Polymer Bulletin (2020) 77:6085–6104
https://doi.org/10.1007/s00289-019-03042-0

REVIEW PAPER

Developed methods for the preparation of electrospun nanofibers containing plant-derived oil or essential oil: a systematic review

Mahmoud Osanloo[1,2] · Javad Arish[2] · Hassan Sereshti[3]

Received: 10 September 2019 / Revised: 25 November 2019 / Accepted: 29 November 2019 /
Published online: 4 December 2019

Abstract

Recently, natural health products as alternatives for synthetic/chemical substances have become a growing area of interest. Plant-derived essential oils or oils (E/Os) with a wide range of bioactivities such as anticancer, antibacterial, antifungal, and antioxidant activities are widely used among natural materials. Furthermore, nanofibers (NFs) with distinct properties, including large surface area, many available ingredients for preparation, and various preparation methods have attracted much attention. The present systematic review is an attempt to collect and document the recent studies from 01.01.2013 to 31.12.2018, indicating the loading of E/O in electrospun NFs. First, a summary of the electrospinning process and applications of electrospun NFs in medicine were given. Then, the three manners, which have been introduced for preparing E/O-loaded NFs so far, were described. Moreover, the main techniques for characterization of such NFs, e.g., evaluation of size and morphology, determination of the loaded amount of E/O in NFs, and investigating their release behavior, were explained.

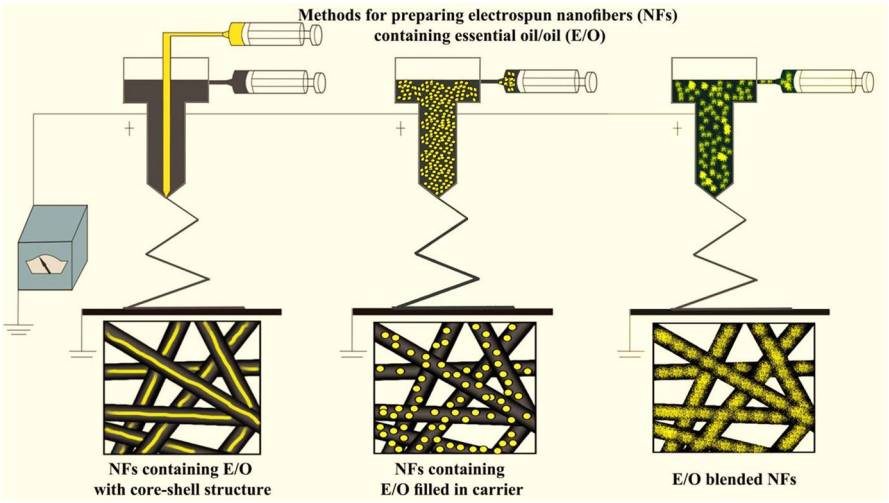
✉ Mahmoud Osanloo
m.osanloo@fums.ac.ir; osanloo_mahmood@yahoo.com

[1] Department of Medical Nanotechnology, School of Advanced Technologies in Medicine, Fasa University of Medical Sciences, Fasa, Iran

[2] Noncommunicable Diseases Research Center, Fasa University of Medical Sciences, Fasa, Iran

[3] Department of Chemistry, Faculty of Science, University of Tehran, Tehran, Iran

Graphic abstract



Keywords Essential oil · Electrospun · Nanofibers · Electrospinning · A systematic review

Nanotechnology

Nanotechnology is defined as targeted manipulations of materials in nanoscale for obtaining size-dependent features or functions [1]. The most common nanomaterials include metallic nanoparticles [2, 3], nanoemulsions [4] polymeric nanoparticle [5, 6], lipidic nanocarrier [7], and nanofibers (NFs) [8]. NFs (diameter ~ 200 nm) with small pores and large surface areas have enormous applications in medicine, such as tissue engineering, drug delivery, and wound dressing [9]. Various techniques, including template-assisted synthesis, electrospinning, phase separation, self-assembly, solvent casting, and drawing–processing, were developed for the fabrication of NFs based on a literature review [10–12]. Electrospinning is a versatile and easily adaptable technique and the most common method for the preparation of NFs [13–15]. Electrospinning, compared with other approaches such as phase separation and self-assembly, has the advantages of versatility and flexibility in the selection of material and control over fibers' morphology and diameter [16]. The preparation of NFs using drawing–processing also needs viscoelastic material that can undergo substantial deformation during this process [17]. In template-assisted synthesis, the elimination of the template often leads to defects in structures of NFs [18].

Electrospinning

An electrospinning setup typically consists of a high-voltage source, a polymer solution or melt, an electrically conductive blunted needle, a syringe pump, and a collector [19, 20]. The electrospinning process consists of three continuous stages, including jet initiation, elongation, and solidification into NFs. During jet initiation, the polymer solution is subjected to an electric field, which was filled into a syringe connected to the spinneret. When the high voltage is applied to the spinneret, typically in the range of 10–30 kV, the surface of the fluid droplet gets electrostatically charged at the tip. As a result, two forces affect droplets, i.e., electrostatic repulsion between the surface charges and the columbic force applied by the external electric field. Due to these electrostatic interactions, the liquid drop elongates into a conical object known as the Taylor cone [16, 21]. When critical electric field intensity is applied between spinneret (positive) and collector (negative), the electrostatic forces on the surface are sufficient to overcome the surface tension holding the droplet together. That leads to a forcible ejection of the liquid jet from the tip; the fluid jet continues to be ejected steadily and elongated. The solvent evaporates before reaching the collector, leading to the formation of a randomly oriented of thin polymeric fibers on the collector [16]. By using types of a collector, such as metallic plate, drum, parallel electrode, and an array of counter electrodes, the morphology and structures are customizable [22].

In fixed environmental conditions, (temperature and relative humidity) optimizations of two types of parameters during the electrospinning are crucial. Instrumental factors include the applied voltage, the injection rate of polymer, and the distance between the needle and collector. Polymer solution parameters are concentration or viscosity, conductivity, and solvent volatility [23, 24]. A schematic of electrospinning and main parameters is shown in Fig. 1.

Applied voltage Applying high voltage into polymeric solution via a metallic needle will cause a spherical droplet to deform into a Taylor cone. At a critical voltage, depending on the used polymer, ultrafine NFs could be harvested. The formation of smaller-diameter NFs by applying higher voltage is attributed to the stretching of the polymer solution in correlation to the charge repulsion within the polymer jet. Interestingly, an increase in the diameter of NFs, as well as the formation of beads or beaded NFs, could occur when a higher voltage than the critical value is applied. That is attributed to the decrease in the size of the Taylor cone and the increase in the jet velocity for the same flow rate [25, 26].

Flow rate Uniform and beadles electrospun NFs could be prepared via a critical flow rate for a polymeric solution, which varies from polymer to polymer. Increasing the flow rate (higher than a critical value) leads to an increase in the pore size and fiber diameter. Also, due to incomplete drying of the NFs jet during the flight between the tip and collector, beads formation is inevitable [21, 27].

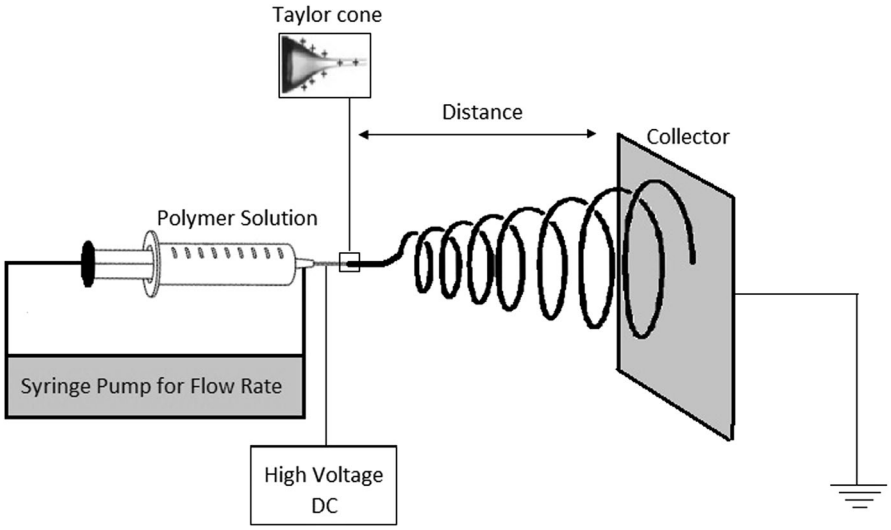


Fig. 1 Electrospinning and main parameters

Distance between tip and collector The morphology of obtained electrospun NFs is critically dependent on the distance between the needle tip and collector and varies with the polymers system. When this distance is kept small and defective, large-diameter NFs are formed. However, by increasing this amount, the diameter of the NFs is decreased [28, 29].

Polymer concentration The stretching of the charged jet is significantly related to the concentration of the polymeric solution. In low concentration, the polymer chains break into fragments before reaching the collector, due to the applied electric field and surface tension. These fragments cause the formation of beads or beaded NFs. Increasing concentration (viscosity) of the polymeric solution leads to better chain entanglement, which can overcome the surface tension and ultimately result in uniform and beadles electrospun NFs [30, 31].

Solution conductivity This factor affects the formation of the Taylor cone as well as controlling the diameter of the NFs. At very low solution conductivity, the surface of the droplet will have no charge to form a Taylor cone; i.e., no electrospinning will start. Increasing the conductivity of the solution to a critical value leads to an increase in charge on the surface of the droplet to form a Taylor cone, which also causes a decrease in the fiber diameter. Increasing the conductivity beyond a critical value results in hindering the Taylor cone formation and electrospinning [17, 32].

Solvent volatility Formation of smooth and beadles electrospun NFs are dependent on the selection of appropriate solvent. The polymer should be completely soluble in the solvent, and it has a low boiling point. The use of highly volatile solvents causes an increase in the rate of evaporation and drying of the jet at the needle tip.

This drying will block the needle tip and will hinder the electrospinning process. In contrast, the use of high-boiling solvents prevents them from drying during the flight of the NFs jet. The deposition of NFs containing solvent on the collector will cause the formation of beaded NFs [25, 33]. A summary of the mentioned factors is given in Table 1.

Application of NFs in medicine

Drug delivery Drug delivery using NFs is based on increasing drug dissolution in their high surface area as a carrier [34]. Interestingly, cargoes are not limited to drugs; numerous kinds of DNA and RNA and proteins were also incorporated with electrospun NFs [35]. This combination can either be loaded into the electrospun NFs or coated on their surface. Both types of mentioned methods can provide a controlled and sustained release of a drug at the target site [25]. The possibility for loading of several medications on/into NFs and proper release profiles leads to enhanced therapeutic efficacy and reduced toxicity [36].

Tissue Engineering Unique properties of electrospun NFs such as the higher surface area-to-volume ratio, porosity, and manipulatable mechanical properties have led to their extensive use in tissue engineering [37]. Also, almost every extracellular matrix (ECM) of connective tissue, such as cartilage, bone, and skin, is based on NF structures [38, 39]. NF-based scaffolds not only have shown an impact on the cell-to-cell interaction but have also increased the interaction between the cells and matrix. Therefore, the growth of many cells on these scaffolds has been reported to be excellent [40]. Besides that, other desirable properties for tissue-engineered scaffolds can be achieved by electrospun NFs mash, for example, regulating porosity, adjusting surface morphology, and capability for surface functionalization [41–43].

Wound dressing Wound healing is a dynamic and intricate process, including homeostasis, inflammation, proliferation, and remodeling. An ideal wound dressing should provide an excellent moist environment for the wound site to enhance wound healing, as well as should have the ability to handle pathogens, especially antibiotic-resistant bacteria [44, 45].

Table 1 Parameters affecting the electrospun NFs

Parameters	Effects
Higher voltage	Decrease in fiber diameter
Higher flow rate	Generation of beads in fiber
Higher distance between tip and collector	Decrease in fiber diameter
Higher polymer viscosity (concentration)	Increase in fiber diameter
Higher solution conductivity	Decrease in fiber diameter
Higher solvent volatility	Decrease in fiber diameter

NF-based scaffolds attract cells to the dermal layer, which can excrete vital extracellular materials (e.g., cytokines, collagen, and growth factors) that assist in the repair of damaged tissues [46]. Numerous such scaffolds were prepared via raw materials such as chitosan, gelatin, and collagen; their role in wound healing has been proven [44, 47]. Furthermore, electrospun NFs can be used in the fabrication of cosmetic masks, skin cleaner, and bandage [48]. Based on the mentioned properties of electrospun NFs, they provided numerous advantages over wound dressing agents prepared using conventional methods [49]. In Fig. 2, schematics of three mentioned applications of E/O-loaded NFs are illustrated.

Plant-derived oil and essential oil

The use of renewable raw materials has a vital role in sustainable development in countries. Some of the most widely applied renewable raw materials are included, such as plant-derived essential oils or oils (E/Os). Essential oils (EOs) are natural liquid oils containing a mixture of many chemical components [50]. Hydro-distillation via the Clevenger-type apparatus is the most common method for extraction of EOs from different parts of plants, such as floret, roots, leaves, peel, bark, stem, and fruits [51]. Furthermore, plant oils are one of the most important renewable raw materials as a primary substance for surfactants, cosmetic products, lubricants, flooring materials, coating, and resin applications [52]. Nowadays, E/Os are

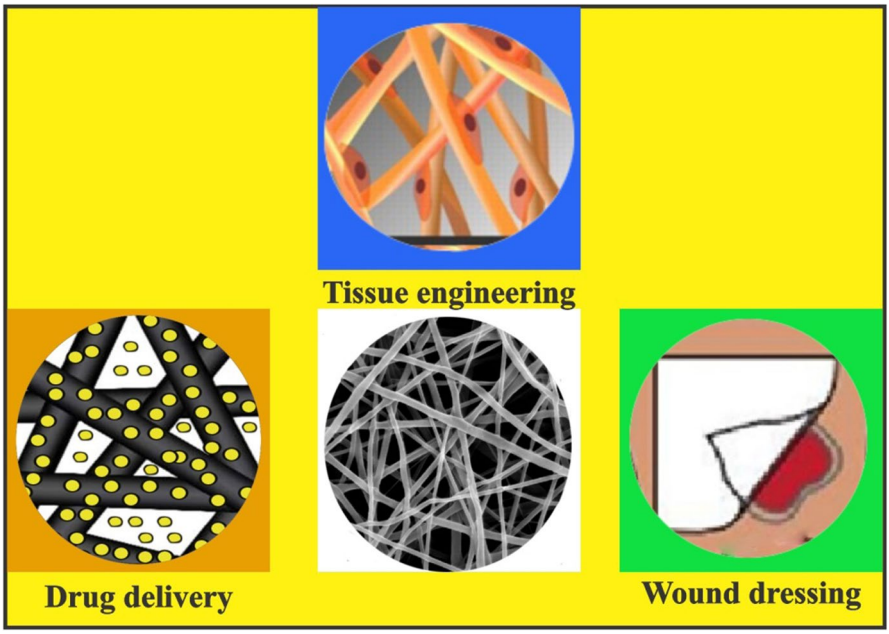


Fig. 2 Three primary applications of E/O-loaded NFs in medicine

commonly used in medicine as an antibacterial or antifungal agent [53], antioxidant-based materials [54], larvicidal bioassays [55], and natural anticancer drugs [56].

Recently, researchers give special attention to improving the mentioned properties of E/Os [57] as well as developing the sustained release formulations using NFs [58]. Excellent review articles have already been published on the applications of NFs in the medical and health sciences. For instance, in one study, reports were categorized by used herbal substance and described the advantages of using NFs and plant-derived elements simultaneously [59]. In another review paper, researches have been conducted in which plant-derived materials (extracts and EOs) were loaded into NFs. The documents have been categorized in the areas of antibacterial, tissue engineering, and food industry by application of the prepared products [16]. Finally, another review article has been found, addressing the biological applications of NFs in drug delivery, wound dressing, and antibacterial activity. Unlike the previous articles, the focus of this article was on collecting information about embedding of metallic nanoparticles (Ag-, Zn-, and Cu-derivative nanoparticles) and common drugs (Ampicillin, Rifampin, and Vancomycin) into NFs [21].

For the first time, in this research, literature was systematically reviewed from 2013.01.01 to 2018.31.12 for collecting data about the methods for the preparation of electrospun NFs containing E/Os and their detailed characterization.

Method for data collection and inclusion criteria

PubMed Web site (https://www.ncbi.nlm.nih.gov/pubmed/advanced) was searched from 2013.01.01 to 2018.31.12 using six special terms, independently (Table 2). Five terms were used for searching for NFs, and one word was assigned to find E/Os (oil*[Title]). Then, every five words were searched binary with "oil*[Title]"

Table 2 Details of systematically search (2013.01.01–2018.31.12) and selected papers

Step no.	Search keyword	Number of papers
1	Nano fiber*[Title]	40
2	Nanofiber*[Title]	3963
3	Nanofibrous*[Title]	935
4	Electrospun*[Title]	2557
5	Electrospin*[Title]	732
6	Oil*[Title]	20,420
7	Step 6 + 5	7
8	Step 6 + 4	33
9	Step 6 + 3	17
10	Step 6 + 2	36
11	Step 6 + 1	0
12	Total results of steps 7–11	93
13	Ignoring duplicated papers	76
14	Reviewing abstracts and including final papers	25

(steps 7–11): Totally, 93 papers were collected (step 12). After ignoring duplicated documents, 76 articles were selected for review (step 13). In the last stage, the papers about E/O-loaded NFs were included, in which finally 25 were selected and reviewed.

Methods for preparing electrospun NFs containing E/O

Three different approaches have been developed for preparing electrospun NFs containing E/O. First, E/Os were mixed with a polymer solution; then, the mixture was subjected to electrospinning for making E/O-blended NFs. Second, E/Os were first loaded into a carrier and then was electrospun for the harvesting of NFs containing E/O filled in a carrier. Third, NFs with core–shell structure (E/O and polymer) were prepared. The examples for these three modes are given in Tables 3, 4, and 5.

E/O-blended NFs

There are 17 reports listed in Table 3. Preparation of E/O-blended NFs has been performed in two steps. First, a homogenous solution of polymer and E/O was prepared using an appropriate solvent. Then, the mixture was subjected to electrospinning.

In one of the reports, a composite of PVA-CHI-GT (polyvinyl alcohol–chitosan–gelatin) was used for blending with *Zataria multiflora* EO. Briefly, the PVA solution (6% w/v) was prepared by dissolving in distilled water (stirring for 4 h at 80 °C). Then, the CHI-GT solution (3:1% w/v) was prepared by dissolving in an aqueous solution of acetic acid. Next, the CHI-GT solution was mixed with prepared PVA solution to a final concentration of 30% v/v acetic acid (stirred for 24 h). Then, various amounts of the EO (0, 2, 5, and 10% v/v) were added to the polymeric solution and stirred for an additional 24 h [60]. In step 2, each prepared polymer solution (containing different amounts of EO) was loaded into a 5-mL syringe with a blunted stainless-steel needle. A DC voltage of 21 kV was applied. The polymer feed rate and distance between needle and collector were fixed at 0.2 mL/h and 15 cm, respectively [60, 61]. The obtained *Z. multiflora* EO-blended NFs were reported as beadles and uniform fibers with a diameter of 95 ± 14, 154 ± 27, 187 ± 40, and 218 ± 58 nm with various amounts of EO (0, 2, 5, and 10%, respectively) [60].

NFs containing E/O filled in the carrier

Some examples for the preparation of NFs containing E/O filled in the carrier and their applications are listed in Table 4. In two of the researches, polymeric carriers were used, while in others, beta-cyclodextrin or its derivate was used.

In such formulations, E/O was first loaded into the carrier; then, the carrier containing E/O was electrospun for preparing the NFs containing E/O filled in a carrier. However, in one report, clove oil was filled in PVA microcapsules and then grafted onto the previously developed nylon NFs via chemical cross-linking [78].

Table 3 E/O-blended NFs and their applications

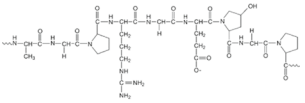
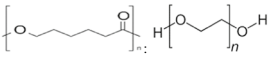
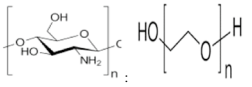
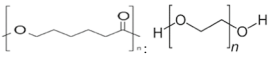
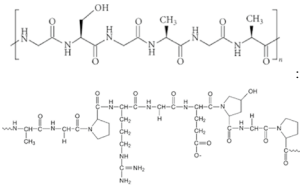
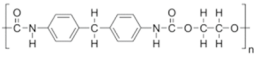
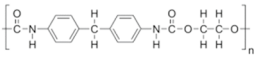
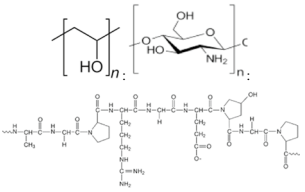
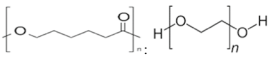
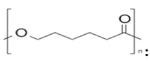
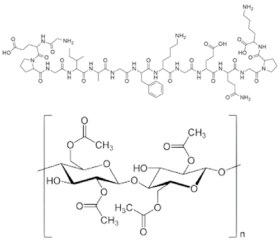
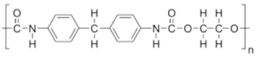
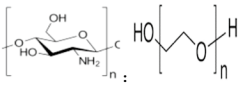
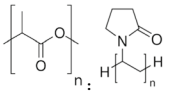
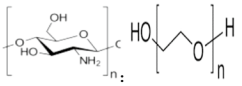
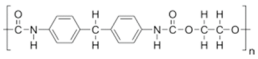
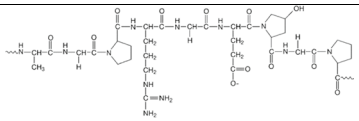
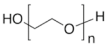
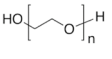
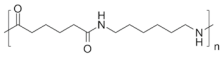
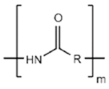
Polymer solution	Chemical structure	E/O	Application	References
GT		Corn oil	Encapsulate of hydrophobic compounds	[64]
PCL[a]:PEG[b]		Emu oil	Control of inflammation	[65]
CHI[c]:PEO[d]		chrysanthemum EO	Antibacterial as beef packaging	[66]
PCL:PEG		Emu Oil	Support for survival, proliferation, and maintaining the stemness of ADSCs[m]	[67]
SF[e]:GT[f]		Thyme EO	Drug delivery	[68]
PU[g]		Grape seed oil, honey, and propolis	Bone tissue regeneration	[69]
PU		Indhulekha oil	Tissue engineering purpose	[70]
PVA[h]:CHI:GT		*Zataria multiflora* EO	Wound dressing	[62]
PCL:PEG		Emu oil	Cytoprotection, proliferation and epidermal differentiation of ADSCs	[71]
PCL:COL[i]		Emu oil	Reinforce the cell adhesion and enhance ADSCs proliferation	[72]
CA[j]		Oregano EO	Antimicrobial Activity	[73]
PU		Bio oil ™	Wound healing application	[74]

Table 3 (continued)

Polymer solution	Chemical structure	E/O	Application	References
CHI:PEO		Cinnamaldehyde oil	Loading of hydrophobic molecules for drug delivery	[75]
PLA[k]		*Matricaria chamomilla* EO	Differentiation of MSCs[n] into IPCs[o]	[76]
PLA:PVP[l]		Copaiba	Antimicrobial activity	[77]
CHI:PEO		Cinnamaldehyde oil	Antimicrobial activity	[78]
PU		Virgin olive oil	Suitable for biomedical applications	[79]

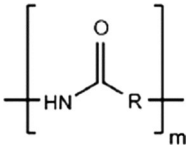
[a]Polycaprolactone, [b]Polyethylene glycol, [c]Chitosan, [d]Polyethene oxide, [e]Silk fibroin, [f]Gelatin, [g]Polyurethane, [h]Polyvinyl alcohol, [i]Collagen, [j]Cellulose acetate, [k]Polylactide acid, [l]Polyvinyl pyrrolidone, [m]Adipose tissue-derived stem cells, [n]mesenchymal stem cells, and [o]insulin-producing cells

Table 4 NFs containing E/O filled in the carrier and their applications

Polymer solution	Chemical structure	Carrier	E/O	Application	References
GT		CHI NPs	Clove oil	Antibacterial activity	[83]
PEO		beta-Cyclodextrin	Tea tree oil	Antibacterial packaging	[84]
PEO		beta-Cyclodextrin proteoliposomes	Cinnamon EO	Antibacterial activity	[82]
Nylon 66		PVA microcapsules	Clove oil	Acaricidal Effects	[80]
Zein[a]		beta-Cyclodextrin	Eucalyptus EO	Antimicrobial activity	[85]
PLA		beta-Cyclodextrin	Cinnamon EO	Antimicrobial packaging	[86]
PVP		2-Hydroxypropyl-beta- Cyclodextrin	Plai oil	Topical application	[87]

[a]Type of protein

Table 5 NFs with core–shell structure (E/O and polymer)

Shell polymer	Chemical structure	EO as core	Application	Reference
Zein		Orange EO	Antimicrobial activity	[88]

The steps for preparing polyethylene oxide (PEO) NFs containing cinnamon EO filled in beta-cyclodextrin proteoliposomes are as follows. First, the EO was loaded into beta-cyclodextrin proteoliposomes as a carrier. Then, a certain amount of PEO powder was dissolved in distilled water (25% w/v) and stirred for 3 h at room temperature. Next, the PEO solution was mixed with EO-beta-cyclodextrin proteoliposomes in the ratio of 2:8 v/v (stirring 12 h at room temperature). Finally, for fabricating NFs containing EO filled in the carrier, the prepared solution was electrospun. The parameters were adjusted as DC voltage of 25 kV, the distance between the syringe needle tip and collector of 12 cm, and the polymer solution flow rate of 0.6 mL/h [79, 80]. Morphology analysis of the obtained NFs showed a rough surface with the diameters mostly ranged within 500–650 nm [80].

NFs with core–shell structure

Among the references, just in one research, orange EO was loaded into the electrospun NFs as core material (Table 5). For preparing NFs with a core–shell structure, two separate syringe pumps are required. Furthermore, the special blunted needle consists of an inner needle (for feeding core) aligned with a surrounded needle (for feeding shell, see Fig. 3) which is also needed [86, 87]. In the mentioned report for preparing core–shell NFs, first, zein powder as shell polymer was dissolved in an aqueous solution of ethanol (80% v/v) with stirring at 300 rpm for 1 h [88]. Then, the solution was loaded into a 5-mL syringe connected to the outer inlet of the needle. The orange EO was loaded into another syringe and perfused into the inner inlet needle. The zein solution flow rate ranged from 1.5 to 3.0 mL/h, and for EO was 1.5 mL/h. The other operational parameters were as follows: DC voltage, 19 kV, and the distance between the needle tip and collector, 15 cm [88]. The minimum diameter of the obtained NFs was around 750 nm [88].

In this manner, to get NFs with proper core–shell structure control of the injection speed of the inner and outer fluid is crucial; the very high or meager speed of the internal fluid is not suitable [89]. At a very lower flow rate, an insufficient amount of core solution is delivered; thus, incorporation of the core into the shell does not continuously occur, while higher flow rates cause an increase in the size of the core until the shell solution is insufficient to surround the core solution and subsequently results in a mixing of core and shell solutions [90]. In fact, the shell cannot uniformly encapsulate the fast-moving of the core, and the overall process becomes unstable [91]. Therefore, at a lower ratio of feed rates of the core and the

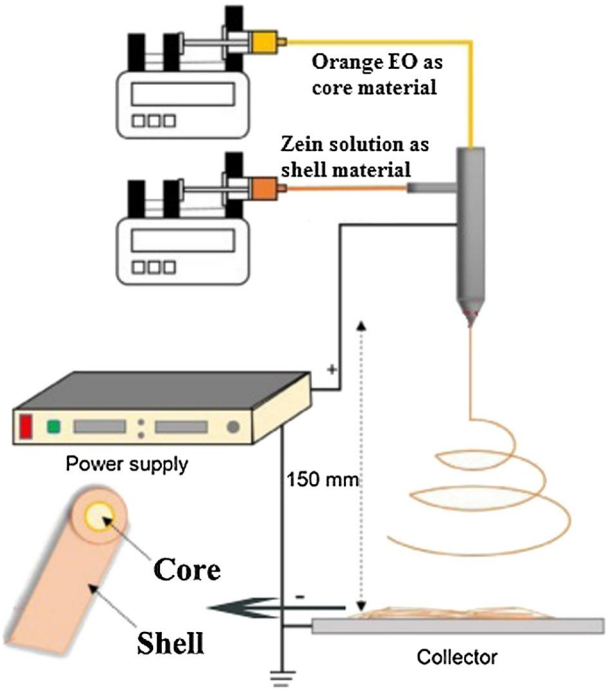


Fig. 3 Schematic for preparing NFs with core–shell structure (EO–polymer) [82]

sheath, better stable core/sheath structures of nanofibers with higher porous density are achievable [92, 93].

For a better comparison of three mentioned methods for loading of E/Os in NFs, drawbacks and advantages of each approach are listed in Table 6.

Characterizations of electrospun NFs containing E/O

Morphology and structure

The first properties to be investigated in NFs are diameter and morphology. It is now widely accepted that at the nanoscale, the surface-to-volume ratio is increasing, leading to new features in fibers. Furthermore, as discussed in the previous sections, one of the advantages of the electrospinning method is the regulation of the morphology of nanofibers for different purposes. For instance, random NFs are used for preparing of mats as wound dressing or aligned NFs in tissue engineering [94, 95]. Scanning electronic microscopy (SEM) is commonly used for determining the size and surface morphology of NFs [84, 85]. Besides, transmission electron microscopy (TEM) is applied to confirm the size, morphology, and core–shell structure of NFs [62, 96].

Table 6 Comparison of developed methods for loading of E/O into NFs

	E/O-blended NFs	NFs containing E/O filled in the carrier	NFs with core–shell structure
Advantages	No need for extra process	Protection of EO for evaporate	Forming regular fibers
		Requires low amounts of E/Os	Loading high amounts of E/Os into NFs
		Possibility of choosing the right carrier according to the NFs polymer	
Drawbacks	The possibility of damage to the volatile components of EO	Requires initial loading of E/Os into the carrier	Requires accessories such as special needles and extra pumps
		Carrier size limitation	
	Lack of a homogeneous mixture of polymer and E/Os	Probability of changing the morphology of NFs	Challenging in the optimization of process
	Requires high amounts of E/Os		Requires high amounts of E/O

Evaluation of E/O loaded into NFs

In the previous section, developed methods for loading of E/Os into electrospun NFs have been described. The purpose of loading E/Os is to utilize its properties as well as to take advantage of NFs simultaneously. Therefore, confirming and quantifying the amount of E/Os loaded into NFs is critical. In the reviewed articles for both parameters, few methods were presented as follows.

Qualitative confirmation The FT-IR analysis is frequently used to confirming the successful loading of E/O into the NFs. The FT-IR spectra of the E/O-loaded NFs with no-E/O-loaded NFs and free E/O are compared. By observing new peaks related to major constituents of E/O in the spectrum of NFs-E/O in comparison with the spectrum of NFs, the loading of E/O can be confirmed [70, 97]. Furthermore, by following SEM images of E/O-NFs and observing the NFs with a larger diameter in comparison with no-E/O-loaded NFs, it was concluded that E/O was loaded into the prepared NFs [64, 81].

Quantitative calculations two methods were used for determining the loaded amount of E/O into NFs: One method is based on weighting the ingredients of E/O-loaded NFs, and the other method was dependent on using analytical instruments (UV–Vis or GC–MS).

A: *Weighting method* E/O-loaded NFs were milled and dissolved in the mixture of water and ethanol (50:50) without exposure to sonicator [81, 97], and the mixture was centrifuged. After discarding the supernatant, the obtained plaque was dried. Using Eq. 1, E/O content in the NFs was calculated [97]:

$$\text{E/O content (\%)} = \frac{\text{Weight of E/O-loaded NFs} - \text{Weight of dried powder}}{\text{Weight of dried powder}} \times 100. \tag{1}$$

B: *Apparatus-dependent methods* E/O-loaded NFs were milled and dissolved in the mixture of water and ethanol (50:50) and centrifuged. In the next step, the amount of E/O in the supernatant was determined using UV–Vis or GC–MS analysis. For GC–MS analysis, the sample should be extracted by *n*-hexane. Using Eqs. (2) and (3), the E/O content and entrapment efficiency were calculated, respectively [5, 85]:

$$\text{E/O content (\%)} = \frac{\text{Weight of E/O in supernatant}}{\text{Weight of E/O-loaded NFs}} \times 100 \tag{2}$$

$$\text{Entrapment efficiency (\%)} = \frac{\text{E/O content (mg)}}{\text{Theoretical amount of primary E/O (mg)}} \times 100. \tag{3}$$

The theoretical amount of primary E/O was calculated by the feeding rate in the optimized electrospinning condition.

Release behavior

In most researches, one method with a slight difference was developed to determining released E/O from NFs. First, E/O content of NFs was determined (as described above). Then, EO-loaded NFs were added to a PBS solution. The amount of released E/O into PBS during different periods (1–15 days) was determined using UV–Vis or GC–MS analyses (described in the previous section). The release rate was calculated by Eq. (4) [64, 82]:

$$\text{Release rate } (\%) = \frac{\text{Released E/O (mg)}}{\text{E/O content (mg)}} \times 100. \tag{4}$$

Additionally, another method was reported for determining the release rate. A defined number of identical pieces of E/O-loaded NFs were placed in a petri dish and stored under constant conditions (room temperature and natural relative humidity). For the determination of the released E/O, the samples at different times were analyzed by UV–Vis or GC–MS technique, as described above. The obtained data were analyzed to determine the remaining amount of E/O in the specimens at each time point. By subtracting the remaining amount from the theoretical amount of primary E/O, the amount of released E/O is measurable [85].

Future perspectives

Most of the process of synthesis of NFs is done by the device (except the preparation of polymeric solution); thus, human error is significantly reduced. Accordingly, it is possible to repeatability and mass production of NF-based products. On the other hand, more side effects of synthetic products in the food, pharmaceutical, and health industries are revealed every day. Therefore, the use of natural products has again attracted the attention of people all over the world.

Plants and their derivatives include a variety of extracts, oils, and EOs which are excellent sources of healthy food, as well as the production of health and even pharmaceutical products. Furthermore, NFs can be made from natural polymers such as chitosan, gelatin, silk, and cellulose. As described in detail in the preceding sections, the loading of E/Os into NFs is expanding, recently. The mentioned applications for NFs containing E/Os in the articles reviewed in this study are mainly focused on antibacterial activity, wound dressing, and tissue engineering. Nevertheless, some other applications are also conceivable such as in food packaging, bed net containing green insecticides, and mosquito-repellent-impregnated clothing in areas with a high prevalence of vector-borne diseases.

The number of articles published in this field is minimal among NF-related papers. However, it is anticipated that in the coming years, products based on E/Os and NFs will be highly developed.

Conclusions

Reviewing the literature, three manners for loading of E/Os in electrospun NFs were developed, until now. Most simply, E/O was mixed with a polymer solution and then directly subjected to electrospinning for preparing E/O-blended NFs. In another manner, E/O was first loaded into the carrier and then was electrospun for the fabrication of NFs containing E/O filled in a carrier. The development of electrospun NFs containing E/O with a core–shell structure is the latest developed manner. In that manner, core and shell substrates were injected using two separate syringes connected to a blunted needle (with two distinct inner and outlet existence). Furthermore, methods for characterization of E/O-loaded NFs, including determining size and morphology, calculating loading, and release, were summarized. Due to the increasing use of E/Os in medicine as well as various products made from NFs, it seems shortly many products will be made using E/O-loaded NFs.

Acknowledgements Fasa University of Medical Sciences (Grant No. 97269) supported this study.

Compliance with ethical standards

Conflict of interest There is no conflict of interest to the authors.

References

1. Definition of Nanotechnology (2019) Iranian nano organization. http://nano.ir/page/1/561/12
2. Shirkhanloo H, Osanloo M, Ghazaghi M, Hassani H (2017) Validation of a new and cost-effective method for mercury vapor removal based on silver nanoparticles coating on micro glassy balls. Atmos Pollut Res 8(2):359–365
3. Osanloo M, Amini SM, Sedaghat MM, Amani A (2019) Larvicidal activity of chemically synthesized silver nanoparticles against *Anopheles stephensi*. J Pharm Negat Res 10(1):69–72
4. Osanloo M, Sereshti H, Sedaghat MM, Amani A (2018) Nanoemulsion of Dill essential oil as a green and potent larvicide against *Anopheles stephensi*. Environ Sci Pollut Res Int 25(7):6466–6473
5. Osanloo M, Sedaghat MM, Sereshti H, Rahmani M, Saeedi Landi F, Amani A (2019) Chitosan nanocapsules of tarragon essential oil with low cytotoxicity and long-lasting activity as a green nano-larvicide. J Nanostruct 9(4):723–735
6. Osanloo M, Sedaghat MM, Sereshti H, Amani A (2019) Nano-encapsulated tarragon (*Artemisia dracunculus*) essential oil as a sustained release nano-larvicide. J Contemp Med Sci 5(2):82–89
7. Osanloo M, Assadpour S, Mehravaran A, Abastabar M, Akhtari J (2018) Niosome-loaded antifungal drugs as an effective nanocarrier system: a mini review. Curr Med Mycol 4(4):31–36
8. Firoozi S, Amani A, Derakhshan MA, Ghanbari H (2016) Artificial neural networks modeling of electrospun polyurethane nanofibers from chloroform/methanol solution. J Nano Res 41:18–30
9. Li D, Xia Y (2004) Electrospinning of nanofibers: reinventing the wheel? Adv Mater 16(14):1151–1170
10. Peng Y, Dong Y, Fan H, Chen P, Li Z, Jiang Q (2013) Preparation of polysulfone membranes via vapor-induced phase separation and simulation of direct-contact membrane distillation by measuring hydrophobic layer thickness. Desalination 316:53–66
11. Yongquan D, Ming W, Lin C, Mingjun L (2012) Preparation, characterization of P (VDF-HFP)/[bmim] BF4 ionic liquids hybrid membranes and their pervaporation performance for ethyl acetate recovery from water. Desalination 295:53–60
12. Zhang Y, Feng Y, Huang Z, Ramakrishna S, Lim C (2006) Fabrication of porous electrospun nanofibres. Nanotechnology 17(3):901–908

13. Sahay R, Kumar PS, Sridhar R, Sundaramurthy J, Venugopal J, Mhaisalkar SG, Ramakrishna S (2012) Electrospun composite nanofibers and their multifaceted applications. J Mater Chem 22(26):12953–12971
14. Kumar PS, Sundaramurthy J, Sundarrajan S, Babu VJ, Singh G, Allakhverdiev SI, Ramakrishna S (2014) Hierarchical electrospun nanofibers for energy harvesting, production and environmental remediation. Energy Environ Sci 7(10):3192–3222
15. Li L, Peng S, Lee JKY, Ji D, Srinivasan M, Ramakrishna S (2017) Electrospun hollow nanofibers for advanced secondary batteries. Nano Energy 39:111–139
16. Zhang W, Ronca S, Mele E (2017) Electrospun nanofibres containing antimicrobial plant extracts. Nanomaterials 7(2):42
17. Almetwally AA, El-Sakhawy M, Elshakankery M, Kasem M (2017) Technology of nano-fibers: production techniques and properties-critical review. J Text Assoc 78:5–14
18. Xie Y, Kocaefe D, Chen C, Kocaefe Y (2016) Review of research on template methods in preparation of nanomaterials. J Nanomater 2016
19. Garg K, Bowlin GL (2011) Electrospinning jets and nanofibrous structures. Biomicrofluidics 5(1):13403
20. Reneker DH, Yarin AL (2008) Electrospinning jets and polymer nanofibers. Polymer 49(10):2387–2425
21. Quirós J, Boltes K, Rosal R (2016) Bioactive applications for electrospun fibers. Polym Rev 56(4):631–667
22. Ulubayram K, Calamak S, Shahbazi R, Eroglu I (2015) Nanofibers based antibacterial drug design, delivery and applications. Curr Pharm Des 21(15):1930–1943
23. Casanova MR, Reis RL, Martins A, Neves NMJOTEN, Scaffolding-Related Developments, Translation (2018) The use of electrospinning technique on osteochondral tissue engineering. Adv Exp Med Biol 1058:247–263
24. Pelipenko J, Kristl J, Janković B, Baumgartner S, Kocbek P (2013) The impact of relative humidity during electrospinning on the morphology and mechanical properties of nanofibers. Int J Pharm 456(1):125–134
25. Sill TJ, von Recum HA (2008) Electrospinning: applications in drug delivery and tissue engineering. Biomaterials 29(13):1989–2006
26. Barnes CP, Sell SA, Boland ED, Simpson DG, Bowlin GL (2007) Nanofiber technology: designing the next generation of tissue engineering scaffolds. Adv Drug Deliv Rev 59(14):1413–1433
27. Megelski S, Stephens JS, Chase DB, Rabolt JF (2002) Micro-and nanostructured surface morphology on electrospun polymer fibers. Macromolecules 35(22):8456–8466
28. Matabola K, Moutloali R (2013) The influence of electrospinning parameters on the morphology and diameter of poly (vinyledene fluoride) nanofibers-effect of sodium chloride. J Mater Sci 48(16):5475–5482
29. Wang T, Kumar S (2006) Electrospinning of polyacrylonitrile nanofibers. J Appl Polym Sci 102(2):1023–1029
30. Bae H-S, Haider A, Selim KK, Kang D-Y, Kim E-J, Kang I-K (2013) Fabrication of highly porous PMMA electrospun fibers and their application in the removal of phenol and iodine. J Polym Res 20(7):158
31. Pillay V, Dott C, Choonara YE, Tyagi C, Tomar L, Kumar P, du Toit LC, Ndesendo VM (2013) A review of the effect of processing variables on the fabrication of electrospun nanofibers for drug delivery applications. J Nanomater 2013
32. Angammana CJ, Jayaram SH (2011) Analysis of the effects of solution conductivity on electrospinning process and fiber morphology. IEEE Trans Ind Appl 47(3):1109–1117
33. Lannutti J, Reneker D, Ma T, Tomasko D, Farson D (2007) Electrospinning for tissue engineering scaffolds. Mater Sci Eng C Mater Biol Appl 27(3):504–509
34. Kenawy E-R, Bowlin GL, Mansfield K, Layman J, Simpson DG, Sanders EH, Wnek GE (2002) Release of tetracycline hydrochloride from electrospun poly (ethylene-co-vinylacetate), poly (lactic acid), and a blend. J Control Release 81(1–2):57–64
35. Lin S, Wang R-Z, Yi Y, Wang Z, Hao L-M, Wu J-H, Hu G-H, He H (2014) Facile and green fabrication of electrospun poly (vinyl alcohol) nanofibrous mats doped with narrowly dispersed silver nanoparticles. Int J Nanomed 9:3937–3947
36. Chung HJ, Park TG (2007) Surface engineered and drug releasing pre-fabricated scaffolds for tissue engineering. Adv Drug Deliv Rev 59(4–5):249–262

37. Li WJ, Laurencin CT, Caterson EJ, Tuan RS, Ko FK (2002) Electrospun nanofibrous structure: a novel scaffold for tissue engineering. J Biomed Mater Res A 60(4):613–621
38. Martins A, Pinho ED, Faria S, Pashkuleva I, Marques AP, Reis RL, Neves NM (2009) Surface modification of electrospun polycaprolactone nanofiber meshes by plasma treatment to enhance biological performance. small 5(10):1195–1206
39. Smith L, Ma P (2004) Nano-fibrous scaffolds for tissue engineering. Colloids Surf B Biointerfaces 39(3):125–131
40. Haider A, Haider S, Kang I-K (2018) A comprehensive review summarizing the effect of electrospinning parameters and potential applications of nanofibers in biomedical and biotechnology. Arab J Chem 11(8):1165–1188
41. Araujo J, Martins A, Leonor I, Pinho ED, Reis R, Neves N (2008) Surface controlled biomimetic coating of polycaprolactone nanofiber meshes to be used as bone extracellular matrix analogues. J Biomater Sci Polym Ed 19(10):1261–1278
42. da Silva MA, Crawford A, Mundy J, Martins A, Araújo JV, Hatton PV, Reis RL, Neves NM (2008) Evaluation of extracellular matrix formation in polycaprolactone and starch-compounded polycaprolactone nanofiber meshes when seeded with bovine articular chondrocytes. Tissue Eng Part A 15(2):377–385
43. Rezvani Z, Venugopal JR, Urbanska AM, Mills DK, Ramakrishna S, Mozafari M (2016) A bird's eye view on the use of electrospun nanofibrous scaffolds for bone tissue engineering: current state-of-the-art, emerging directions and future trends. Nanomedicine 12(7):2181–2200
44. Gallant-Behm CL, Yin HQ, Liu S, Heggers JP, Langford RE, Olson ME, Hart DA, Burrell RE (2005) Comparison of in vitro disc diffusion and time kill-kinetic assays for the evaluation of antimicrobial wound dressing efficacy. Wound Repair Regen 13(4):412–421
45. Jones SA, Bowler PG, Walker M, Parsons D (2004) Controlling wound bioburden with a novel silver-containing Hydrofiber® dressing. Wound Repair Regen 12(3):288–294
46. Chen J-P, Chang G-Y, Chen J-K (2008) Electrospun collagen/chitosan nanofibrous membrane as wound dressing. Colloids Surf A Physicochem Eng Asp 313:183–188
47. Khil MS, Cha DI, Kim HY, Kim IS, Bhattarai N (2003) Electrospun nanofibrous polyurethane membrane as wound dressing. J Biomed Mater Res B Appl Biomater 67(2):675–679
48. Sohrabi A, Shaibani P, Etayash H, Kaur K, Thundat T (2013) Sustained drug release and antibacterial activity of ampicillin incorporated poly (methyl methacrylate)–nylon6 core/shell nanofibers. Polymer 54(11):2699–2705
49. Gao Y, Bach Truong Y, Zhu Y, Louis Kyratzis I (2014) Electrospun antibacterial nanofibers: production, activity, and in vivo applications. J Appl Polym 131(18)
50. Bakkali F, Averbeck S, Averbeck D, Idaomar M (2008) Biological effects of essential oils–a review. Food Chem Toxicol 46(2):446–475
51. Osanloo M, Amani A, Sereshti H, Shayeghi M, Sedaghat MM (2017) Extraction and chemical composition essential oil of *Kelussia odoratissima* and comparison its larvicidal activity with Z-ligustilide (major constituent) against *Anopheles stephensi*. J Entomol Zool Stud 5(4):611–615
52. Meier MA, Metzger JO, Schubert US (2007) Plant oil renewable resources as green alternatives in polymer science. Chem Soc Rev 36(11):1788–1802
53. Kalemba D, Kunicka A (2003) Antibacterial and antifungal properties of essential oils. Curr Med Chem 10(10):813–829
54. Juteau F, Masotti V, Bessiere JM, Dherbomez M, Viano J (2002) Antibacterial and antioxidant activities of Artemisia annua essential oil. Fitoterapia 73(6):532–535
55. Osanloo M, Sedaghat MM, Esmaeili F, Amani A (2018) Larvicidal activity of essential oil of syzygium aromaticum (Clove) in com-parison with its major constituent, eugenol, against *Anopheles stephensi*. J Arthropod Borne Dis 12(4):361–369
56. Guesmi F, Prasad S, Tyagi AK, Landoulsi A (2017) Antinflammatory and anticancer effects of terpenes from oily fractions of *Teucruim alopecurus*, blocker of IkappaBalpha kinase, through down-regulation of NF-kappaB activation, potentiation of apoptosis and suppression of NF-kappaB-regulated gene expression. Biomed Pharmacother 95:1876–1885
57. Osanloo M, Amani A, Sereshti H, Abai MR, Esmaeili F, Sedaghat MM (2017) Preparation and optimization nanoemulsion of Tarragon (*Artemisia dracunculus*) essential oil as effective herbal larvicide against *Anopheles stephensi*. Ind Crops Prod 109:214–219
58. Jamil B, Abbasi R, Abbasi S, Imran M, Khan SU, Ihsan A, Javed S, Bokhari H (2016) Encapsulation of cardamom essential oil in chitosan nano-composites: in vitro efficacy on antibiotic-resistant bacterial pathogens and cytotoxicity studies. Front Microbiol 7:1580

59. Khan R, Xiangyang S, Ahmad A, Mo X (2018) Electrospinning of crude plant extracts for antibacterial and wound healing applications: a review. SM J Biomed Eng 4(1):1–8
60. Ardekani NT, Khorram M, Zomorodian K, Yazdanpanah S, Veisi H, Veisi H (2018) Evaluation of electrospun poly (vinyl alcohol)-based nanofiber mats incorporated with *Zataria multiflora* essential oil as potential wound dressing. Int J Biol Macromol 125:743–750
61. Sirc J, Kubinova S, Hobzova R, Stranska D, Kozlik P, Bosakova Z, Marekova D, Holan V, Sykova E, Michalek J (2012) Controlled gentamicin release from multi-layered electrospun nanofibrous structures of various thicknesses. Int J Nanomed 7:5315–5325
62. Zhang C, Zhang H (2018) Formation and stability of core-shell nanofibers by electrospinning of gel-like corn oil-in-water emulsions stabilized by gelatin. J Agric Food Chem 66(44):11681–11690
63. Zamani R, Pilehvar-Soltanahmadi Y, Alizadeh E, Zarghami N (2018) Macrophage repolarization using emu oil-based electrospun nanofibers: possible application in regenerative medicine. Artif Cells Nanomed Biotechnol 46(6):1258–1265
64. Lin L, Mao X, Sun Y, Rajivgandhi G, Cui H (2018) Antibacterial properties of nanofibers containing chrysanthemum essential oil and their application as beef packaging. Int J Food Microbiol 292:21–30
65. Jalilzadeh-Tabrizi S, Pilehvar-Soltanahmadi Y, Alizadeh E, Alipour S, Dadashpour M, Nejati-Koshki K, Zarghami N (2018) A biomimetic emu oil-blended electrospun nanofibrous mat for maintaining stemness of adipose tissue-derived stem cells. Biopreserv Biobank 16(2):66–76
66. Dadras Chomachayi M, Solouk A, Akbari S, Sadeghi D, Mirahmadi F, Mirzadeh H (2018) Electrospun nanofibers comprising of silk fibroin/gelatin for drug delivery applications: thyme essential oil and doxycycline monohydrate release study. J Biomed Mater Res A 106(4):1092–1103
67. Chao CY, Mani MP, Jaganathan SK (2018) Engineering electrospun multicomponent polyurethane scaffolding platform comprising grapeseed oil and honey/propolis for bone tissue regeneration. PLoS ONE 13(10):1–17
68. Ayyar M, Mani MP, Jaganathan SK, Rathanasamy R (2018) Preparation, characterization and blood compatibility assessment of a novel electrospun nanocomposite comprising polyurethane and ayurvedic-indhulekha oil for tissue engineering applications. Biomed Tech Berl 63(3):245–253
69. Pilehvar-Soltanahmadi Y, Nouri M, Martino MM, Fattahi A, Alizadeh E, Darabi M, Rahmati-Yamchi M, Zarghami N (2017) Cytoprotection, proliferation and epidermal differentiation of adipose tissue-derived stem cells on emu oil based electrospun nanofibrous mat. Exp Cell Res 357(2):192–201
70. Nejati-Koshki K, Pilehvar-Soltanahmadi Y, Alizadeh E, Ebrahimi-Kalan A, Mortazavi Y, Zarghami N (2017) Development of Emu oil-loaded PCL/collagen bioactive nanofibers for proliferation and stemness preservation of human adipose-derived stem cells: possible application in regenerative medicine. Drug Dev Ind Pharm 43(12):1978–1988
71. Liakos IL, Holban AM, Carzino R, Lauciello S, Grumezescu AM (2017) Electrospun fiber pads of cellulose acetate and essential oils with antimicrobial activity. Nanomaterials 7(4):1–10
72. Ayyar M, Mani MP, Jaganathan SK, Rathinasamy R, Khudzari AZ, Krishnasamy NP (2017) Surface, thermal and hemocompatible properties of novel single stage electrospun nanocomposites comprising polyurethane blended with bio oilTM. An Acad Bras Cienc 89(3 Suppl):2411–2422
73. Rieger KA, Birch NP, Schiffman JD (2016) Electrospinning chitosan/poly(ethylene oxide) solutions with essential oils: correlating solution rheology to nanofiber formation. Carbohydr Polym 139:131–138
74. Fazili A, Gholami S, Minaie Zangi B, Seyedjafari E, Gholami M (2016) In vivo differentiation of mesenchymal stem cells into insulin producing cells on electrospun poly-l-lactide acid scaffolds Coated with *Matricaria chamomilla* L. Oil. Cell J 18(3):310–321
75. Bonan RF, Bonan PR, Batista AU, Sampaio FC, Albuquerque AJ, Moraes MC, Mattoso LH, Glenn GM, Medeiros ES, Oliveira JE (2015) In vitro antimicrobial activity of solution blow spun poly(lactic acid)/polyvinylpyrrolidone nanofibers loaded with Copaiba (*Copaifera* sp.) oil. Mater Sci Eng C 48:372–377
76. Rieger KA, Schiffman JD (2014) Electrospinning an essential oil: cinnamaldehyde enhances the antimicrobial efficacy of chitosan/poly(ethylene oxide) nanofibers. Carbohydr Polym 113:561–568
77. Amna T, Hassan MS, Yang J, Khil MS, Song KD, Oh JD, Hwang I (2014) Virgin olive oil blended polyurethane micro/nanofibers ornamented with copper oxide nanocrystals for biomedical applications. Int J Nanomed 9:891–898
78. Kim JR, Kim SH (2017) Eco-friendly acaricidal effects of nylon 66 nanofibers via grafted clove bud oil-loaded capsules on house dust mites. Nanomaterials 7(7):1–14

79. Ge L, Zhao Y-s, Mo T, Li J-r, Li P (2012) Immobilization of glucose oxidase in electrospun nanofibrous membranes for food preservation. Food Control 26(1):188–193
80. Lin L, Dai Y, Cui H (2017) Antibacterial poly(ethylene oxide) electrospun nanofibers containing cinnamon essential oil/beta-cyclodextrin proteoliposomes. Carbohydr Polym 178:131–140
81. Cui H, Bai M, Rashed MMA, Lin L (2018) The antibacterial activity of clove oil/chitosan nanoparticles embedded gelatin nanofibers against Escherichia coli O157:H7 biofilms on cucumber. Int J Food Microbiol 266:69–78
82. Cui H, Bai M, Lin L (2018) Plasma-treated poly(ethylene oxide) nanofibers containing tea tree oil/beta-cyclodextrin inclusion complex for antibacterial packaging. Carbohydr Polym 179:360–369
83. Dias Antunes M, da Silva Dannenberg G, Fiorentini AM, Pinto VZ, Lim LT, da Rosa Zavareze E, Dias ARG (2017) Antimicrobial electrospun ultrafine fibers from zein containing eucalyptus essential oil/cyclodextrin inclusion complex. Int J Biol Macromol 104(Pt A):874–882
84. Wen P, Zhu DH, Feng K, Liu FJ, Lou WY, Li N, Zong MH, Wu H (2016) Fabrication of electrospun polylactic acid nanofilm incorporating cinnamon essential oil/beta-cyclodextrin inclusion complex for antimicrobial packaging. Food Chem 196:996–1004
85. Tonglairoum P, Chuchote T, Ngawhirunpat T, Rojanarata T, Opanasopit P (2014) Encapsulation of plai oil/2-hydroxypropyl-beta-cyclodextrin inclusion complexes in polyvinylpyrrolidone (PVP) electrospun nanofibers for topical application. Pharm Dev Technol 19(4):430–437
86. Irene B, Veronica A, Laura A, Cosimo C (2014) A hyperbranched polyester as antinucleating agent for Artemisinin in electrospun nanofibers. Eur Polym J 60:145–152
87. Li F, Zhao Y, Song Y (2010) Core-shell nanofibers: nano channel and capsule by coaxial electrospinning. In: Nanofibers, IntechOpen
88. Yao ZC, Chen SC, Ahmad Z, Huang J, Chang MW, Li JS (2017) Essential oil bioactive fibrous membranes prepared via coaxial electrospinning. J Food Sci 82(6):1412–1422
89. Wang C, Yan K-W, Lin Y-D, Hsieh PC (2010) Biodegradable core/shell fibers by coaxial electrospinning: processing, fiber characterization, and its application in sustained drug release. Macromolecules 43(15):6389–6397
90. Díaz JE, Barrero A, Márquez M, Loscertales IG (2006) Controlled encapsulation of hydrophobic liquids in hydrophilic polymer nanofibers by co-electrospinning. Adv Funct Mater 16(16):2110–2116
91. Yu JH, Fridrikh SV, Rutledge GC (2004) Production of submicrometer diameter fibers by two-fluid electrospinning. Adv Mater 16(17):1562–1566
92. Nguyen TTT, Ghosh C, Hwang S-G, Chanunpanich N, Park JS (2012) Porous core/sheath composite nanofibers fabricated by coaxial electrospinning as a potential mat for drug release system. Int J Pharm 439(1–2):296–306
93. Xia X, Wang X, Zhou H, Niu X, Xue L, Zhang X, Wei Q (2014) The effects of electrospinning parameters on coaxial Sn/C nanofibers: morphology and lithium storage performance. Electrochim Acta 121:345–351
94. Rieger KA, Birch NP, Schiffman JD (2013) Designing electrospun nanofiber mats to promote wound healing–a review. J Mater Chem B 1(36):4531–4541
95. Gui X, Hu J, Han Y (2019) Random and aligned electrospun gelatin nanofiber mats for human mesenchymal stem cells. Mater Res Innov 23(4):208–215
96. Sfakis L, Sharikova A, Tuschel D, Costa FX, Larsen M, Khmaladze A, Castracane J (2017) Core/shell nanofiber characterization by Raman scanning microscopy. Biomed Optics Express 8(2):1025–1035
97. Ghayempour S, Montazer M (2019) A novel controlled release system based on Tragacanth nanofibers loaded Peppermint oil. Carbohydr Polym 205:589–595