, from 200°C–425°C, resulted in a 34.7% mass loss associated with the breakdown of organic constituents. A final 5.0% mass loss occurred between 425°C–500°C, corresponding to the complete decomposition of residual organic matter [37]. The remaining residue at 500°C (44.8%) is consistent with carbonized plant-derived material, as organic components are converted to carbon and minor ash under such extreme conditions [38]. Although lavender extract contains volatile compounds, the residue at high temperature consists predominantly of stable carbonaceous material, indicating full decomposition of reactive substances.

The DSC thermogram of PVP (Figure 5a) shows a broad endotherm between 40°C and 150°C. This is consistent with the desorption of water, and mass loss over this temperature range is also observed in TGA [39]. There is additionally a baseline shift visible in DSC at approximately 180°C, indicating the glass transition (Tg). This value is consistent with the reported literature values of 170°C–180°C [40]. The DSC trace of the lavender extract in Figure 5a is complex owing to its multicomponent nature. There is a broad endotherm from 40°C to 200°C, attributed to the loss of water and volatile components. There is then an irregular baseline, which can be ascribed to degradation events. These findings agree with the mass losses observed in TGA over the same temperature ranges. Phenolic acids such as those found in lavender extract typically decompose in the range of 180°C to 300°C [41], while flavonoids usually decompose at slightly higher temperatures, in the range of 200°C to 350°C [42]. Therefore, the complex broad endotherm observed for lavender extract in Figure 5a was not solely due to the loss of water but also results from the decomposition of polyphenols from lavender water extract during heating.

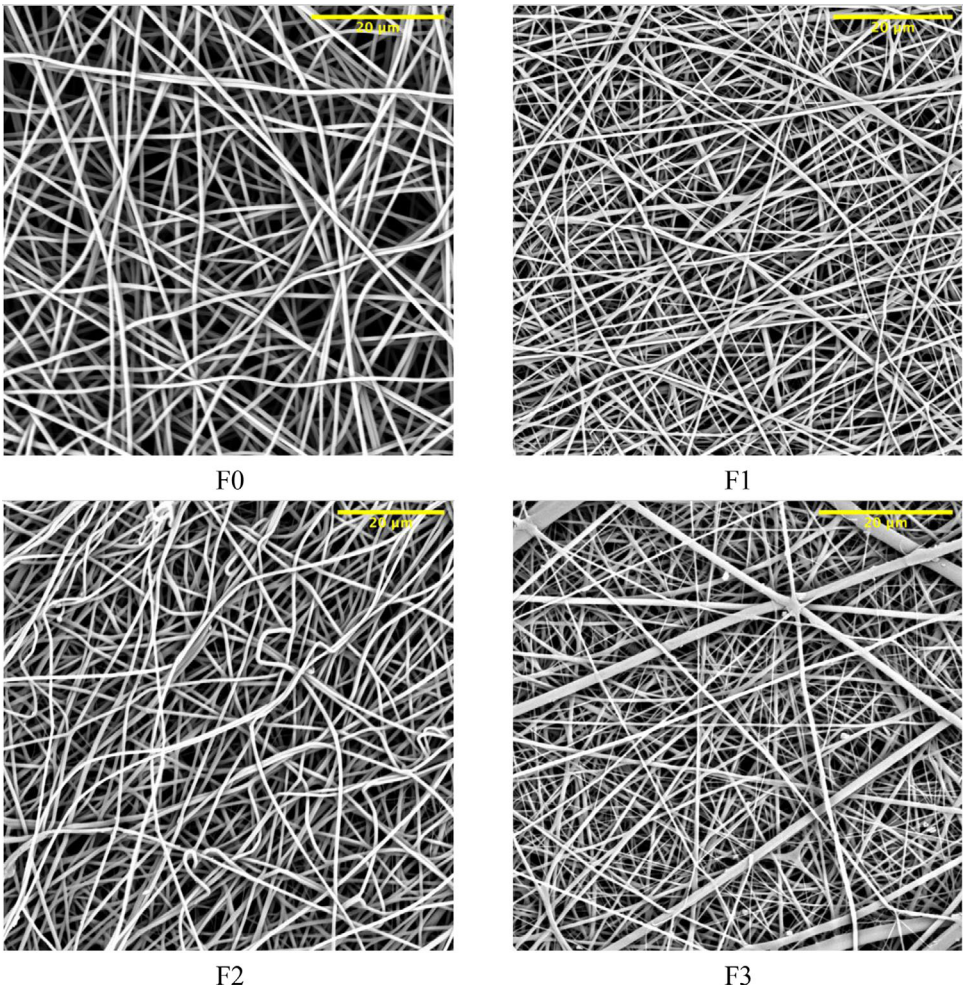

FIGURE 1 | SEM images of the fibers. Scale bar: 20 µm.

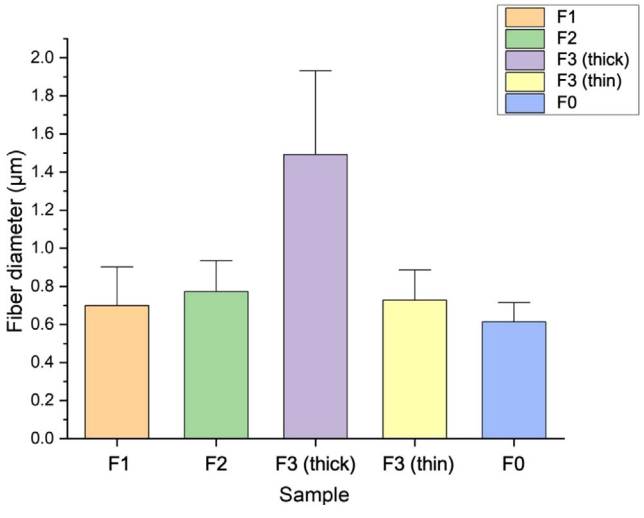

FIGURE 2 | Diameter distribution of electrospun PVP/lavender extract fibers.

The DSC traces of the fibers in Figure 5b are similar to that of PVP. An endothermic peak is observed in the temperature range of 40°C to ca. 130°C, indicating the evaporation of water. This is supported by mass loss in TGA experiments. The Tg values measured for the electrospun fibers (F1: 176.4°C; F2: 174.2°C; F3: 173.0°C) correspond closely to that of pure PVP (177.2°C) but progressively decrease with increasing lavender extract content. This can be attributed to the lavender extract disrupting the polymer chain packing and increasing the free volume within the PVP matrix. The observed Tg reduction follows the expected behavior for polymer-additive systems, where higher concentrations of low-molecular-weight components typically enhance chain mobility and lower the glass transition temperature [34].

3.5 | IR Spectroscopy

IR spectroscopy was used to investigate the potential interactions between lavender extract and PVP. Spectra are given in Figure 6. PVP exhibits a broad band centered around ~3430 cm^{-1}, corresponding to O—H stretching and confirming the presence of water suggested by DSC and TGA. The peak at ~2950 cm^{-1} is attributed to C-H stretching, while the sharp peak at ~1650 cm^{-1} is due to the stretching of C═O groups. These observations align with the existing literature [43]. Lavender extract demonstrates a broad O-H stretching band over the range of ~3500–3200 cm^{-1}, which arises both from water and the presence of phenols. A small peak at ~3000–2800 cm^{-1} is likely because of C—H stretching. A broad band peak centred at approximately ~1591 cm^{-1} may be due to C═O and C═C stretching of carbonyl groups and

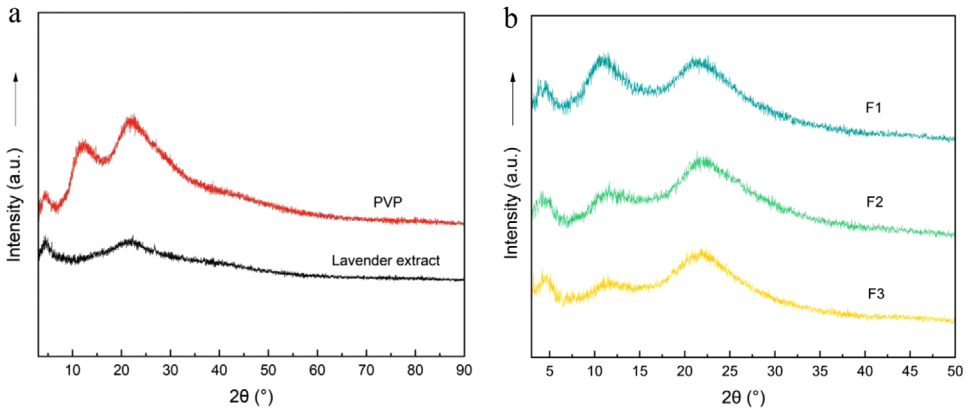

FIGURE 3 | XRD patterns of the (a) raw materials and (b) electrospun fibers.

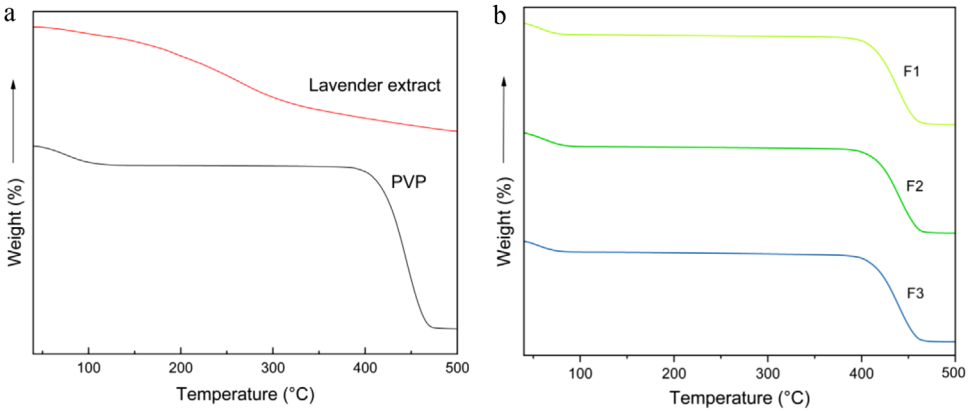

FIGURE 4 | TGA data of (a) raw materials and (b) electrospun fibers from 40°C to 500°C.

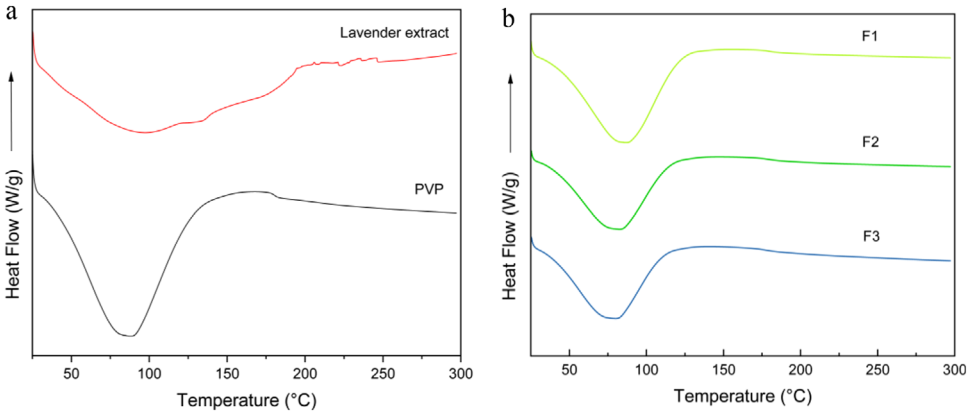

FIGURE 5 | DSC data (exo up) of (a) raw materials and (b) the electrospun fibers from 25°C to 300°C.

aromatic rings. A strong peak centred at ~1050 cm^{-1} represents C—O stretching. The spectrum matches the known composition of lavender extract [44, 45].

The spectra of the fibers look very similar to that of PVP alone. However, the C═O bands are at approximately 1648, 1649, and 1651 cm^{-1} for F1, F2, and F3, respectively, shifted to higher wavenumbers compared to PVP. This indicates interactions between the lavender extract components and polymer, likely due to hydrogen bonding.

3.6 | Disintegration Tests

Video-captured images of the fiber disintegration process revealed that the F1 system broke down into sub-visual fragments within 513 ± 260 ms (see Figure 7). As the lavender extract proportion increased, disintegration slowed: F2 required 850 ± 156 ms, and F3 1673 ± 269 ms (Figure S5). In stark contrast, pure lavender extract exhibited a disintegration time of 30 ± 9 s (Figure S6), demonstrating that the PVP-based fibers accelerated disintegration by ~58-fold (F1) to ~18-fold (F3).

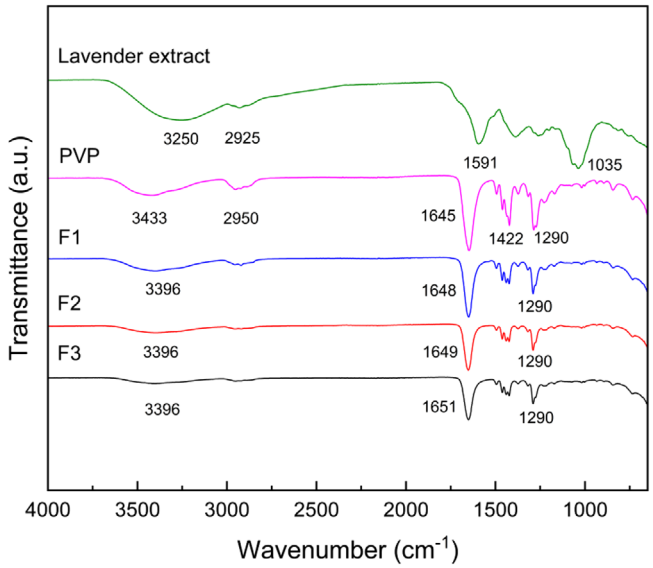

FIGURE 6 | IR spectra of the plant extract and electrospun fibers.

This fast disintegration aligns with previous studies on PVP-based electrospun systems, where rapid hydration enhances solubility and immediate bioactive compound release. While such fast disintegration can be advantageous for initial antimicrobial action, further formulation tuning may be required to achieve sustained release for long-term wound healing applications. For example, it is reported that PVP nanofibers rapidly hydrate in wound exudate, promoting quick drug release and moisture retention [46]. Similarly, our results suggest that PVP enhances the solubility of lavender's hydrophobic compounds through molecular dispersion, enabling faster disintegration compared to the bulk extract. The delayed disintegration of high lavender extract loaded fibers (F3) is consistent with literature findings, where increased fiber diameter correlated with reduced drug release rates [47]. In addition, in the F3 system there is less PVP present to help carry the extract into solution, and particles believed to correspond to the extract were visible in SEM images (Figure 1).

3.7 | Dissolution Tests

The extract release plots are shown in Figure 8. The plots can be seen to be similar in shape for all three formulations. The plots show the "spring and parachute" patterns often seen with amorphous solid dispersions. There is an initial rapid release of the lavender extract, resulting in ca. 30 – 60% of the cargo being freed within the first 30s (F1: 59%; F2: 42%; F3: 29%). This is followed by a reduction in the extract concentration in solution as some precipitates out, and a plateau at 16 – 44% release (F1: 44%; F2: 24%; F3: 16%). This arises owing to initial supersaturation and the extract concentration being above the equilibrium solubility value. At the end of the experiment, the extract concentration is approximately the same with each of F1, F2 and F3, at ca. 0.02 mg/mL.

It was not possible to construct a quantitative dissolution profile for the crude lavender extract, as it forms a heterogeneous suspension in PBS rather than a true solution, preventing reliable spectrophotometric measurement.

During the initial release phase, the fibrous membrane rapidly disintegrates, leading to the swift release of a substantial amount of extract molecules. As release progresses, however, a fraction of the extract, particularly its more hydrophobic components, interacts with PVP's carbonyl groups and precipitates out from solution, ultimately leading to the plateau phase.

Recent studies have demonstrated the potential of rapidly soluble ENs with plant extracts and natural compounds for wound healing. For example, electrospun polyvinyl alcohol (PVA) nanofibers with the addition of *Moringa oleifera* Lam. leaf extract were developed [48]. These fibers showed good water solubility and were effective in promoting chronic wound healing. In another study, ENs composed of polycaprolactone (PCL) and PVP were loaded with *Punica granatum* L. peel extract [49]. The extract contained phenolic compounds such as rutin and kaempferol and the resulting nanofibers showed significant antibacterial activity and provided controlled release of active components. Other EN consisting of PCL, carboxyethyl chitosan (CECS) and PVA with *Matricaria recutita* L. extract demonstrated pronounced antibacterial activity, excellent mechanical properties and controlled release [14]. Fast-dissolving nanofibers with pure natural compounds have also shown rapid release, wound healing properties, and to have potential biomedical applications [50, 51].

Several studies have reported the creation of fibers containing essential oils in combination with polymers such as polylactic acid [52], PVA/PCL [53], polyacrylonitrile [54], and alginate [55]. Lavender essential oil, rich in linalool and linalyl acetate, has a soothing and antimicrobial effect. In contrast, lavender herb extract contains a wider range of compounds and has wider pharmacological applications [3, 6, 56].

Overall, ENs show significant potential in addressing the limitations of traditional topical drug delivery methods and offer promising solutions to current therapeutic challenges. The findings reported herein underscore the potential of lavender extract for incorporation into fast-acting bioactive delivery systems. Further studies could focus on isolating and characterizing individual bioactive metabolites/compounds of lavender or other potential plant-derived compounds, as well as tailoring nanofiber systems for site-specific or controlled release applications in wound healing and dermatological treatments.

4 | Conclusion

This study successfully developed rapid-dissolving ENs loaded with lavender extract using PVP as a polymeric matrix. The fibers exhibited uniform and smooth morphology, with diameters ranging between 0.70–1.49 μm. Physicochemical analyses confirmed the formation of an amorphous solid dispersion stabilized by hydrogen bonding between PVP and the extract. The resulting nanofibers disintegrated within 1.5 s and enhanced dissolution relative to the pure extract.

Our findings validate the core hypothesis that electrospinning into a fast-dissolving PVP matrix can overcome the dissolution

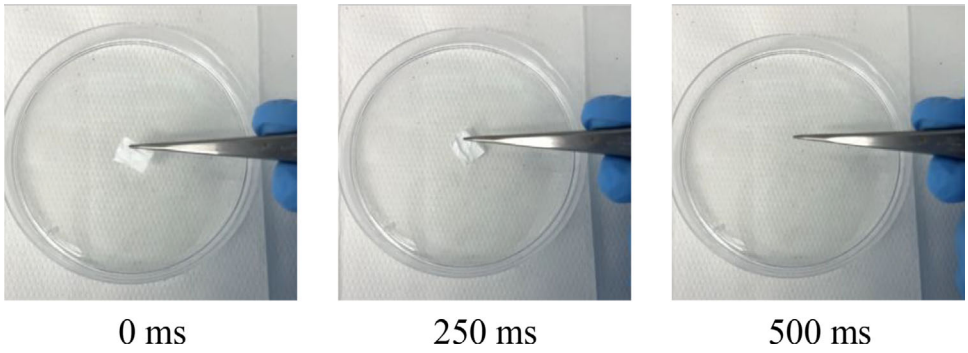

FIGURE 7 | Camera images captured during the disintegration of formulation F1.

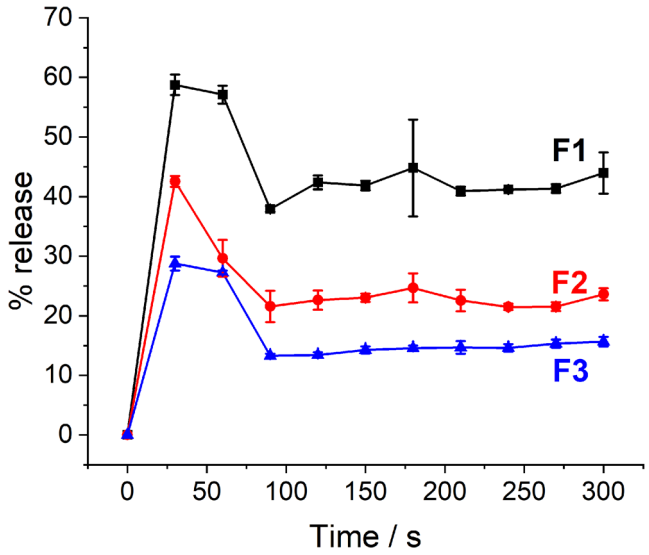

FIGURE 8 | In vitro dissolution profiles of F1, F2, and F3, given as mean ± SD.

limitations of lavender water extract. The concept of a "lavender-loaded amorphous nanofiber patch" represents a novel approach in phytochemical delivery for potential wound care. Unlike previously reported sustained-release herbal fiber systems, this work emphasizes ultra-rapid release, positioning it as a promising platform for applications requiring immediate bioactive delivery.

Compared to composite wound dressings with robust mechanical properties [57, 58] or controlled-release systems [59], the current system prioritizes dissolution speed over structural integrity or prolonged release. Future work will focus on developing composite scaffolds that integrate rapid-release fibers within a mechanically supportive matrix, alongside comprehensive biological evaluation including antibacterial, antioxidant, and in vivo wound healing studies.

Acknowledgements

Dr. Mykhailenko is grateful to CARA (the Council for At-Risk Academics) for a fellowship which made it possible to untertake scientific research at the UCL School of Pharmacy, UK, during the period of Russian military aggression in Ukraine.

Funding

OM was funded via a personal fellowship award from CARA.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. S. Kasper, "An Orally Administered Lavandula Oil Preparation (Silexan) for Anxiety Disorder And Related Conditions: An Evidence Based Review," *International Journal of Psychiatry in Clinical Practice* 17 (2013): 15–22, https://doi.org/10.3109/13651501.2013.813555.

2. B. Jalil and M. Heinrich, "Short Lecture "Quality of Oral Solid Formulation Of Herbal Medicinal Products—A Case Study With Lavandula Species Products"," *Planta Medica* 89 (2023): 1299, https://doi.org/10.1055/s-0043-1773878.

3. B. Jalil and M. Heinrich, "Pharmaceutical Quality of Herbal Medicinal Products and Dietary Supplements—a Case Study With Oral Solid Formulations Containing Lavandula Species," *European Journal of Pharmaceutical Sciences* 208 (2025): 107042, https://doi.org/10.1016/j.ejps.2025.107042.

4. M. Dold, L. Bartova, H.-P. Volz, et al., "Efficacy of Silexan in Patients With Anxiety Disorders: A Meta-analysis of Randomized, Placebo-controlled Trials," *European Archives of Psychiatry and Clinical Neuroscience* 273 (2023): 1615–1628, https://doi.org/10.1007/s00406-022-01547-w.

5. O. Mykhailenko, V. Hurina, L. Ivanauskas, et al., "Lavandula Angustifolia Herb From Ukraine: Comparative Chemical Profile and in Vitro Antioxidant Activity," *Chemistry & Biodiversity* 21 (2024): 202400640, https://doi.org/10.1002/cbdv.202400640.

6. O. Mykhailenko, V. Hurina, L. Ivanauskas, et al., "Lavandula Angustifolia Herb From Ukraine: Comparative Chemical Profile and In Vitro Antioxidant Activity," *Chemistry & Biodiversity* 21 (2025): 289–316, https://doi.org/10.1002/cbdv.202400640.

7. M. Kazemi, M. Mohammadifar, E. Aghadavoud, Z. Vakili, M. H. Aarabi, and S. A. Talaei, "Deep Skin Wound Healing Potential of Lavender Essential Oil and Licorice Extract in a Nanoemulsion Form: Biochemical, Histopathological and Gene Expression Evidences," *Journal of Tissue Viability* 29 (2020): 116–124, https://doi.org/10.1016/j.jtv.2020.03.004.

8. M. Bedi and P. Shenefelt, "Herbal Therapy in Dermatology," *Archives of Dermatology* 138 (2002): 232–242, https://doi.org/10.1001/archderm.138.2.232.

9. M. Dubský, S.-R. Kubinová, J. Sirc, et al., "Nanofibers Prepared by Needleless Electrospinning Technology as Scaffolds for Wound Healing," *Journal of Materials Science: Materials in Medicine* 23 (2012): 931–941, https://doi.org/10.1007/s10856-012-4577-7.

10. Q. Liu, S. Luo, J. Peng, and R. Chang, "Electrospun Nanofibers From Plant Natural Products: A New Approach Toward Efficient Wound Healing," *International Journal of Nanomedicine* 19 (2024): 13973–13990, https://doi.org/10.2147/IJN.S501970.

11. R. Goyal, L. K. Macri, H. M. Kaplan, and J. Kohn, "Nanoparticles and Nanofibers for Topical Drug Delivery," *Journal of Controlled Release* 240 (2016): 77–92, https://doi.org/10.1016/j.jconrel.2015.10.049.

12. X. Lan, H. Wang, J. Bai, et al., "Multidrug-loaded Electrospun Micro/Nanofibrous Membranes: Fabrication Strategies, Release Behaviors and Applications in Regenerative Medicine," *Journal of Controlled Release* 330 (2021): 1264–1287, https://doi.org/10.1016/j.jconrel.2020.11.036.

13. Y. Pilehvar-Soltanahmadi, M. Dadashpour, A. Mohajeri, A. Fattahi, R. Sheervalilou, and N. Zarghami, "An Overview on Application of Natural Substances Incorporated With Electrospun Nanofibrous Scaffolds to Development of Innovative Wound Dressings," *Mini-Reviews in Medicinal Chemistry* 18 (2018): 414–427, https://doi.org/10.2174/1389557517666170308112147.

14. M. Shokrollahi, S. H. Bahrami, M. H. Nazarpak, and A. Solouk, "Multilayer Nanofibrous Patch Comprising Chamomile Loaded Carboxyethyl Chitosan/Poly(vinyl alcohol) and Polycaprolactone as a Potential Wound Dressing," *International Journal of Biological Macromolecules* 147 (2020): 547–559, https://doi.org/10.1016/j.ijbiomac.2020.01.067.

15. W.-H. Dong, J.-X. Liu, X.-J. Mou, et al., "Performance of Polyvinyl Pyrrolidone-isatis Root Antibacterial Wound Dressings Produced in Situ by Handheld Electrospinner," *Colloids and Surfaces B: Biointerfaces* 188 (2020): 110766, https://doi.org/10.1016/j.colsurfb.2019.110766.

16. X. Yang, Q. Wang, Z. Zhu, et al., "A Modified Triaxial Electrospinning for a High Drug Encapsulation Efficiency of Curcumin in Ethylcellulose," *Pharmaceutics* 17, no. 9 (2025): 1152, https://doi.org/10.3390/pharmaceutics17091152.

17. D.-G. Yu, W. He, C. He, H. Liu, and H. Yang, "Versatility of Electrospun Janus Wound Dressings," *Nanomedicine* 20, no. 3 (2025): 271–278, https://doi.org/10.1080/17435889.2024.2446139.

18. Y. Hu, F. Zhang, J. Zhou, et al., "Electrospun Tri-Layer Core-Sheath Nanofibrous Coating for Sequential Treatment of Postoperative Complications in Orthopedic Implants," *Small* 21, no. 42 (2025): 05523, https://doi.org/10.1002/smll.202505523.

19. M. Adaszyńska-Skwirzyńska and M. Dzięcioł, "Comparison of phenolic acids and flavonoids contents in various cultivars and parts of common lavender (Lavandula angustifolia) derived from Poland," *Natural Product Research* 31, no. 21 (2017): 2575–2580, https://doi.org/10.1080/14786419.2017.1320792.

20. K. Pokajewicz, M. Białoń, L. Svydenko, R. Fedin, and N. Hudz, "Chemical Composition of the Essential Oil of the New Cultivars of Lavandula angustifolia Mill. Bred in Ukraine," *Molecules (Basel, Switzerland)* 26, no. 18 (2021): 5681, https://doi.org/10.3390/molecules26185681.

21. K. Christos, "Antioxidant Contribution of Lavender (Lavandula angustifolia), Sage (Salvia officinalis), Tilia (Tilia tomentosa) and Sideritis (Sideritis perfoliata) Beverages Prepared at Home," *SDRP Journal of Food Science & Technology* 3, no. 1 (2018): 360–377.

22. U. Sadowska, A. R. Villavicencio, K. Dziadek, J. Skoczylas, S. K. Sadowski, and A. Kopeć, "The Identification of Polyphenolic Compounds and the Determination of Antioxidant Activity in Extracts and Infusions of Peppermint, Lemon Balm and Lavender," *Applied Sciences* 14, no. 2 (2024): 699, https://doi.org/10.3390/app14020699.

23. M. Kurakula and G. S. N. K. Raom, "Pharmaceutical assessment of polyvinylpyrrolidone (PVP): As excipient from conventional to controlled delivery systems with a spotlight on COVID-19 inhibition," *Journal of Drug Delivery Science and Technology* 60 (2020): 102046–102068, https://doi.org/10.1016/j.jddst.2020.102046.

24. S. Esnaashari, Y. Javadzadeh, H. K. Batchelor, and B. R. Conway, "Solubilisation in Aqueous Micellar Solutions Of Block Copoly(Oxyalkylene)s," *International Journal of Pharmaceutics* 293, no. 1-2 (2005): 91–100, https://doi.org/10.1016/j.ijpharm.2004.12.005.

25. D. Q. M. Craig, "The Mechanisms of Drug Release From Solid Dispersions in Water-soluble Polymers," *International Journal of Pharmaceutics* 231, no. 2 (2002): 131–144, https://doi.org/10.1016/S0378-5173(01)00891-2.

26. S. B. Balakrishnan, S. Kuppu, and S. Thambusamy, "Biologically Important Alumina Nanoparticles Modified Polyvinylpyrrolidone Scaffolds in Vitro Characterizations and It Is in Vivo Wound Healing Efficacy," *Journal of Molecular Structure* 1246 (2021): 131195, https://doi.org/10.1016/j.molstruc.2021.131195.

27. P. Pusporini, D. Edikresnha, I. Sriyanti, T. Suciati, M. M. Munir, and K. Khairurrijal, "Electrospun Polyvinylpyrrolidone (PVP)/Green Tea Extract Composite Nanofiber Mats and Their Antioxidant Activities," *Materials Research Express* 5, no. 5 (2018): 054001, https://doi.org/10.1088/2053-1591/aac1e6.

28. C. A. Schneider and W. S. Rasband, "NIH Image to ImageJ: 25 Years of Image Analysis," *Nature Methods* 9 (2012): 671–675, https://doi.org/10.1038/nmeth.2089.

29. M. do Rocio Duarte and D. Carvalho de Souza, "Microscopic Characters of the Leaf and Stem of Lavandula Dentata L. (Lamiaceae)," *Microscopy Research and Technique* 77 (2014): 647–652, https://doi.org/10.1002/jemt.22384.

30. M. Koleilat, K. Raafat, A. El-Lakany, and M. Aboul-Ela, "Designing Monographs for Rosmarinus officinalis L. and Lavandula Angustifolia L.: Two Lebanese Species With Significant Medicinal Potentials," *Pharmacognosy Journal* 9 (2017): 452–474, https://doi.org/10.5530/pj.2017.4.75.

31. A. L. Yarin, W. Kataphinan, and D. Reneker, "Branching in Electrospinning of Nanofibers," *Journal of Applied Physics* 98 (2005): 064501, https://doi.org/10.1063/1.2060928.

32. G. Bakeri, A. F. Ismail, M. Shariaty-Niassar, and T. Matsuura, "Effect of Polymer Concentration on the Structure and Performance of Polyetherimide Hollow fiber Membranes," *Journal of Membrane Science* 363 (2010): 103–111, https://doi.org/10.1016/j.memsci.2010.07.018.

33. W. Cui, X. Li, X. Zhu, G. Yu, S. Zhou, and J. Weng, "Investigation of Drug Release and Matrix Degradation of Electrospun Poly(DL-lactide) Fibers With Paracetanol Inoculation," *Biomacromolecules* 7 (2006): 1623–1629, https://doi.org/10.1021/bm060057z.

34. W. Mosad, H. H. A. Sherif, B. Hemdan, I. W. Khalil, and S. Khalil, "Assessment of in Situ-prepared Polyvinylpyrrolidone-silver Nanocomposite for Antimicrobial Applications," *Acta Physica Polonica A* 131 (2017): 1554–1560, https://doi.org/10.12693/APhysPolA.131.1554.

35. M. Balaz, Z. Bedlovicová, N. Daneu, et al., "Mechanochemistry as an Alternative Method of Green Synthesis of Silver Nanoparticles With Antibacterial Activity: A Comparative Study," *Nanomaterials* 11 (2021): 1139–1164, https://doi.org/10.3390/nano11051139.

36. C. Peniche, D. Zaldívar, M. Pazos, S. Páz, A. Bulay, and J. S. Román, "Study of the Thermal Degradation of poly(N -vinyl-2-pyrrolidone) by Thermogravimetry–FTIR," *Journal of Applied Polymer Science* 50, no. 3 (1993): 485–493, https://doi.org/10.1002/app.1993.070500312.

37. J. Fliou, O. Riffi, Z. Mhamdi, M. Elhourri, A. Zriouel, and A. Amechrouq, "Analysis of Organic Extracts of the Plant, Lavandula X Intermedia by Different Spectroscopic Techniques," *Indian Journal of Agricultural Biochemistry* 35 (2022): 58–65, https://doi.org/10.5958/0974-4479.2022.00009.0.

38. M. B. Bodí, S. J. Mataix-Solera, S. H. Doerr, and A. Cerdà, "The Wettability of Ash From Burned Vegetation and Its Relationship to Mediterranean Plant Species Type, Burn Severity and Total Organic Carbon Content," *Geoderma* 160, no. 3 (2011): 599–607, https://doi.org/10.1016/j.geoderma.2010.11.009.

39. G. Bettinetti, G. Bruni, F. Giordano, and P. Mura, "Thermal Analysis of the Dehydration Process of Cross-linked Polyvinylpyrrolidone and Its Mixtures With Naproxen," *Drug Development and Industrial Pharmacy* 20 (1994): 2215–2225, https://doi.org/10.3109/03639049409050234.

40. D.-G. Yu, C. Branford-White, G. R. Williams, et al., "Self-assembled Liposomes From Amphiphilic Electrospun Nanofibers," *Soft Matter* 7 (2011): 8239–8248, https://doi.org/10.1039/c1sm05961k.

41. Y. Cheng, Q. Xu, J. Liu, C. Zhao, F. Xue, and Y. Zhao, "Decomposition of Five Phenolic Compounds in High Temperature Water," *Journal of the Brazilian Chemical Society* 25 (2014): 2102–2107, https://doi.org/10.5935/0103-5053.20140201.

42. C. Tsioptsias and I. Tsivintzelis, "On the Thermodynamic Thermal Properties of Quercetin and Similar Pharmaceuticals," *Molecules (Basel, Switzerland)* 27 (2022): 6630–6643, https://doi.org/10.3390/molecules27196630.

43. I. Erel-Unal and S. A. Sukhishvili, "Hydrogen-bonded Multilayers of a Neutral Polymer and a Polyphenol," *Macromolecules* 41 (2008): 3962–3970, https://doi.org/10.1021/ma800186q.

44. C. Radulescu, C. Stihi, M. Ilie, et al., "Characterization of Phenolics in Lavandula Angustifolia," *Analytical Letters* 50 (2017): 2839–2850, https://doi.org/10.1080/00032719.2016.1264409.

45. L. Mačák, O. Velgosova, E. Múdra, M. Vojtko, S. Dolinská, and F. Kromka, "Preparation of Green Silver Nanoparticles and Eco-Friendly Polymer–AgNPs Nanocomposites: A Study of Toxic Properties Across Multiple Organisms," *Polymers* 16 (2024): 1865–1878, https://doi.org/10.3390/polym16131865.

46. Y. Tomar, N. Pandit, S. Priya, and G. Singhvi, "Evolving Trends in Nanofibers for Topical Delivery of Therapeutics in Skin Disorders," *ACS Omega* 8 (2023): 18340–18357, https://doi.org/10.1021/acsomega.3c00924.

47. Y. Geng, F. Zhou, and G. R. Williams, "Developing and Scaling Up Fast-dissolving Electrospun Formulations Based on Poly(vinylpyrrolidone) and Ketoprofen," *Journal of Drug Delivery Science and Technology* 61 (2021): 102138–102166, https://doi.org/10.1016/j.jddst.2020.102138.

48. C. Y. Chin and S. F. Ng, "Development of Moringa Oleifera Standardized Leaf Extract Nanofibers Impregnated Onto Hydrocolloid Film as a Potential Chronic Wound Dressing," *Fibers and Polymers* 21 (2020): 2462–2472, https://doi.org/10.1007/s12221-020-1356-9.

49. M. Paczkowska-Walendowska, M. Ignacyk, A. Miklaszewski, et al., "Electrospun Nanofibers With Pomegranate Peel Extract as a New Concept for Treating Oral Infections," *Materials* 17 (2024): 2558–2577, https://doi.org/10.3390/ma17112558.

50. X. Z. Sun, G. R. Williams, X. X. Hou, and L. M. Zhu, "Electrospun Curcumin-loaded Fibers With Potential Biomedical Applications," *Carbohydrate Polymers* 94 (2013): 147–153, https://doi.org/10.1016/j.carbpol.2012.12.064.

51. N. Palani, P. Vijayakumar, P. Monisha, S. Ayyadurai, and S. Rajadesingu, "Electrospun Nanofibers Synthesized From Polymers Incorporated With Bioactive Compounds for Wound Healing," *Journal of Nanobiotechnology* 22 (2024): 211–241, https://doi.org/10.1186/s12951-024-02491-8.

52. D. Ismaili, F. N. Parın, Y. Sıcak, Y. Öztürk, and P. Terzioğlu, "Electrospun Lavender Essential Oil-loaded Polylactic Acid Nanofibrous Mats for Antioxidant Applications," *Polymer Bulletin* 81 (2024): 13975–13992, https://doi.org/10.1007/s00289-024-05370-2.

53. D. Kang, Y. Li, X. Dai, et al., "A Soothing Lavender-scented Electrospun Fibrous Eye Mask," *Molecules (Basel, Switzerland)* 29 (2024): 5461–5476, https://doi.org/10.3390/molecules29225461.

54. K. Balasubramanian and K. M. Kodam, "Encapsulation of Therapeutic Lavender Oil in an Electrolyte Assisted Polyacrylonitrile Nanofibres for Antibacterial Applications," *RSC Advances* 4 (2014): 54892–54901, https://doi.org/10.1039/C4RA09425E.

55. H. Hajiali, M. Summa, D. Russo, et al., "Alginate–lavender nanofibers With antibacterial and anti-inflammatory activity to effectively promote burn healing," *Journal of Materials Chemistry B* 4 (2016): 1686–1695, https://doi.org/10.1039/c5tb02174j.

56. O. Bogatyrova, V. Hurina, O. Naboka, et al., "Lavandula angustifolia Mill. Of Ukrainian Origin: A Comparative Study of the Chemical Composition and Antimicrobial Potential of Herb Extracts," *ScienceRise: Pharmaceutical Science* 5 (2024): 4–14, https://doi.org/10.15587/2519-4852.2024.313236.

57. J. Pan, Q. Meng, L. Zhang, C. Zhang, S. Wu, and H. Zhai, "Electrospun Amine-modified Polysuccinimide/Polycaprolactone Nanofiber Hydrogel Dressings as Antibacterial and Hemostatic Wound Dressing Applications," *Colloids and Surfaces B: Biointerfaces* 252 (2025): 114648, https://doi.org/10.1016/j.colsurfb.2025.114648.

58. Y. Wang, X. Huang, J. Jiang, et al., "Functionalization of Cotton Nonwoven Dressings With Herbal Compound-loaded PHBV Short Nanofibers and Gelatin Hydrogel Coating for Accelerated Diabetic Wound Healing," *ACS Applied Materials & Interfaces* 17, no. 39 (2025): 54593–54607, https://doi.org/10.1021/acsami.5c14731.

59. M. Rahman, M. Kabir, H. Liu, L. Zhang, S. Chen, and S. Wu, "Curcumin Delivery and Release by Using a Dual Cooperative Encapsulation System Constructed With ZIF-8 MOFs and Silk Fibroin/Polycaprolactone Nanofibers for Accelerated Wound Healing," *Biomaterials Advances* 178 (2026): 214441, https://doi.org/10.1016/j.bioadv.2025.214441.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: mame70169-sup-0001-SuppMat.docx.