3rd International Conference on Scientific and Academic Research

December 25-26, 2023 : Konya, Turkey

AS-Proceedings
https://alls-academy.com/index.php

© 2023 Published by AS-Proceedings

https://www.icsarconf.com/

Nanofibers produced from medicinal and aromatic plant extracts by electrospinning method

Kübra Turan[1*] and Rukiye Saygılı Canlıdinç[2]

[1] *Department of Chemistry/ Science Faculty, Ankara University, Türkiye*
[2] *Department of Chemistry/Art and Science Faculty, Kütahya DumlupınarUniversity, Türkiye*

[*]*(kubraturan17@gmail.com)*

Abstract – Electrospinning (ES) is a fiber fabrication technology that uses electrical force with polymer solutions or polymer melts. ES is a flexible and economical technique for producing continuous nano- and microfiber membranes with tunable structures, properties, and functionalities. Since 2000, there have been significant advances in the field of electrospinning. ES has proven to be the most cost-effective, simple, and reliable method for producing nanofibers. ES is a carrier system that can be used for these purposes and is a suitable platform for the production of new materials. Many research studies have been conducted using both natural and synthetic polymers. In the ES process, bioactive chemicals are incorporated into polymers because of many advantages. Plant extracts are a storehouse of bioactive chemicals with medicinal applications. These medicinal and beneficial properties of plants can be transferred to nanofibers. Nanofibers are a subset of nanostructures. One of the most efficient methods to produce nanofibers is electrospinning. The aim of this review is to present a summary of some recent studies in which crude plant extracts have been loaded with various natural or synthetic polymers for applications.

Keywords – Aromatic Plant, Electrospinning, Medical Plant, Nanofiber, Plant Extract.

I. NANOFIBER

Nanofibers are a unique class of nanomaterials with many interesting properties due to their nanoscale diameter and large aspect ratio. They have excellent mechanical properties, and their surfaces can be easily modified due to their high surface area-to-volume ratio [1]. Nanofibers can be simply defined as fibers with dimensions in the range of 1-100 nm or smaller in diameter. However, the scope of nanofibers has been expanded in recent years to include all fibers smaller than 1 μm [2]. Recently, electrospun fibers have been used by researchers around the world for various purposes [3-6]. Various synthetic and natural polymers or a mixture of these polymers, called biopolymers, have been successfully used for nanofiber production. Electrospinning is one of the most effective technologies for producing nanofibers [7].

Nanofibers have the most promising applications including semiconductors, protective materials, water purification, sustainable energy applications, drug delivery carriers, and biomedical applications including cosmetics, implants, tissue engineering, and wound dressings [8,9].

II. ELECTROSPINNING

Electrospinning (ES) is a nanofabrication technology that uses high electrical voltages to extrude nanometer-diameter polymer fibers. The electrospinning process is an electrohydrodynamic phenomenon that uses electrical force to extrude and stretch thin films of polymer solutions or melts [10]. A typical electrospinning setup consists of three basic components. It consists of a high-voltage power supply, a metal needle connected to a syringe, and a syringe pump. A metal needle is usually connected to a syringe filled with a polymer solution. When a high-voltage power supply applies a voltage in the range of 5-60 kV between the needle and the grounded metal collector, electric charges are generated on the surface of the polymer droplet at the tip of the needle [2, 10, 11]. As the voltage increases until a critical voltage is reached, electrical charges accumulate on the droplet surface. This causes a droplet of polymer solution to form at the tip of the needle. At this point, the surface tension and viscoelastic forces of the polymer solution are overcome, and the droplet transforms into a conical shape known as a Taylor cone. A jet of liquid is released from the tip of the Taylor cone and propelled toward the collector. The jet expands at the tip of the spinneret, gradually decreases in diameter, bends, and is deposited on the aluminum plate [12].

ES is a simple and effective method for producing nanofibers with nanoscale diameters, high specific surface area, strong interconnectivity, and structural stability. It is also a potential approach for spinning natural, synthetic, polymer blends, and other composite materials [13, 14]. ES is still the most preferred and attractive approach for the production of nanofibers from various polymer materials [14]. It is easy to produce nanofibers of various sizes that are difficult to produce using other typical manufacturing processes. Due to these properties, electrospun nanofibers are useful in various applications such as filtration and adsorption materials, "smart" materials, catalytic materials, and so on. The produced nanofiber has a higher surface area/volume ratio and a wider range of potential applications. However, existing electrospun nanofibers are usually made of non-biodegradable polymers, which may raise disposal concerns [13,14].

Various parameters such as flow rate, concentration, voltage, tip-collector distance (TCD), molecular weight, viscosity, surface tension, and conductivity together determine the morphology and properties of electrospun fibers [15].

Over the years, more than 200 different polymers have been electrospun for various applications and the number of these polymers continues to increase [17]. Polymers used in the preparation of electrospun nanofibers can be classified into three types: synthetic polymers, natural polymers, and natural/synthetic hybrid polymers. Synthetic polymers have high mechanical properties, thermal stability, and a favorable degradation profile [18]. ES, most of the research on synthetic polymers has been done to investigate their potential applications in the pharmaceutical and food industries. Other synthetic polymers and polyester have poor mechanical properties. For these reasons, extensive research has been conducted on biopolymers such as polysaccharides and proteins due to their biocompatibility, biodegradability, and low cost [19]. Natural polymers have been proposed as an alternative. However, the biodegradability and mechanical properties of these natural materials are limited [18]. Natural polymers are often difficult to convert into nanofibers, so a synthetic polymer is often used in combination with the natural polymer, or the natural polymer is chemically modified. Electrospinning has also given a whole new perspective to the use of natural polymers in many fields, especially biomedical [20]. The limitations of natural and synthetic polymers can be overcome by combining these polymers.

Poly(lactic acid) (PLA) [21], poly(vinyl alcohol) (PVA) [16, 22], polyvinylpyrrolidone (PVP) [23-25], polyurethane (PU) [26], polyethylene glycol (PEG) [27], polycaprolactone (PCL) [28], polyethylene oxide (PEO), polylactic acid (PLGA), polystyrene (PS) and polyglycerol (PG), chitosan (CS), gelatin, pectin, collagen [18] are widely used in ES in the literature.

In the food, pharmaceutical, and cosmetic industries, encapsulation technology is a successful method for coating flavor ingredients with suitable materials. During processing and storage, this approach increases the functionality, bioavailability, and solubility of the loaded bioactive components. The electrospinning process is one of the latest encapsulation methods used to encapsulate and protect sensitive components such as flavors [16]. Antimicrobial activity has been associated with phytochemicals such as phenolics, terpenoids, and alkaloids. The encapsulation of botanicals using electrospinning can greatly enhance their therapeutic potential. This method increases bioavailability and maximizes therapeutic potential by maintaining a constant drug concentration at the target site [14].

III. PLANT AND PLANT EXTRACTIONS

Plants have been used for therapeutic purposes since ancient times. However, due to their natural structure and many useful and effective properties, plant extracts have gained more popularity in recent years [27]. According to the World Health Organization, there are approximately 20,000 medicinal plants in 91 countries. The first step in the utilization of biologically active compounds is pharmacological screening, extraction, isolation, and characterization of a bioactive compound, toxicological, and clinical evaluation [29].

Plants have significant potential as a source of new antimicrobial drugs due to a variety of chemical and structural secondary metabolites classified as terpenoids, phenolics, polyphenols, and alkaloids [30]. Plant extracts contain a high concentration of bioactive chemicals such as polyphenols and carotenoids and therefore can be used as health foods, pharmaceuticals, cosmetics, biopesticides, chemical alternatives, etc. [27].

Due to the beneficial effects of phytochemicals on human health, researchers are increasingly interested in the use of bioactive extracts of plant origin. Plants produce phytochemical components, especially polyphenols, as secondary metabolites through various metabolic pathways within plant cells. Extraction is a natural product research process in which selected solvents are used to separate bioactive compounds from various natural sources and pharmaceutically active components from inactive or inert fractions [31]. In the literature, it can produce a wide range of bioactive extracts that can be synthesized using different extraction methods. Extracts are a mixture of various plant constituents dissolved in a solvent. They are usually obtained from fresh or dried plants by extracting active compounds with solvents such as water or organic solvents [10]. During the extraction process, solvents penetrate solid raw materials and solubilize molecules with comparable polarities according to the "like dissolves like" principle. Non-polar solvents such as ether, chloroform, and n-hexane, polar solvents such as ethanol, water, and methanol, and medium polar solvents such as methylene chloride, ethyl acetate, and acetone, are widely used in natural product extraction. In addition to using an appropriate extraction technique, the choice of an acceptable solvent is also critical. Extraction methods such as Soxhlet extraction, maceration, percolation, and boiling are used [31].

Crude extracts are easily obtained by organic solvent extraction from fresh plants or ground-dried plants. Several crude plant extracts have been successfully encapsulated in electrospun fibers, such as baicalein, *Azadirachta indica*, aloe vera, chamomile, Calendula officinalis, *Centella asiatica*, *Garcinia mangostana*, *Grewia mollis*, green tea, grape seed, *Indigofera aspalathoides*, *Memecylon edule*, *Myristica andanica* and *Tecomella undulata*, [10].

IV. PLANT-BASED NANOFIBERS

Many herbal extracts have been effectively used in nanofiber electrospinning technology. Some of the plants that have been used include *Zataria multiflora* [21,22], *Salvia hispanica L.* [19], *Malva syvestris* [26, 54], *Laurus nobilis* [32], *Rosmarinus officinalis* [32], garlic [23, 33], Bergamot [16], *Melissa officinalis* [27], *Inula graveolens (L.)* [28], *Allium cepa L.* [34, 35], *Juniperus chinensis* [26], Panax Ginseng [36], *Allium ursinum L.* [37], *Rhodomyrtus tomentosa* [24], *Opuntia ficus-indica* [38], *Garcinia mangostana* L. [39], *Lawsonia Inermis* [40, 41], *Cleome droserifolia* [42], *Tridax Procumbens* [43], *Moringa oleifera* [44].

Recently, there has been increased interest in the research of nanofibrous scaffolds prepared by electrospinning bioactive plant extracts. Çiftçi et al., The electrospinning approach was used to prepare 8% poly(lactic acid) were treated with antioxidant *Zataria Multiflora* (ZM, EO) and antibiotic-effective Bacitracin (BAC) materials. The antioxidant components of ZM EO were investigated by GC-MS after extraction by rotary.

While carvacrol is the major component of ZM, the content range was found to be 48.06% carvacrol and 25.47% thymol. ZM was found to have a total antioxidant rate of 99.87% with 20 components. PLA/BAC/ZM nanofiber inhibited the development of all microorganisms tested in antibacterial tests (*E. coli, S. aureus, B. cereus, S. epidermidis, B. subtilis*). The PLA/BAC/ZM nanofiber used in the adhesion and 40,6-diamidino-2-phenylindole results showed very good adherence to cells in the Cell XTT cytotoxicity assay [45].

Stoyanova et al. prepared hybrid fiber materials using *Melissa officinalis* (*M. officinalis*) plant extract, biocompatible polyether-polyethylene glycol (PEG), and biodegradable polyester-poly(L-lactide) (PLA) polymer. The extracted content was optimized to 0%, 5%, or 10% of the polymer weight to investigate the effect of electrospray on the shape and physicochemical properties of the hybrid materials. An increase in fiber diameter and water contact angle was observed with the addition of *M. officinalis* to the fibers. The incorporation of polyether into the fibers resulted in hydrophilicity (water contact angle was 0). Hybrid fibers were shown to have high antioxidant activity due to the components contained in the extracts. These properties make *M. officinalis*-containing fibrous hybrid biomaterials interesting candidates for pharmacological, cosmetic, and biological applications [46].

The ES technique is a very practical encapsulation approach to preserve and prevent the degradation of bioactive materials. Therefore, this technique is often used to prepare new fibers to preserve bioactive substances and exploit their existing properties in new materials. Cruz et al. also used ES to prepare ultrafine fibers from red onion peel extract (ROSE; 0, 3, 6, and 9% w/w) and yellow and white sweet potato starch. Many properties of the fibers were evaluated, such as antioxidant activity, thermogravimetric properties, thermal resistance, morphology, in vitro release simulation, and wettability. The diameters of ROSE fibers were found to be 251-611 nm; apigenin provided the best thermal protection. Phenolic compounds were released less when 10% ethanol was used and more when 50% ethanol was used. Ultrafine fibers and unencapsulated ROSE were both found to be inhibitory to *E. coli* and *S. aureus*, but only unencapsulated ROSE was bactericidal [35].

In their study, Zhang et al. prepared a dressing material with antibacterial activity. For this purpose, garlic oil, a natural antibacterial agent, was coated with β-CD (β-cyclodextrin) to form garlic oil/β-CD microcapsule (MC) and then added to an electrospinning solution containing PVA and chitosan (CS) to prepare garlic oil/CS/PVA nanofibers. The addition of garlic oil/β-CD microcapsule was found to impart antibacterial properties to the material. The results showed that the antibacterial effect increased in direct proportion to the increase of MC. MC showed the best antibacterial effect against *E. coli* and *S. aureus* with 67.28% and 69.15%, respectively [33].

In another plant-based nanofiber study, Edikresnha et al. used electrospinning to produce a composite fiber mat composed of PVP/CA (cellulose acetate) and garlic extract. Uniform and bead-free fibers were produced. The average fiber diameter of the composite fiber increased with voltage. No sputtering was observed when the applied voltage was higher than 14 kV [47].

In a similar study, Edikresnha et al. prepared fibers from a mixture of PVP, CA, glycerin, and garlic extract in 98% (v/v) acetic acid by electrospinning with garlic extract as the active ingredient and glycerin as an additive [23].

In this study, Al Karabi et al. prepared electrospun nanofibers using 5 wt% and 8 wt% polycaprolactone (PCL) polymer from the extracted material of the medicinal plant *Inula graveolens L.* Fourier transform infrared (FT-IR) spectroscopy, scanning electron microscopy (SEM) and X-ray diffraction were used for characterization. Hydrophilicity was determined by contact angle experiments. At the same time, the toxicity of the prepared nanofibers on, fibroblast cell lines were investigated. The results showed that *I. graveolens*/PCL polymeric scaffolds dispersed as homogeneous nanofibers at 72-963 nm in a ratio of 70/30 (v:v) have minimal cell toxicity and can be used for biomedical applications [28].

Göksen et al. created innovative active edible electrospun coatings with antibacterial capabilities by encapsulating essential oils (EOs) from *Laurus nobilis* and *Rosmarinus officinalis* to create active food packaging. GC-MS was used to investigate the EOs and compounds found in the dried leaves of the plants. Both EOs were more effective against gram-positive bacteria than gram-negative bacteria. The antibacterial activity of EO-zein nanofiber (ZNF) films was then tested against *Listeria monocytogenes*, *S. aureus*, and mesophilic bacteria. *Laurus nobilis* essential oil outperformed *Rosmarinus officinalis* in terms of antibacterial activity. The antibacterial efficacy of the active films increased with time, and after 28 days at 4 °C, the highest concentration of 1,8-cineol-rich EOs and films prepared by electrospinning showed a significant 2-log unit decrease in antibacterial efficacy [32].

In the study, Almasian and colleagues developed new polyurethane (PU)-based nanofiber wound dressings containing *Malva sylvestris* extract and evaluated their effect on the diabetic wound healing process. Different amounts of carboxymethyl cellulose (CMC) were used to improve the absorption capacity of wound exudate. Based on the antibacterial activity of the dressing and the wound healing process, the 15% w/w amount of herbal extract was selected as the most appropriate. Examples of extracted wound dressings have shown satisfactory effects on the bacteria *S. aureus* and *E. coli*. In vivo, observations of wound healing and histologic performance have shown that using plant extract in wound reinforcement significantly improves wound healing. Compared to control groups, treatment with extract-loaded dressings was found to be effective in reducing acute and chronic inflammation. It can be suggested that this product can be considered a good binary anti-inflammatory-antimicrobial wound dressing candidate to improve diabetic wound healing [26].

This work aimed to prepare fast-dissolving fiber mats based on balangu seed gum (BSG) coated with bergamot essential oil (BEO) by electrospinning. Increasing the concentration of BSG in BSG-PVA blends increased the values of electrical conductivity, surface tension, and consistency coefficient. The prepared mats can dissolve in aqueous media within 5 seconds. The release kinetics of the loaded BEO were investigated in simulated aqueous tea media. The Fickian transfer phenomenon was shown to be the main mechanism involved in the release process. The developed method, which provides a burst release of aroma compounds, could be considered a promising step in the food sector [16].

In a study by Khezri and colleagues, Opopanax gum/gelatin nanofibers were prepared by electrospinning, and the effectiveness of this new technique for encapsulating garlic essential oil was investigated. The FTIR results showed improved physical and weak interactions between Opopanax and gelatin, as well as thermal stability in the nanofiber structure. The best percentage was found to be the addition of 10% of garlic essential oil based on the weight of the biopolymer in the nanofibers. The results confirmed the presence of garlic essential oil in nanofibers and improved thermal stability by trapping it in the nanofiber structure [48].

In the study, Ramalingam and his colleagues investigated the use of electrospun nanofibers containing a natural extract of *Gymnema sylvestre* (GS), which supports the adhesion of human dermal fibroblasts (hDFs). Overall, GS has demonstrated that functional electrospun poli-e-caprolactone nanofibers are suitable as effective wound dressing with broad-spectrum antimicrobial properties [49].

In another study, *Rhodomyrtus tomentosa* extract and PVA were electrospun into nanofibers. The antibacterial activity was evaluated using the paper disc diffusion method against *E. coli*, *P. aeruginosa*, *B. subtilis*, and *E. faecalis*. The amount of myricetin and rhodomyrtone may have contributed to the antibiotic activity against all bacterial strains tested. The average diameter of nanofibers increased from 120.4 to 214.8 nm as the content of *R. tomentosa* extract increased from 0.5% to 2.5%. The antibacterial activity of nanofibers against all test organisms was significantly stronger at higher extract concentrations (1.5% and 2.5%), with a distinct zone of inhibition of 7-12 mm. The results demonstrated that electrospun nanofibers are a promising platform for the delivery of bioactive chemicals such as wound dressings or other antibacterial methods [24].

In their research, Fahami and Fathi produced a new source of biomacromolecules, cress seed mucilage (CSM), CSM-PVA nanofibers under different conditions using the electrospinning technique. The results showed that CSM could be used as a new source of biopolymers to produce nanofibers that could be used for different applications, such as distribution systems and the manufacture of packaging films. However, no processes were carried out. In this study, only a characterization operation was carried out [50].

In a study by colleagues at Urena-Saborio, electrospun nanofibers (ESNFs) were prepared from mucilage isolated from chan and linaza beans and mozote stems, which are commercially available in Costa Rica. PVA was used as an adjuvant and various volume ratios (100:0, 80:20, 60:40, 40:60, 20:80, and 0:100) of mixture/PVA solutions were prepared. In vitro studies were conducted. The results showed that mucilage/PVA ESNFs can improve biocompatibility and activation for fibroblast cells, thus being considered a good candidate for potential applications in tissue engineering [51].

In a study conducted by Kurd and his colleagues, nanofibers were prepared using the electrospinning technique using basil seed mucilage (BSM) as a novel source of hydrocolloids. PVA was used as an adjuvant. BSM-based nanofibers were found to be available for various applications, such as bioactive encapsulation and packaging film production. However, no processes have been carried out. In this study, only a characterization operation was carried out [52].

The goal of Yousefi and his colleagues' work is to produce chitosan-based nanofibers loaded with traditional plant extract from *Lawsonia inermis* (henna) leaves to enhance antibiotic efficacy and promote the healing of pioneering nanoparticles. The characterization studies, antibacterial activity, cell biocompatibility evaluations, and wound healing activity were investigated [41].

In their study, he and his colleagues used the electrospinning technique to incorporate the nanoencapsulation of the ethanol extract of *Moringa oleifera* (MO) leaves in the fish-derived gelatin matrix. The characterization studies have shown that the nanoencapsulation does not affect the antioxidant properties of the phenolic compounds in the extract and the safety of the nanofibers. It has been investigated whether the cell vitality is increased [44].

In the study, Ganesan and Pradeepa prepared nanofibers using a methanol extract of *Tridax procumbens* (TP) leaves (%10) with PVA (%10), a biodegradable polymer. Nanofibers are characterized by fundamental properties such as thickness, elasticity, and density. The genericity of the nanofiber was analyzed using the flow rate parameter, and the results showed that it had the largest diameter of the molecule at 2.26 μm. The morphological studies to evaluate the diameter and surface structure of PVA/TP nanofibers were performed by SEM, and chemical compound analysis was performed by FT-IR. The antimicrobial activity of the nanofibers was investigated against *E. co*li and *S. aureus* bacteria, and it was observed that it has an excellent inhibition zone and better resistance to both gram-positive and gram-negative bacteria. [43].

Mouro et al. used emulsion electrospinning to incorporate *Chelidonium majus L.*, a medicinal plant with several pharmacological properties, into electrospun nanofibers composed of PCL, PVA, and pectin (PEC). The membranes developed have properties that make them suitable for use as wound dressings. They showed enhanced bactericidal activity against *S. aureus* and *P. aeruginosa*, while producing minimal cytotoxicity in normal human dermal fibroblasts (NHDFs) [53].

Turan et al. in their study prepared electrospun nanofibers from biocomposite of PVA/*M. sylvestris L.* seed extract (MSs). Q-TOF LC-MS was used to characterize the metabolites in MSs extract. Biocomposites with different polymer/extract ratios were prepared for the preparation of nanofibers. From these biocomposites, bionanofibers were prepared under optimal electrospinning conditions and their morphology was studied using SEM and FTIR methods. The average diameters of the nanofibers ranged from 180 to 244 nm. They also showed antibacterial activity against a variety of microbes, including gram-negative such as *P. aeruginosa* and *E. coli* [54].

V. CONCLISION

For more than 80 years, the electrospinning approach has been used as a potential continuous fiber synthesis technology. Electrospun nanofibers can be used in a variety of applications such as biomedical engineering, filtration, battery research, electrical engineering, bio-textiles, textiles, and renewable energy by varying parameters such as molecular weight, voltage, concentration, flow rate, surface tension, viscosity, syringe-to-collector distance, and so on. Over the past decade, there has been a great deal of scientific interest in nanofiber architectures produced by electrospinning bioactive plant extracts. The resulting structures possess antibacterial, anti-inflammatory, and antioxidant properties, making them attractive for biological applications and the food sector. This study presents the different plant-based nanofibers created by naturally derived chemical compounds. The efficacy of these composite nanofibers as tissue engineering, wound dressings, antibacterial materials, and active food packaging solutions will be explored.

ACKNOWLEDGMENT

Kübra Turan was supported by the Council of Higher Education (CoHE) with a 100/2000 Ph.D. scholarship in the sub-field of New Generation Composites and Multifunctional Nanocomposite Materials.

REFERENCES

[1] Mishra, R., Militky, J. & Venkataraman, M. (2019). Electrospun nanofibers. in: R. Mishra & J. Militky (eds.) Nanotechnology in textiles (pp. 35-161). Duxford, CB22 4QH, United Kingdom: Woodhead Publishing.

[2] Zdraveva, E., Fang, J., Mijovic, B. & Lin, T. (2017). Electrospun nanofibers. In G. Bhat (Ed.), Structure and Properties of High-Performance Fibers (pp. 267-300). Cambridge, USA: Woodhead Publishing.

[3] Eatemadi, A., Daraee, H., Zarghami, N., Melat Yar, H., Akbarzadeh, A. (2016). Nanofiber: Synthesis and biomedical applications. Artificial Cells, Nanomedicine and Biotechnology, 44, 111-121. doi: 10.3109/21691401.2014.922568

[4] Thenmozhi, S., Dharmaraj, N., Kadirvelu, K. & Kim, H.Y. (2017). Electrospun nanofibers: New generation materials for advanced applications. Materials Science and Engineering: B, 217, 36-48. doi: 10.1016/j.mseb.2017.01.001

[5] Kumar, S.S.D., Rajendran, N.K., Houreld, N.N. & Abrahamse, H. (2018). Recent advances on silver nanoparticle and biopolymer-based biomaterials for wound healing applications. International Journal of Biological Macromolecules, 115, 165-175. doi: 10.1016/j.ijbiomac.2018.04.003

[6] Abid, S., Hussain, T., Nazir, A., Zahir, A. & Khenoussi, N. (2019). A novel double-layered polymeric nanofiber-based dressing with controlled drug delivery for pain management in burn wounds. Polymer Bulletin, 76(12), 6387-6411. doi: 10.1007/s00289-019-02727-w

[7] Xue, J., Xie, J., Liu, W., & Xia, Y. (2017). Electrospun nanofibers: new concepts, materials, and applications. Accounts of chemical research, 50(8), 1976-1987.

[8] Al-Enizi, A. M., Zagho, M. M., & Elzatahry, A. A. (2018). Polymer-based electrospun nanofibers for biomedical applications. Nanomaterials, 8(4), 259.

[9] Patel PR, Gundloori RVN. A review on electrospun nanofibers for multiple biomedical applications. Polym Adv Technol. 2023;34(1):44-63. doi:10.1002/pat.5896

[10] Zhang, W., Ronca, S., & Mele, E. (2017). Electrospun nanofibres containing antimicrobial plant extracts. Nanomaterials, 7(2), 42.

[11] Peijs, T. (2018). Electrospun polymer nanofibers and their composites. In C.H. Zweben and P. Beaumont (Eds.), Comprehensive composite materials II, Volume 6 (pp. 162-200). Amsterdam, Netherlands: Elsevier.

[12] Mele, E. (2020). Electrospinning of essential oils. Polymers, 12(4), 908.

[13] Zhang, Y., Zhang, C., & Wang, Y. (2021). Recent progress in cellulose-based electrospun nanofibers as multifunctional materials. Nanoscale Advances, 3(21), 6040-6047.

[14] Khan, A.R., Xiangyang, S., Ahmad, A. and Mo, X. . (2018), Electrospinning of Crude Plant Extracts for Antibacterial and Wound Healing Applications: A Review. SM J Biomed Eng, 4(1): 1024

[15] Agarwal, A., Rao, G. K., Majumder, S., Shandilya, M., Rawat, V., Purwar, R., ... & Srivastava, C. M. (2022). Natural protein-based electrospun nanofibers for advanced healthcare applications: progress and challenges. 3 Biotech, 12(4), 92.

[16] Rezaeinia, H., Emadzadeh, B., & Ghorani, B. (2020). Electrospun balangu (Lallemantia royleana) hydrocolloid nanofiber mat as a fast-dissolving carrier for bergamot essential oil. Food Hydrocolloids, 100, 105312.

[17] Bhardwaj, N. & Kundu, S.C. (2010). Electrospinning: a fascinating fiber fabrication technique. Biotechnology Advances, 28(3), 325-347. doi: 10.1016/j.biotechadv.2010.01.004

[18] Fatehi, P., & Abbasi, M. (2020). Medicinal plants used in wound dressings made of electrospun nanofibers. Journal of Tissue Engineering and Regenerative Medicine, 14(11), 1527-1548.

[19] Dehghani, S., Noshad, M., Rastegarzadeh, S., Hojjati, M., & Fazlara, A. (2020). Electrospun chia seed mucilage/PVA encapsulated with green cardamonmum essential oils: Antioxidant and antibacterial property. International Journal of Biological Macromolecules, 161, 1-9.

[20] Vineis, C., & Varesano, A. (2018). Natural polymer-based electrospun fibers for antibacterial uses. In Electrofluidodynamic Technologies (EFDTs) for Biomaterials and Medical Devices (pp. 275-294). Woodhead Publishing.

[21] Ciftci, F., Duygulu, N., Yilmazer, Y., Karavelioğlu, Z., Çakır Koç, R., Gündüz, O., & Ustündag, C. B. (2023). Antibacterial and cellular behavior of PLA-based bacitracin and zataria multiflora nanofibers produced by electrospinning method. International Journal of Polymeric Materials and Polymeric Biomaterials, 72(4), 319-334.

[22] Ardekani-Zadeh, A. H., & Hosseini, S. F. (2019). Electrospun essential oil-doped chitosan/poly (ε-caprolactone) hybrid nanofibrous mats for antimicrobial food biopackaging exploits. Carbohydrate Polymers, 223, 115108.

[23] Edikresnha, D., Suciati, T. & Khairurrijal, K. (2021). Study of morphology of composite fibers polyvinylpyrrolidone/cellulose acetate loaded by garlic extract with glycerin as an additive. Materials Today: Proceedings, 44(3), A5-A8. doi: 10.1016/j.matpr.2021.04.345

[24] Zeyohanness, S.S., Abd Hamid, H. & Zulkifli, F.H. (2018). Poly(vinyl alcohol) electrospun nanofibers containing antimicrobial Rhodomyrtus tomentosa extract. Journal of Bioactive and Compatible Polymers, 33(6), 585-596. doi: 10.1177/0883911518801040Khan AR, Xiangyang S, Ahmad A and Mo X. Electrospinning of Crude Plant Extracts for Antibacterial and Wound Healing Applications: A Review. SM J Biomed Eng. 2018; 4(1): 1024

[25] Kim, J.H., Lee, H., Jatoi, A.W., Im, S.S., Lee, J.S., & Kim, I.-S. (2016). Juniperus chinensis extracts loaded PVA nanofiber: Enhanced antibacterial activity. Materials Letters, 181, 367-370. doi: 10.1016/j.matlet.2016.05.164

[26] Almasian, A., Najafi, F., Eftekhari, M., Ardekani, M.R.S., Sharifzadeh, M. & Khanavi, M. (2020). Polyurethane/carboxymethylcellulose nanofibers containing Malva sylvestris extract for healing diabetic wounds: Preparation, characterization, in vitro and in vivo studies. Materials Science and Engineering: C Materials for Biological Applications, 114, 111039. doi: 10.1016/j.msec.2020.111039

[27] Stoyanova, N.; Nachev, N.; Spasova, M. (2023). Innovative Bioactive Nanofibrous Materials Combining Medicinal and Aromatic Plant Extracts and Electrospinning Method. Membranes, 13, 840. https://doi.org/10.3390/ membranes13100840

[28] Al-Kaabi, W.J.; Albukhaty, S.; Al-Fartosy, A.J.M.; Al-Karagoly, H.K.; Al-Musawi, S.; Sulaiman, G.M.; Dewir, Y.H.; Alwahibi, M.S.; Soliman, D.A. Development of Inula graveolens (L.) Plant Extract Electrospun/Polycaprolactone Nanofibers: A Novel Material for Biomedical Application. Appl. Sci. 2021, 11, 828. https://doi.org/ 10.3390/app11020828

[29] Sasidharan, S., Chen, Y., Saravanan, D., Sundram, K.M. & Yoga Latha, L. (2011). Extraction, ısolation and characterization of bioactive compounds from plants'extracts. African Journal of Traditional, Complementary and Alternative Medicines, 8(1), 1-10. doi: PMC3218439

[30] Seukep, A. J., Mbuntcha, H. G., Zeuko'o, E. M., Woquan, L. S., Nembu, N. E., Bomba, F. T., ... & Kuete, V. (2023). Established antibacterial drugs from plants. In Advances in Botanical Research (Vol. 106, pp. 81-149). Academic Press.

[31] Ponphaiboon, J., Krongrawa, W., Aung, W. W., Chinatangkul, N., Limmatvapirat, S., & Limmatvapirat, C. (2023). Advances in Natural Product Extraction Techniques, Electrospun Fiber Fabrication, and the Integration of Experimental Design: A Comprehensive Review. Molecules, 28(13), 5163.

[32] Göksen, G., Fabra, M.J., Ekiz, H.I. & López-Rubio, A. (2020). Phytochemical-loaded electrospun nanofibers as novel active edible films: Characterization and antibacterial efficiency in cheese slices. Food Control, 112, 107133. doi: 10.1016/j.foodcont.2020.107133

[33] Zhang, R., Lei, M., Hu, B., Tu, H. & Hu, M. (2022). Preparation of the Garlic Oil Microcapsule/CS/PVA Nanofiber Membrane and the Antibacterial Properties. Fibers and Polymers, 23(2), 343-351. doi: 10.1007/s12221-021-3008-0

[34] Chu, L. L., Kang, X. J., & Wang, Y. (2017). Extraction of onion (Allium cepa) essential oil by polystyrene nanofibrous membranes. Journal of Food Process Engineering, 40(1), e12318.

[35] Cruz, E. P., Pires, J. B., Jansen, E. T., Santos, F. N., Fonseca, L. M., Hackbart, H. C. S., ... & Dias, A. R. G. (2023). Zein electrospun fibers with red onion extract (Allium cepa L.): Bioactive compounds, thermal stability, hydrophilicity, and antioxidant activity.

[36] Pajoumshariati, S., Yavari, S. K. & Shokrgozar, M.A. (2016). Physical and biological modification of polycaprolactone electrospun nanofiber by panax ginseng extract for bone tissue engineering application. Annals of Biomedical Engineering, 44(5), 1808-1820. doi: 10.1007/s10439-015-1478-1

[37] Radusin, T., Torres-Giner, S., Stupar, A., Ristic, I., Miletic, A., Novakovic, A. & Lagaron, J. M. (2019). Preparation, characterization and antimicrobial properties of electrospun polylactide films containing Allium ursinum L. extract. Food Packaging and Shelf Life, 21, 100357. doi: 10.1016/j.fpsl.2019.100357

[38] Thomas, S.W., Alcantar, N.A. & Pais, Y. (2012), Electrospinning and characterization of novel Opuntia ficus-indica mucilage biomembrane, Materials Research Society Symposium Proceedings 1480, Imrc12-1480-s2b-0017. doi: 10.1557/opl.2012.1614

[39] Charernsriwilaiwat, N., Rojanarata, T., Ngawhirunpat, T., Sukma, M. & Opanasopit, P. (2013). Electrospun chitosan-based nanofiber mats loaded with Garcinia mangostana extracts. International Journal of

Pharmaceutics, 452(1-2), 333- 343. doi: 10.1016/j.ijpharm.2013.05.012

[40] Avci, H., Monticello, R. & Kotek, R. (2013). Preparation of antibacterial PVA and PEO nanofibers containing Lawsonia Inermis (henna) leaf extracts. Journal of Biomaterials Science:Polymer Edition, 24(16), 1815-1830. doi: 10.1080/09205063.2013.804758

[41] Yousefi, I., Pakravan, M., Rahimi, H., Bahador, A., Farshadzadeh, Z. & Haririan, I. (2017). An investigation of electrospun Henna leaves extract-loaded chitosan based nanofibrous mats for skin tissue engineering. Materials Science and Engineering C: Materials for Biological Applications, 75, 433-444. doi: 10.1016/j.msec.2017.02.076

[42] Sarhan, W.A., Azzazy, H.M. & El-Sherbiny, I.M. (2016). Honey/chitosan nanofiber wound dressing enriched with Allium sativum and Cleome droserifolia: Enhanced antimicrobial and wound healing activity. ACS Applied Materials & Interfaces, 8(10), 6379-6390. doi: 10.1021/acsami.6b00739

[43] Ganesan, P. & Pradeepa, P. (2017). Development and characterization of nanofibrous mat from PVA/Tridax Procumbens (TP) leaves extracts. Wound Medicine, 19, 15- 22. doi: 10.1016/j.wndm.2017.09.004

[44] 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 the Science of Food and Agriculture, 97(10), 3348-3358. doi: 10.1002/jsfa.8185

[45] Ciftci, F., Duygulu, N., Yilmazer, Y., Karavelioğlu, Z., Çakır Koç, R., Gündüz, O., & Ustündag, C. B. (2023). Antibacterial and cellular behavior of PLA-based bacitracin and zataria multiflora nanofibers produced by electrospinning method. International Journal of Polymeric Materials and Polymeric Biomaterials, 72(4), 319-334.

[46] Stoyanova, N.; Spasova, M.; Manolova, N.; Rashkov, I.; Kamenova-Nacheva, M.; Staleva, P.; Tavlinova-Kirilova, M. (2023), Electrospun PLA-Based Biomaterials Loaded with Melissa officinalis Extract with Strong Antioxidant Activity. Polymers, 15, 1070. https://doi.org/10.3390/polym15051070

[47] Edikresnha, D., Suciati, T. & Khairurrijal, K. (2021). Preliminary study of composite fibers polyvinylpyrrolidone/cellulose acetate loaded by garlic extract by means of electrospinning method. Materials Today: Proceedings, 44(3), A1-A4. doi: 10.1016/j.matpr.2021.04.344

[48] Khezri, Z., Shekarchizadeh, H. & Fathi, M. (2020). Stability enhancement of garlic essential oil using new opopanax gum/gelatin nanofibres. International Journal of Food Science and Technology, 56(5), 2255-2263. doi: 10.1111/ijfs.14843

[49] Ramalingam, R., Dhand, C., Leung, C.M., Ong, S.T., Annamalai, S.K., Kamruddin, M., Verma, N.K., Ramakrishna, S., Lakshminarayanan, R. & Arunachalam, K.D. (2019). Antimicrobial properties and biocompatibility of electrospun polyepsilon-caprolactone fibrous mats containing Gymnema sylvestre leaf extract. Materials Science and Engineering C: Materials for Biological Applications 98, 503-514. doi: 10.1016/j.msec.2018.12.135

[50] Fahami, A. & Fathi, M. (2018). Fabrication and characterization of novel nanofibers from cress seed mucilage for food applications. Journal of Applied Polymer Science, 135, 45811. doi: 10.1002/app.45811

[51] Urena-Saborio, H., Alfaro-Viquez, E., Esquivel-Alvarado, D., Madrigal-Carballo, S. & Gunasekaran, S. (2018). Electrospun plant mucilage nanofibers as biocompatible scaffolds for cell profibereration. International Journal of Biological Macromolecules, 115, 1218-1224. doi: 10.1016/j.ijbiomac.2018.04.129

[52] Kurd, F., Fathi, M. & Shekarchizadeh, H. (2017). Basil seed mucilage as a new source for electrospinning: Production and physicochemical characterization. International Journal of Biological Macromolecules, 95, 689-695. doi: 10.1016/j.ijbiomac.2016.11.116

[53] Mouro, C., & Gouveia, I. C. (2023). Electrospun wound dressings with antibacterial function: a critical review of plant extract and essential oil incorporation. Critical Reviews in Biotechnology, 1-19.

[54] Turan, K., Akcan, M., & Kalfa, O. M. (2021). Preparation, Characterization and Antibacterial Activity of Malva Sylvestris L. Seed Extract Containing Novel Electrospun PVA Nanofibers. Gazi University Journal of Science, 34(4), 987-998. https://doi.org/10.35378/gujs.794638