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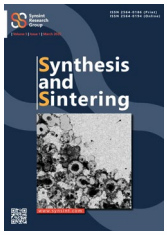

Review article

Advances in electrospinning techniques for synthesis of nanofibers loaded with herbal extracts and natural ingredients: A comprehensive review

Rashid Forouzande [a], **Ali Akbar Gharehaghaji** [a,*], **Dina Mohammadi** [b]

[a] *Department of Textile Engineering, Amirkabir University of Technology, Hafez Ave., Tehran 159163-4311, Iran*
[b] *Department of Mechanics and Industries, Qazvin Branch, Islamic Azad University, Qazvin, Iran*

A B S T R A C T

Electrospinning offers a versatile method for synthesizing polymeric nanofibers integrated with natural compounds such as medicinal extracts, antibacterial agents, and antioxidants (e.g., Aloe vera, honey, curcumin). These composite fibers exhibit diverse potential applications spanning wound dressing, tissue engineering, drug delivery, and the food industry. Tailoring nanofiber morphologies and loading techniques enables modulation of release kinetics and controlled diffusion of extracts tailored to specific applications. Recent literature showcases an array of studies exploring the electrospinning of various polymers, including natural ingredients, for biomedical and industrial purposes. This article aims to compile and review methodologies for combining and encapsulating natural extracts within polymers via electrospinning synthesis method, alongside their applications. Our review presents a comprehensive analysis of electrospun nanofibers containing extracts and natural ingredients, encompassing their architectural diversity and factors influencing release kinetics. As more people become interested in natural materials, we expect to see a huge increase in research efforts in this field in the years to come.

KEYWORDS

Electrospinning
Synthesis
Nanofibers
Natural extract
Drug loading
Release rate

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1. Introduction

These days, the advancement of nanotechnology and nanofibers has enhanced in the bioavailability of these bioactive chemicals. This has also contributed to the advancement of convenient, safe, and efficient drug delivery methods as well as tissue engineering [1]. Several manufacturing methods are developed for synthesizing nanofibers such as physical and chemical vapor deposition [2], self-assembly [3], stretching [4], solvent casting [5], template synthesis [6], phase separation [7], force spinning [8], electrochemical deposition [9], freeze-drying [10], laser ablation [11], dry-wet spinning [12], solution blowing [13], and electrospinning [14]. One of these methods, i.e., electrospinning, a branch of electrohydrodynamic atomization (EHDA), is a very straightforward procedure, inexpensive, highly reproducible, efficient, and uses a variety of raw materials. By optimizing its processing parameters, continuous nanofibers with sizes ranging from microns to nanometers can be produced.

Polymeric materials, both natural and synthetic, are essential to the manufacturing process (Fig. 1). They ascertain the efficacy and mode of action of herbal medicines. The majority of natural polymers are non-toxic, biocompatible, appropriately biodegradable, and adaptable. Its extracellular matrix (ECM)-like characteristics, which encourage cell proliferation and adhesion, demonstrate its versatility. To create the optimal environment for the growth and proliferation of cells, it can also be utilized in the scaffold-building process. They do, however, have certain drawbacks, including the potential for pathogen

* Corresponding author. *E-mail address:* aghaji@aut.ac.ir (A.A. Gharehaghaji)
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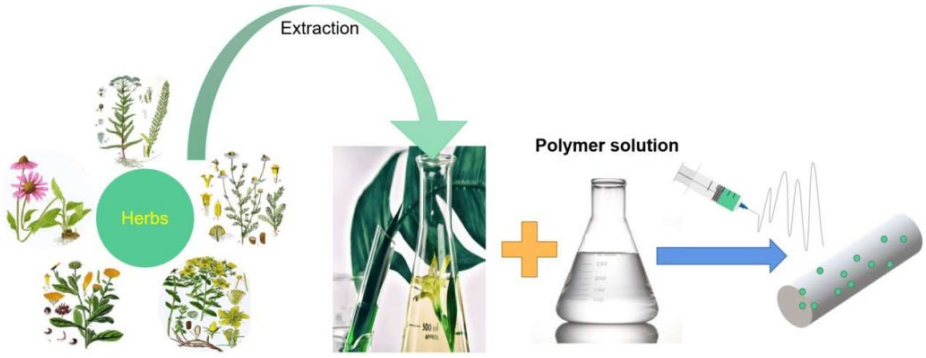

Fig. 1. Schematic overview of extract-loaded electrospun nanofibers (ELENs) fabrication methodology.

contamination, uncontrollably quick breakdown, and poor mechanical behavior. Some biologically inspired synthetic polymers have been explored as potential solutions to these issues because of their consistent quality, adaptability during synthesis, processing, and modification, and high in vivo mechanical stability.

To provide controllability and target delivery capabilities, these synthetic biological polymers are coated. Therefore, by preserving the biological characteristics of natural polymers to offer good durability, mechanical behavior, and controlled biodegradability, a mixture of natural and biological synthetic polymers can enable improved proliferation and cell adhesion [15].

Herbs are also commonly utilized in traditional Indian medicine (Ayurveda, Unani, Xida), Chinese medicine (TCM), Korean medicine, Japanese Kampo, and other traditional medical practices. For hundreds or possibly thousands of years, people have used it [16, 17]. Herbal medicine comprises several components that can play a multi-target synergistic effect, in contrast to synthetic medications that are delivered and treated using a "one disease, one target, and one drug" approach [18]. Traditional herbal remedies mostly contain saponins, phenols, alkaloids, terpenoids, tannins, and flavonoids as their bioactive ingredients. Their actions include immunological modulation, tissue regeneration, analgesic, antibacterial, antiviral, anti-inflammatory, antioxidant, and anti-tumor [19].

Humans have utilized natural resources such as plants, animals, microorganisms, and aquatic organisms in medicine since ancient times to treat diseases. Due to plants' exceptional effects on various illnesses, treating patients with herbal medicines has remained a traditional practice [20].

Additionally, growing concerns over the health risks posed by synthetic compounds in cosmetics, pharmaceuticals, and the food industry, coupled with the rise of antibiotic-resistant pathogens, have driven recent advancements in electrospinning research. These developments have focused on creating nanofibers infused with natural extracts and ingredients, offering safer and more sustainable alternatives for various applications [21]. Indeed, plants contain various chemical compounds with antimicrobial [22] and antioxidant [23] properties, such as thymol, carvacrol, ferulic acid, etc.

According to Fig. 2, we looked up the quantity and trends of papers published on the SCOPUS over the previous years on the topics of "Herbal AND Medicine" (Fig. 2a) and "Electrospinning AND Herbal" (Fig. 2b). Research on herbal medicine has reached thousands. Nonetheless, there aren't many studies on "electrospinning AND herbal" in total. In comparison to other years, the quantity of publications has steadily increased since the new coronavirus epidemic broke out. This demonstrates that single compounds are no longer the only drugs that can be delivered using electrostatic spinning technology [15]. The goal of this review is to examine the most recent developments in applications, i.e., drug delivery systems (DDSs), wound healing (WHL), tissue regeneration, and food packaging using electrospun herbal medicine nanofibers. We talk about the development of various polymer materials and electrospinning technology for the encapsulation of herbal medication.

In other words, much research on electrospinning with extracts and natural ingredients has been conducted in recent years, owing to their multiple benefits and applications. Due to the processability of electrospinning and the variety of natural materials that possess beneficial properties for different applications, it is expected that more extensive research will be conducted in this field in the coming years. This review aims to provide an integrated and comprehensive overview of the work performed in this area, focusing on applications.

2. Electrospinning

Through modifying solvents, polymers, or additives like surfactants and cross-linking agents, the electrospinning (ES) method can be applied to create morphologically controlled single-layer (SL) or multi-layer (ML) fibers (1 to 3D or complex (nano-)structures) at the micron (µm) and nano scales (nm) [24, 25].

In addition, heat generation during the electrospinning process is avoided, which is crucial for preserving the structural elements of bioactive compounds during application [26]. One advantage of electrospinning for nanofiber manufacture is its simplicity, easy scalability, low cost, flexibility concerning various materials and operations, as well as high efficiency [27].

During the electrospinning process, a high-voltage electrical field is utilized to generate a charged liquid jet from the surface of a polymer solution, overcoming its viscosity. A high-voltage power supply creates a strong electric field between the needle and the metal collector. When the electric field is applied, the spinning solution (which can be a solution, melt, or suspension) [28] is drawn through the needle at a controlled flow rate, producing micro- or nanofibers that are randomly deposited onto the grounded collector [29]. The standard electrospinning setup typically consists of five main components (Fig. 3) [15].

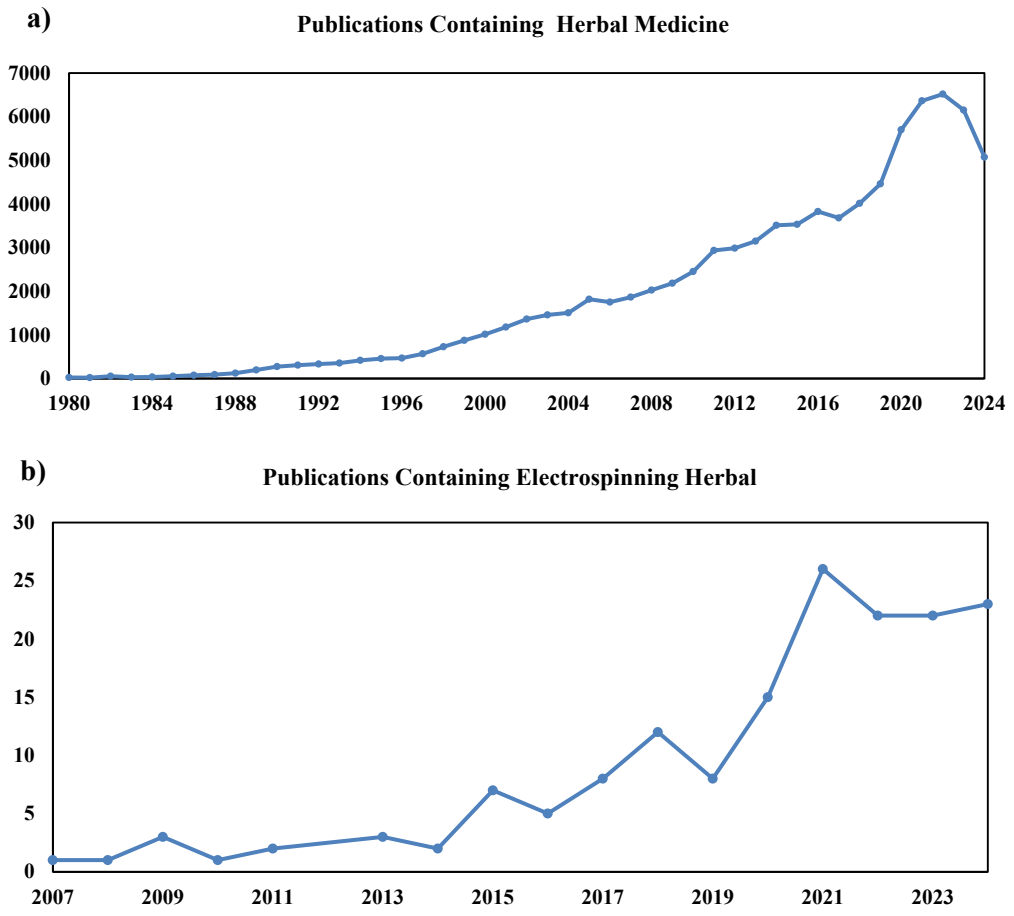

Fig. 2. Publications containing a) herbal Medicine and b) electrospinning herbal materials keywords.

The electrospinning setup typically includes five key components: (1) a high-voltage power supply (HVPS); (2) an injection pump to regulate the flow of the working fluid; (3) syringes containing the polymer solution; (4) a metal spinning needle (which can be single or structured); and (5) a fiber collector. The core principle of this technology involves applying a high voltage through a conductive needle. The HVPS, controlled by the injection pump, generates an electrostatic force that acts on the spinning solution as it moves from

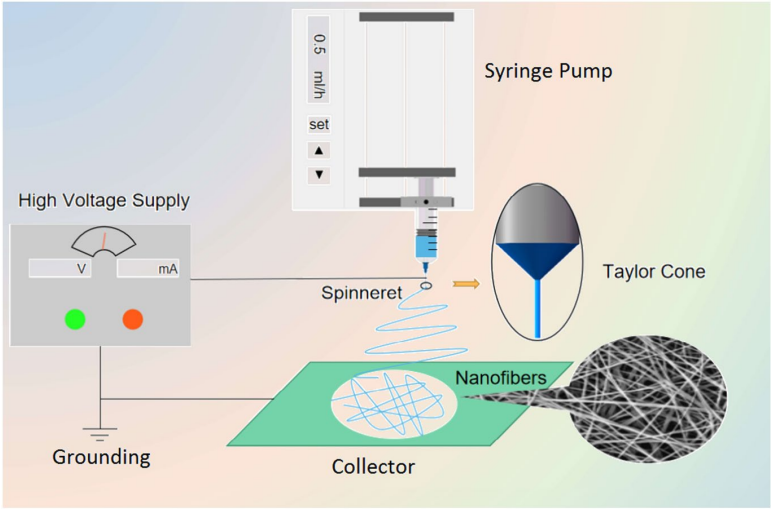

Fig. 3. Schematic illustration of electrospinning device [15].

the syringe to the needle. This electrostatic force, along with other forces and charges acting on the solution, overcomes the fluid's surface tension, causing the spinning droplets to form a "Taylor cone" at the needle's tip [15].

When the electrostatic force exceeds the critical surface tension of the conical droplets, a jet is ejected. Simultaneously, the volatile solvent in the spinning solution evaporates (a drying process), and long, thin filaments are ejected from the tip. These filaments solidify and are deposited onto the grounded collector, forming uniform nanofibers [26, 30].

Flexibility, small fiber diameter, high porosity, high surface area, and ease of functionalization are the attributes of electrospun nanofibers. High encapsulation efficiency, biodegradability, high mechanical characteristics, biocompatibility, low toxicity, sustained release properties, and structural resemblance to the extracellular environment of tissues are among the attributes of nanofibers made of natural and synthetic polymers. Certain protein production in cells as well as other biochemical and biological activities necessary for normal tissue growth can be supported by these characteristics [31]. As a result, electrospun fibers are now top choices for a wide range of uses, including biomedicine [32–35], biosensors [36–38], cosmetics [39], water treatment [40–43], filtration [44], and food packaging [45, 46].

3. Synthesis of nanofibers via electrospinning

Nanofibers play a significant role in targeted medical therapies due to their exceptional encapsulation capabilities, which enable them to protect and deliver a variety of bioactive agents. These include antibacterial, anti-inflammatory, anticancer, and antioxidant drugs (used in both traditional Chinese and Western medicine), as well as bioactive compounds (such as extracts), DNA, small molecules, growth factors, proteins, and more [14, 47, 48]. Additionally, the physical and chemical properties of nanofibers—such as density, hydrophilicity, and fiber diameter—can be tailored by modifying their composition, for instance, by blending different natural or synthetic polymers. This flexibility allows for the controlled release of active substances, either gradually or rapidly, depending on the desired application [24, 29].

Since they can motivate cell migration, adhesion, differentiation, and proliferation, waste can be diffused from the cell structure. This allows the drug molecules to spread more readily from the matrix to achieve effective WHL, cell respiration, exudate to diffuse, and gas to permeate. This makes them appropriate for the development of dressings and tissue scaffolds for WHL. Furthermore, they increase tissue regeneration, keep wounds from drying out, and control wound moisture [49, 50]. By forming a three-dimensional extracellular matrix, nanofibers can serve as suitable scaffolds to encourage cell attachment and growth, thereby enhancing damaged tissue and restoring organ function [51]. According to certain research, nanofibers can be employed for various tissue regeneration [52] applications such as skin regeneration, neuronal repair [53], and bone transplantation [54].

The list of polymers that can be electrospun is available elsewhere [55]. Numerous factors impact the electrospinning procedure, such as ambient parameters, processing parameters (i.e., flow rate, voltage, distance between needle tip and collector, type of collector), and solution parameters (i.e., surface charge density, solvent dielectric property, concentration, surface tension, molecular weight, and solution viscosity). The differences in the morphology and diameters of the nanofibers generated by electrospinning are caused by these characteristics [56]. For example, it has been discovered that the ideal spinning viscosities lie between 1 and 200 poise roughly, whereas consistent nanofibers can be formed at viscosity levels between 1 and 20 [57]. Additionally, the flow rate of the solution to be electrospun has a significant impact on the geometry, diameter, and porosity of the electrospun nanofiber [55].

4. Challenges and limitations of synthetic polymers

It is worth noting to pay attention to the existing limitations of synthetic polymers, which highlights the application of natural polymers in the nanofiber production field. It can be said that the most important challenges of synthetic polymers include environmental impact, biocompatibility concerns, production challenges, and recycling and end-of-life issues.

4.1. Environmental impact

It is reported that, although synthetic polymers, e.g., PCL (polycaprolactone) and PLA (polylactic acid), are biodegradable, they are often derived from fossil fuels or require energy-intensive production processes. This reduces their sustainability credentials [58, 59]. Also, it is said that PCL degrades over 1–2 years in vivo, which can lead to environmental persistence [59].

4.2. Biocompatibility concerns

The existence of residual solvents or monomers in synthetic polymers like polyvinylpyrrolidone (PVP) can cause cytotoxicity. This limits their application in biomedical applications [60]. Also, hydrophobic synthetic polymers like PLA show poor cell adhesion in comparison with natural polymers. This necessitates surface modifications for tissue engineering [60].

4.3. Production challenges

It is known that synthetic polymers are sensitive to processing parameters like humidity and voltage. This complicates their scalability and reproducibility [61].

Table 1 shows the molecular weight ranges, fundamental properties, and process-specific roles of synthetic polymers including polyethylene oxide (PEO), PVP, polylactic acid (PLA), and polycaprolactone (PCL), which are widely used in electrospinning. It highlights how variations in molecular weight and intrinsic characteristics affect the mechanical performance, fiber morphology, and application suitability.

5. Challenges and limitations of natural extracts

Natural extracts often suffer from instability due to oxidation, as well as pH and temperature sensitivity, which can affect their shelf life and bioactivity. Moreover, since variations in extraction conditions and raw material composition can lead to inconsistencies, it is required to use an optimized method to ensure cost-effectiveness and reproducibility. Also, the solubility of natural extracts in the polymer is a vital step in nanofiber production. However, several natural extracts are insoluble or poorly soluble in common solvents used for electrospinning [61, 65, 66].

From the mechanical properties point of view, natural extracts often lack the mechanical strength needed for nanofiber applications,

Table 1. Chemical properties and electrospinning impacts of common auxiliary polymers.

Polymer	Molecular weight (kDa)	Key properties	Impact on electrospinning	Ref.
PEO	100–8,000	High hydrophilicity, water solubility	Lower MW reduces viscosity, enabling thinner fibers; higher MW improves mechanical strength but risks nozzle clogging	[62, 63]
PVP	10–1,300	Amorphous structure, tunable solubility	Low MW (<50 kDa) enhances conductivity for uniform fibers; high MW (>1,000 kDa) stabilizes natural extract emulsions	[60, 63]
PLA	50–300	Semi-crystalline, hydrophobic	High MW (>150 kDa) increases tensile strength but reduces degradation rate, limiting controlled release applications	[59]
PCL	20–80	Low T_g (~ -60 to -65 °C), slow degradation	Moderate MW balances flexibility and processability for potential sustained drug delivery	[60, 64]

incorporation of natural extracts in nanofibers can alter the surface tension and viscosity of the polymer solution. This leads to challenges in controlling fiber morphology and diameter. Therefore, addressing these aspects provides a more balanced perspective and highlights the practical limitations that need further research [61, 65, 66].

6. Extract-loaded electrospun nanofibers (ELENs)

Many plant raw materials can be utilized to treat wounds; the most commonly used raw material is Aloe vera (AlVer) [67], Centella asiatica [68], and Calendula officinalis [69]. The anti-inflammatory characteristics of plant-based raw materials are linked to polyphenols and other particular classes of secondary metabolites. Extracts from Calendulae flos have been shown in numerous in vitro and in vivo investigations to have positive effects on WHL. According to the investigations, the extracts promote angiogenesis, slow down the deterioration of collagen, and boost the migration and proliferation of keratinocytes and human fibroblasts [70, 71]. Aside from its suggested application in wound care, some extracts have pharmacological qualities that include antioxidant and anti-inflammatory qualities, as well as antiviral, antibacterial, and antifungal qualities against a variety of pathogens like Staphylococcus aureus and Bacillus subtilis.

Several attempts have been made to develop novel nanofiber-based extract/drug delivery methods for WHL. Hydrogels based on chitosan (CH) [69], polyvinyl alcohol (PVA) [72], and polyacrylamide [73] have all been studied. Furthermore, PCL has generated a promising substrate for a range of applications, including WHL nanofibers, because of its distinct structural properties, slow biodegradation attributes, and biocompatibility [74]. It was discovered that the PCL/gelatin and PCL/gum arabic nanocomposite scaffolds were suitable for the proliferation of fibroblast cells [75]. PVA/sodium alginate (SAlg)-containing nanofibers were found to adhere to the inflammatory site properly and have good release kinetics of active chemicals. Active chemicals are first released, and their concentrations are guaranteed by the release profile [76].

Extract-loaded electrospun nanofibers are innovative materials designed for controlled release and targeted delivery of bioactive compounds. These nanofibers are created through the electrospinning process, which involves putting a polymer solution in the presence of a strong electric field mixed with specific extracts, e.g., medicinal plant extracts. The resulting fibers are ultra-thin, with diameters ranging from nm to μm, and exhibit an improved ratio of surface area to volume, which increases the efficiency of encapsulation and bioavailability of the loaded extracts. These nanofibers have diverse applications, i.e., tissue engineering, drug delivery, and WHL, due to their ability to provide sustained release, protect sensitive bioactives from degradation, and adhere closely to biological tissues. Their unique properties make them a promising tool in advancing medical treatments and enhancing the effectiveness of therapeutic agents [77].

7. Release mechanisms of ELENs

The release mechanism in extract-loaded electrospun nanofibers is governed by several factors, i.e., the nature of the polymer matrix, the characteristics of the loaded extract, and environmental conditions. The key mechanisms are listed as follows:

- Diffusion: The most common release mechanism in nanofibers is diffusion. In this mechanism, the extract molecules migrate from the nanofiber matrix to the surrounding environment. This process is driven by the concentration gradient between the nanofibers as well as the external medium.
- Degradation: In biodegradable polymers, the breakdown of the polymer matrix can facilitate the release of the encapsulated extract. As the polymer degrades, the extract is gradually released. The rate of degradation can be influenced by factors such as temperature, pH, and the presence of enzymes.
- Swelling: Some polymers absorb water and swell. This process creates pores and channels through which the extract can diffuse out. The extent of swelling and the pore size can affect the release rate.
- Erosion: Physical erosion of the nanofibers can also contribute to the release mechanism. As the fibers erode, either through dissolution or mechanical action, the encapsulated extract is released.
- Burst release: At the beginning, there may be an initial burst release of the extract present on or near the surface of the nanofibers. Subsequently, a slower and more regulated release occurs from the inner layers of the fibers.

It should be noted that the overall release profile of the release mechanism is typically a combination of the mentioned mechanisms. This can be tailored by adjusting the fiber morphology, polymer composition, and processing conditions during electrospinning. This versatility allows for the design of nanofiber systems with specific release characteristics suitable for various applications, such as DDSs, WHL, and tissue engineering [78–80].

8. Applications of ELENs

8.1. ELENs for wound healing and antibacterial application

Nanofibers are suitable for WHL since their nano-dimensions are close to those of native extracellular matrix elements. Moreover, their fibrillar arrangement emulates the native extracellular matrix, providing vital cues for cellular survival and organization [81]. Electrospun scaffolds offer many benefits over conventional wound dressings, including high absorption of wound secretions, physical defense of injured tissue, effective exchange of gases and nutrients to strengthen cells, and the ability to release usable molecules [82]. In this section, current studies on the electrospinning of nanofibers with natural extracts for WHL and antibacterial are discussed.

8.1.1. Achillea lycaonica

Cam et al. [81] successfully loaded different concentrations of Achillea Lycaonia extract on PLA nanofiber mats using the electrospinning technique. They showed that the addition of plant extracts decreased the diameter of electrospun nanofibers. This could be due to increased electrical conductivity. The nanofiber containing 0.500 wt% of Achillea Lycaonia showed the lowest fiber average diameter (571.89 nm). They demonstrated that nanofibers are non-cytotoxic, have excellent cell compatibility, and improve cell viability. They also reported that Achillea Lycaonia had sustained release at concentrations of 0.125 and 0.250 wt%, but burst release at a concentration of 0.500 wt% in 24 hours. They concluded that PLA nanofibers containing Achillea Lycaonia have exciting potential for cell proliferation, resulting in rapid and improved WHL.

8.1.2. Aloe vera

Uslu et al. [83, 84] fabricated electrospun nanofibers using PVA/PVP/PEG/PAA. They investigated the effect of adding AlVer on the structure and morphology of nanofibers. Their results exhibited that the diameter of fibers was reduced by adding AlVer. Inserting AlVer resulted in the creation of finer fibers with no beading, according to SEM micrographs. This beadless structure can result in increased porosity, allowing moisture and oxygen to penetrate the wound more easily. This is important for the healing and treatment process. They concluded that the AlVer-containing fibers are good candidates for applications in wound dressing regarding the creation of an intermingled porous fiber structure. In another study, ciprofloxacin HCl and AlVer-containing PVA/PAA nanofibers were fabricated [85]. It was found that nanofibers had a porous structure. Marya and Deva [86] developed electrospun nanofibers for wound dressing using a mixture of AlVer extract and PCL. They discovered that the hydrophilicity of the mats assisted HDF cell proliferation. The integrity of the mats was maintained up to the 5^{th} day. This is an optimal necessity for wound dressing, according to the deterioration reports. Other researchers discovered that, in the long run, in comparison to PCL/collagen scaffolds, the PCL-Aloe vera 10 wt% scaffolds are better scaffolds for tissue engineering because of their natural origin, low cost, and water retention capabilities—properties that are often anticipated for wounds with mild to moderate exudate [87].

Somewhere else, it is also found that PLACL-silk fibroin-AlVer scaffolds would show better tissue engineering scaffold characteristics in the long run than collagen/gelatin-based scaffolds due to their lower cost and higher mechanical properties—usually needed for dermal demands [88]. Garcia-Oruea et al. [89] in their study produced AlVer emulsified into polylactic-co-glycolic acid (PLGA) to create a nanofibrous dressing filled with recombinant human Epidermal Growth Factor. The obtained membranes were uniform with diameter, porosity, and thickness of 356.03 nm, 87.52%, and 45.92 mm, respectively. These findings suggested that PLGA-AlVer- Epidermal Growth Factor (EGF) nanofibers containing a high concentration of AlVer are promising candidates for treating chronic wounds. AlVer nanofibers with PVA were successfully developed in another work [90].

According to the findings, in the first hour, at least 60% of the AlVer in the electrospun nanofibrous matrix of PVA is released, and in the next two to four hours, the remaining 90% is released into the phosphate buffer solution. It is demonstrated that there is some variation in the release time based on the diameter of the nanofibers. In a different study, asymmetric membranes composed of PCL, AlVer, PEO, and CH, were produced via the electrospinning technique [91].

The inclusion of AlVer in a CH-PEO nanofiber system allowed the development of a bottom layer that can supply sufficient moisture at the wound position while also supporting faster and better fibroblast attachment and propagation. According to Jouybar et al.'s investigation, [92] a nanofibrous poly-L-lactic acid (PLLA) scaffold covered by AlVer gel is good for WHL and skin regenerative medicine. In another study, Erythropoietin/AlVer released in PVA/CH was developed as a wound dressing for treating full-thickness excisional wounds [93]. The developed dressing demonstrated no toxicity toward L929 cells and was capable of releasing AlVer and erythropoietin over periods of at least one day and seven days, respectively. Another research used electrospinning to effectively fabricate core-sheath nanofibrous structures of Silk Fibroin-PVA-AlVer containing various quantities of Vitamin E-loaded in starch nanoparticles [94]. It has been reported that Vitamin E-loaded in starch nanoparticles can be successfully loaded inside uniform Silk Fibroin-PVA-AlVer nanofibers. Additionally, the researchers discovered that applying AlVer and vitamin E to silk fibroin-PVA nanofibers increases cellular viability and cell-matrix interaction and that the dressing could be used to heal skin wounds. Ezhilarasu et al. [95] confirmed that tetracycline hydrochloride-loaded PCL/AlVer mats exhibited high biological and physical characteristics for topically delivering bioactive drugs to enhance wound treatment. Researchers have stated that a nanofibrous membrane synthesized by PLGA-AlVer-lipid nanoparticles may be a potential method for treating chronic wounds [49]. Bootdee and Nithitanakul [96] developed a nanosphere/nanofiber complex made of PVA/AlVer/PLGA with the ability to slow protein release and antibacterial properties for wound dressing. Another study used the electrospinning process to successfully synthesize PVP composites of AlVer and AlVer acetate [97]. The obtained results revealed the PVP mat structure, which supplies oxygen and moisture permeability, all of which are critical for WHL. Nevertheless, nanopores hindered bacteria from infiltrating. Zinc oxide nanoparticles and AlVer electrospun nanofibers incorporating zein/PCL/collagen were successfully synthesized using the electrospinning technique for WHL applications [98].

Somewhere else, it is shown that the variation in the distribution and amount of layers of the system significantly affects AlVer (rich with alloin) release kinetics [79]. The multilayer device provides continuous AlVer (rich with alloin) release, while the burst release is primarily detected in the monolayer structure. Also, the researchers demonstrated that attaching PVA nanofibers to AlVer-containing CH films can

compensate for the loss of integrity resulting from the addition of AlVer while also increasing the water absorption potential owing to PVA's hydrophilic nature. This makes it a highly cost-effective substrate for WHL applications [99]. Yin and Xu [100] have shown how to make large amounts of PCL/CH/AlVer nanofiber membranes using a sloped free surface electrospinning unit. Their findings showed that sloping free surface electrospinning could produce high-quality PCL/CH/AlVer nanofiber membranes in batches, with a yield of PCL/CH/AlVer nanofiber membranes that was 10 times higher than single-needle electrospinning. The fabricated nanofiber membranes also had outstanding antibacterial efficiency and biocompatibility, making them ideal for wound dressings. Another study used the coaxial electrospinning technique to create core-shell electrospun fibers containing medicinal herbs (AlVer extract) for WHL [101]. The core is made of PEO and AlVer, and the shell is made of PCL, CH, and keratin. It is shown that on the core-shell structure, there was improved cell adhesion. Guleken et al. [102] demonstrated that nanofibers made of gelatin and PCL along with AlVer and Hypericum perforatum oil can be used as a viable substitute for surgical diabetic WHL. They also showed that Hypericum perforatum oil is better for biological applications. A new core-shell nanofiber mat was created, consisting of gelatin/PVA as the core and AlVer/arabinose/PVP as the shell, designed to promote the healing of bacteria-infected wounds in a sample [103]. Pathalamuthu et al. [104] created a novel mechanical Spirograph-based system for an electrospinning collector and showed that it generates nanofibrous mat CH and polyethylene oxide with AlVer plant extract with almost homogenous characteristics, which is ideal for wound treatment.

8.1.3. Astragaloside

Researchers found that an astragaloside-loaded silk fibroin/gelatin nanofibrous dressing can improve cell adhesion and proliferation while being biocompatible and ideal for burn wounds [105, 106].

8.1.4. Azadirachta indica (neem)

Ali et al. [107, 108] developed a PVA-neem blend nanofiber and PVA-neem-CH nanofibrous mat using a layer by layer electrospinning technique under optimal processing conditions, which provides bacterial protection against S. aureus bacteria that can be applied as a wound dressing material that is biodegradable, bio-based, and antibacterial.

8.1.5. Baicalein

In a study, researchers used an electrospinning technique to create Silk fibroin/baicalein and Silk fibroin/PVP/baicalein nonwoven mats that were highly biocompatible with skin cells, highly antibacterial against skin natural flora like S. aureus, as well as high anti-inflammatory to suppress nitrite formation. They discovered that the Silk fibroin/PVP/baicalein nonwoven mat had a slower drug release rate than the one without the PVP co-incorporation [109]. In another research, an innovative antioxidant and antibacterial material was developed by incorporating the baicalein-hydroxypropyl-cyclodextrin inclusion complex into PVA nanofibers [110]. The antioxidant activities of the nanofibers improved as the baicalein content increased, and the inhibition area of the PVA-baicalein-hydroxypropyl—cyclodextrin nanofiber was wider than the inhibition region of the PVA-baicalein nanofiber.

8.1.6. Catechin

Nontoxic natural catechin can be electrospun with PCL, and a water-soluble eggshell membrane is inserted into the obtained PCL/catechin nanofibers via hydrogen bonding as a wound dressing in the medical field [111]. Catechin content affects the fiber formation uniformity, and that catechin and water-soluble eggshell membrane increases PCL nanofiber wettability. Certain concentrations of the naturally occurring polyphenolic antioxidant catechin are present in PLGA bicomponent fibers.

Ghitescu et al. synthesized catechin as the core and PLGA as the fiber sheath for WHL [112]. In vitro studies of catechin release experiments revealed a burst release at first. A linear delivery was observed over time, owing to a diffusion-controlled mechanism.

8.1.7. Biophytum sensitivum

Namboodiri and Parameswaran synthesized an antibacterial nanofibrous wound dressing via PCL and crude extract of biophytum sensitivum [113]. The crude extract was fully incorporated into the fibers. The medicine was fully incorporated into the fibers and in the total immersion method, more than 40% of the drug was released.

8.1.8. Bromelain

Using PVA/gelatin in the shell and PCL containing salvianolic acid B and bromelain in the core, a biomimetic core-shell nanofiber scaffold can be successfully created that has the versatility to release two chemicals in a sustained and rapid pattern for WHL [114].

On the wound model of full-thickness rat skin, rapid in vivo WHL was observed using a burst release of bromelain and a gradual release of salvianolic acid B. Another study used the electrospinning approach to create CH-bromelain nanofiber formulations [115]. This method can be recommended as a viable system for treating burns in humans based on adequate findings on burn injuries in animal models and strong properties in drug release studies. Due to their high surface area, non-toxic properties, strong absorbency, and effective enzyme release capabilities, electrospun nanofibers made from cellulose triacetate derived from sugarcane bagasse and blended with cellulose acetate show potential for immobilizing bromelain, making them suitable for biomedical applications [116].

8.1.9. Eremanthus

In a study by Mori, nanofibers made from PLA and candeia (Eremanthus erythropappus) essential oil were electrospun successfully for a wide range of applications, i.e., cosmetics, controlled drug release, and antibacterial [117]. By adding essential oil, the diameter of the nanofibers was raised, thus lowering their melting and glass transition temperatures.

8.1.10. Centella asiatica

Sikareepaisan et al. [118] developed electrospun gelatin fiber mats. The mats contained a Centella asiatica extract for WHL. The research demonstrated that asianicoside was released from the fiber mat samples in a lesser total quantity than it was from their film equivalents.

Another project created ultra-fine cellulose acetate fiber mats for a wound dressing that contained asiaticoside from the Centella asiatica plant [119]. In a study, the medical Centella asiatica extract was incorporated into electrospun gelatin membranes to improve WHL in a rat model [120]. The volume of Centella asiatica released from

electrospun gelatin membranes was found to be more effective in promoting cell proliferation. Another study created safe and biocompatible coaxially electrospinning nanofibers of PVA, alginate, and CH for treating burn injuries [121]. To synthesize the drug-loaded coaxial nanofibers, asiaticoside was applied to the core, and its continuous release from the nanofibers was verified. Natural antibacterial agents, such as hinokitiol, Centella, and propolis, were successfully incorporated into poly[(R)-3-hydroxybutyrate-co-(R)-3-hydroxyhexanoate] (PHBH) composite nanofibers using the electrospinning method, and release tests revealed that Hinokitiol and Centella released faster from the composite nanofibers than that of propolis [122]. In another research, a PCL, PVA, and CH-Sodium tripolyphosphate electrospun bi-layered nanocomposite membrane was combined with Centella asiatica extract to enhance WHL [123]. The findings revealed that the PCL layer could serve as a protective shield against external pollutants, while the bottom layer of PVA CH-Sodium tripolyphosphate Centella asiatica effectively absorbed exudate and maintained a moist environment, demonstrating its success in this regard.

8.1.11. Chrysin

Deldar et al. [124, 125] effectively produced PCL/PEG nanofibers and their blends with chrysin through the electrospinning technique, targeting applications in wound treatment.

The fibers were shown to be cytocompatible and anti-oxidant as well as a cytoprotective impact on human fibroblast cells under oxidative stress. In another research, Mohammadi et al.'s findings revealed that the nanofibres containing chrysin–curcumin had anti-inflammatory characteristics in many levels of the wound-healing process by influencing the MMP-2, IL-6, TIMP-2, TIMP-1, and iNOS gene expression by electrospinning a solution of PCL-PEG chrysin–curcumin for WHL [126]. Also, other researchers demonstrated that an electrospun PCL/GEL containing Chrysin could modulate macrophage phenotypic polarization [127].

8.1.12. Clerodendrum phlomidis

Ravichandran et al. [128] fabricated PCL nanofibers containing Clerodendrum phlomidis leaf extract via an electrospinning approach that can be successfully utilized in wound dressing applications. Clerodendrum phlomidis embedded nanofibers mats have superior wettability, mechanical properties, and antioxidant and anti-bacterial function.

8.1.13. Clove

Unalan et al., in their project, successfully fabricated clove oil-loaded PCL-GEL nanofiber mats for WHL applications. It was found that the nanofibers can be considered a potential biomaterial for preventing bacterial infections offering an alternative to traditional antibiotic use [129]. Their findings showed that bead-free, uniform, and smooth fibers could be collected, and that clove oil increased the mean fiber diameter. In another study, Yadav and Balasubramanian found that Syzygium aromaticum (clove) oil contained in electrospun polyacrylonitrile fibers exhibited antibacterial and hydrophilic characteristics which are compatible with NIH/3T3 cell lines, allowing them to be utilized in antibacterial DDSs [130]. The Korsmeyer–Peppas model was used to explain the kinetics and mechanism of the antibacterial drug release system in the nanofibers mat. Encapsulation of Clove oil in CH and polyethylene oxide exhibits an initial burst release followed by sustained release, is non-cytotoxic to fibroblast cell lines, and demonstrates excellent antibacterial and wound-healing activities [131].

8.1.14. Coconut oil

Mohamadi and their team successfully developed PCL/gel nanofibers loaded with coconut oil for WHL purposes [132]. The study found that the inclusion of coconut oil boosted water vapor permeability, highlighting the suitability of these electrospun membranes for wound dressing applications.

8.1.15. Copaiba

The development of PVP and PLA micro and nanofiber mats with encapsulated Copaiba oil using solution blow spinning for biomedical application was demonstrated in a report by Bonan et al. [133]. PLA electrospun fiber had a very low oil release rate in vitro controlled release experiments, while PLA/PVP fibers had a release rate that depended on the blend ratio.

8.1.16. Coptidis Rhizoma

Jeong and Lee, created nanofibrous membranes incorporating Coptidis Rhizoma extracts, utilizing PVA as the drug carrier, for application in wound dressings [134]. The release profile of the Coptidis Rhizoma-loaded nanofibrous membranes exhibited an initial rapid release, followed by a sustained release for 48 hours. These membranes demonstrated significant antibacterial activity against both Staphylococcus aureus and Staphylococcus epidermidis.

8.1.17. Coptis chinensis

PVA nanofibers containing Coptis chinensis extract were prepared by the electrospinning process, making them suitable for applications in both the medical and cosmetic industries. These fibers exhibited notable antibacterial effects against Staphylococcus aureus and Staphylococcus, as well as antifungal properties against Aureobasidium pullulans and Penicillium pinophilum [135].

8.1.18. Emu oil

Unnithan et al., synthesized nanofibers of PU/emu oil blended composite for wound dressing and skin disease treatment applications [136]. To solve the emu oil solution's low electrospinnability, synthetic polymers, e.g., PU, must be mixed in with the emu oil solution to increase its spinnability. Electrospinning was used to produce Emu oil-loaded nanofibers based on PCL/collagen materials in another research [137]. In vitro experiments with tissue-derived stem cells revealed that this composite nanofibrous scaffold increases proliferation and cell adhesion while maintaining the stemness of tissue-derived stem cells. Electrospun emu oil PCL/PEG nanofibrous mat promotes adipose tissue-derived stem cell proliferation and prevents them from oxidative stress [138]. The electrospun emu oil-PCL/PEG nanofibrous mats were also shown to polarize RAW264.7 macrophages against an anti-inflammatory phenotype [139].

8.1.19. Garcinia

Mangosteen extract-loaded ultra-fine PVA fiber mats were synthesized by Opanasopit and others [140]. The complete immersion method was used to release Mangosteen extracts from electrospun PVA fiber mats, and the results were reported as a burst release. Electrospinning was

used to make PLLA fiber mats containing a rudimentary extract of Garcinia in another research [141, 142]. In the phosphate buffer/Tween/methanol medium, the overall total volume of Garcinia cowa released from the Garcinia cowa filled PLLA fiber mats was higher than that released in the acetate buffer/Tween/methanol medium. Also, Garcinia cowa-loaded mats have shown antimicrobial properties. Researchers have proved that electrospun nanofiber mats with Garcinia mangostana loaded into CH-ethylenediaminetetraacetic acid/PVA are biodegradable, biocompatible, and antibacterial. They also are good candidates for use as useful wound dressings [143]. These mats are non-toxic and facilitate the rapid release of mangostin, maintaining antioxidant and antibacterial properties, which accelerates WHL. In another study, researchers found that mangostin containing synthesized thiolated CH/PVAnanofiber mats were non-toxic, had a strong mouthfeel, and quickly adhered to the buccal, after which the mangosteen was released to kill oral bacteria, as well as decreasing its amount [144].

8.1.20. Grape seed

Nanofibrous mats of grape seed extract-loaded silk fibroin/PEO composite can be used for WHL [145]. It is shown that grape seed extract was released from the nanofibers under a sustained release mechanism. The grape seed-loaded silk fibroin/PEO mats have also been shown to have outstanding cytocompatibility, as evidenced by their ability to promote cell proliferation while also shielding skin fibroblast cells from oxidative stress. In a study, biodegradable and biocompatible PLA and PLA/PEO loaded with grape seed extract nanofibrous membranes have been fabricated by the electrospinning for wound dressing application [146]. With a conventional Fickian diffusion process, researchers demonstrated that the grape seed extract release profile is dependent on nanofiber composition, by adding a hydrophilic polymer extending the grape seed extract release duration. Cell culture tests with fibroblasts on membranes have also shown that the grape seed extract-loaded materials are highly biocompatible and that the addition of PEO improved cell adherence and proliferation. Also, somewhere else, an aqueous gelatin solution was obtained via an $AgNO_3$/grape seed polyphenols complex and electrospun into a composite fiber membrane composed of grape seed polyphenols, gelatin, and AgNPs. This was achieved using a glass heat-retaining device for wound dressing applications. The resulting fiber membranes demonstrated significant antibacterial activity against both S. aureus and E. coli [147].

8.1.21. Green seaweed ulva rigida

Electrospinning was used in a study to produce uniform ulvan-based nanofibers that were mixed with PVA [148]. Under transmission electron microscopy, the nanofibers have shown a highly organized crystalline structure with a mean diameter adjustable down to ~85 nm. This anionic sulfated polysaccharide-rich extract's spinnability, together with its intriguing physicochemical and biological features, might lead to new biomedical applications, e.g., drug release systems. It has been proved that ulvan, a marine heparin analogues of algal origin, can have anti-thrombogenic effects when combined with the water-soluble PEO [149]. This biocomposite can also be employed as a medication delivery system and a WHL medium. It is observed that a 1:2 ratio of ulvan-PVA produces a well-handled and smooth nanofiber for biomedical purposes [150].

8.1.22. Green tea

Because green tea leaf extract contains various biological and pharmacological activities, including antibacterial, anti-inflammatory, and antioxidative qualities, CH/PEO/green tea extract nanofibers can be applied as a wound dressing material to boot better and faster WHL [151]. CH/PEO/green tea extract nanofibers composite has shown high swelling and stability properties. Higher swelling means nanofibers store more moisture in their structure, and during the healing process, the wound surface remains wet, preventing nanofibers from adhering to the wound surface. the antioxidant properties of the nanofiber mats of PVP/green tea extract composite [152].

8.1.23. Tea

Liu et al. found that tea polyphenols/polystyrene composite membranes coated with Ag nanoparticles could serve as effective antibacterial agents for medical and environmental purposes, as well as reusable catalysts for reducing dye pollution in water treatment applications [153].

8.1.24. Gymnema sylvestre

Gymnema sylvestre integrated PCL nanofiber mats have been found to offer many advantages, including strong antibacterial activity, biocompatibility, excellent mechanical behavior, as well as wettability, and could be used as antimicrobial wound dressings or sterile skin replacements in situations where microbial colonization slows down WHL [154]. Electrospun PCL/gelatin mats incorporating antibacterial Gymnema sylvestre extracts have also been shown to be useful for WHL [155]. When gelatin is added to the PCL/Gymnema sylvestre system, the wettability increases.

8.1.25. Hypericum perforatum

Pourhojat and colleagues reported encapsulation of pure Hypericum perforatum extract in PCL using electrospinning for drug delivery and WHL applications [156]. These electrospun fibers' antibacterial activity was successfully used in suppressing varied fractions of Staphylococcus aureus strains.

Also, the extract exhibited remarkable capabilities as a cell growth promoter, enhancing cell accumulation, and providing a favorable environment for the viability and proliferation of human skin fibroblast cells cultured on nanofibrous mats. In another study, a two-layered wound dressing material was developed, with the upper layer consisting of electrospun PCL nanofibers to ensure membrane integrity and mechanical strength [157]. The bottom layers, intended to be in contact with the wound, were synthesized using electrospraying and electrospinning PCL polymer solutions with PEG/Hypericum perforatum oil.

It has been shown that Hypericum perforatum oil is released in a regulated manner. Using a multilayer electrospinning process, a double-layer nanocomposite PLLA/PEO-CH nanofibrous material consisting of crude Hypericum perforatum extract has been created in another work for wound dressing [158]. The incorporation of crude Hypericum perforatum extract results in an increased swelling ratio in PBS. This is beneficial for having an advantageous moisture balance within the wound position and inhibits nanofibers from sticking to the wound surface, and causing additional damage. A bilayer membrane was used in a research to induce WHL with the controlled release of Hypericum perforatum oil at which the top layer is made up of Hypericum perforatum oil incorporated zein film containing

montmorillonite, and the bottom layer is composed of electrospun zein/montmorillonite nanofibers [159]. The results of an in vitro scratch testing revealed that Hypericum perforatum oil had a wound-healing impact through fibroblast migration.

8.1.26. Lavender

Balasubramanian et al. developed electrospun polyacrylonitrile (PAN)/lavender oil nanofibers for antibacterial applications [160]. They discovered that adding electrolytic solution to PAN solution improved the likelihood of medicinal oils being incorporated into nanofibres. In another study, researchers found that sodium alginate and lavender are essential oils in nanofibrous dressings that not only were antibacterial against S. aureus but also highly suppressed the generation of pro-inflammatory cytokines in vivo and in vitro [161]. In vitro investigations have shown that polyurethane-based nanofibrous dressings infused with lavender oil and silver nanoparticles exhibit synergistic antibacterial effects against S. aureus and E. coli [162]. The lavender oil changes the hydrophobicity of the polyurethane fibers, reducing their rigidity through diffusion and penetration.

8.1.27. Lawsonia inermis (henna)

Henna leaf extract has been blended into PVA and PEO electrospun fibers [163]. The antibacterial behavior of henna leaf extract has been demonstrated to be highly effective against *E. coli* and *S. aureus* bacteria. Researchers have shown that synergistic antibacterial activity, high biocompatibility, WHL acceleration, and suitable mechanical and swelling properties of henna leaf extract incorporated into CH/PEO nanofibrous mats made these scaffolds good candidates for eventual skin tissue engineering applications i.e., WHL dressings [164]. Wound dressings made of henna-loaded gelatin-oxidized starch mat have been developed to treat burn wounds [165]. It has been claimed that increased henna content improves water uptake, weight reduction, fibroblast proliferation, collagen production, and antimicrobial action. PLLA-Gelatin hybrid nanofibrous scaffolds loaded with Lawsonia inermis show potential as wound dressings to prevent infections and accelerate WHL [166]. The Lawsonia inermis release pattern from these nanofibers is quite similar to Hixson's model. In addition, the nanofibers are proved to be biocompatible with fibroblast cells.

8.1.28. Moringa

For antibacterial characteristics and wound dressing, a cost-effective and simple material made of PAN nanofibers containing moringa leaf extracts has been developed [167]. The rise in moringa leaf extract concentrations altered the material's healing qualities as well as its antibacterial activity. Chin et al. [168] created a hybrid dressing of poly-(ethylene oxide) electrospun nanofiber infused with Moringa oleifera leaf extract layered over an alginate-pectin hydrocolloid film with no cytotoxic effect for chronic WHL. They discovered that the time of electrospinning could affect the amount of Moringa oleifera leaf extract released from the nanofibrous film.

8.1.29. Murivenna oil

PU/murivenna oil nanocomposites have been created with hydrophilicity, delay in the activation of the blood clot, and low damage to red blood cells properties that are important in the WHL process and might be used to make wound dressing scaffolds [169].

8.1.30. Oregano essential oil

Khan et al. [170] created nanofiber membranes of PLCL/silk fibroin polymers encapsulated with oregano essential oil for wound dressing. They proved that the membrane not only sped up the healing process, but also improved granulation, re-epithelialization, collagen fiber organization, and capillary network creation. In another research, an electrospun mat of Eudragit E100 (EE100), a cationic copolymer based on methyl methacrylate, butyl methacrylate, and dimethylaminoethyl methacrylate, has been employed as a delivery strategy for oregano ethanolic extract [171]. Optimized Electrospun mats demonstrated good encapsulation efficiency, rapid release, and oregano ethanolic extract stability. In another study, rosemary and oregano oils encapsulated in cellulose acetate electrospun nanofiber have been shown to exhibit antibacterial effects [172]. Oregano oil has been proven to have more antibacterial activity than rosemary oil.

8.1.31. Zataria

It has been reported that electrospun Zataria multiflora essential oil incorporated in CH/PVA/gelatin nanofiber mats can be utilized as wound dressing in burn wounds and surgery [47]. This nanofiber mat is shown to be safe for the cell line examined by, as well as having acceptable swelling and mechanical properties. The major element of the Zataria multiflora essential oil is thymol, which may show the antibacterial activity of the nanofiber mats against Candida albicans, Pseudomonas aeruginosa, and Staphylococcus aureus. The antibacterial activity of cellulose acetate/gelatin/Zataria multiflora nanofiber composite against S. aureus and E. coli and significant WHL has been revealed in another research [48].

8.1.32. Stryphnodendron adstringens

Using an electrospinning approach with Stryphodedron barbatimao extract barbatimo/PVA/pineapple nanofibers, a new nanocomposite with homogenous porosity distribution and potential natural antibacterial characteristics has been produced [173].

8.1.33. Pomegranate

Nanofibers containing honey, pomegranate peel extract, and bee venom mixed with PVA have been used for wound dressing application [174]. This mat possesses antibacterial properties against S. aureus and E. coli and is non-cytotoxic and in turn promotes WHL.

8.1.34. Tea tree

It is reported that tea tree and manuka essential oils improve the qualities of PLA electrospun fibers in terms of both antibacterial and mechanical qualities [175].

It is reported that Tea Tree and manuka essential oils improve the qualities of PLA electrospun fibers, improving both their antibacterial and mechanical characteristics. Therefore, it shows good potential for wound dressing applications.

8.1.35. Sophora

Electrospinning can be used to make an ethanolic extract of Sophora flavescens and PVP nanofibers for an antibacterial air filter [176]. The filtering efficiency of nanofiber air filter and its antibacterial activity against S. epidermidis bioaerosols are shown to be 99.9% and 99.5 percent, respectively.

8.1.36. Tecomella undulata

Suganya et al. demonstrated that the combination of PCL/PVP nanofibers with raw leaf extracts of Tecomella undulata by electrospinning because of its potent antibacterial properties can be used as a wound dressing [177]. Even after being exposed to a high electrical charge, the loaded herbal medication maintained its biological functioning.

8.1.37. Thyme

In a research coaxial electrospinning was used to make Thyme extract mixed with PVA as the core and PCL as the sheath. It was suggested that homogeneous surface shape, appropriate tensile strength, and antibacterial activity were sought in nanofibers to have the potential to be utilized as a wound-healing substance [178]. Elsewhere, emulsion electrospinning was used to create antibacterial PVP/gelatin nanofibers containing thyme essential oil for biomedical applications [179]. It was shown that the concentration of thyme essential oil enhanced the absorbance and antibacterial properties, and after 192 hours showed antibacterial effects. Also, it has been proved that thyme essential oil/zein/PEO in situ Nanofibrous membranes have super hydrophilicity and antibacterial properties that can help the WHL [180]. In another study, it was found that thymol loaded in hybrid nanofibrous mats of poly(e-caprolactone) and PLA had antibacterial effects for S. aureus, which is more than E. coli, as well as good wound-closure [181]. It has been shown that the amounts of thymol released for poly(e-caprolactone), PLA, and their hybrid nanofibers decrease, respectively.

8.1.38. Cinnamon

It has been illustrated that cinnamaldehyde added into CH/PEO electrospun nanofibers, results in a high anti-bacterial effect versus E. coli and Pseudomonas aeruginosa. That's because of the inherent antibacterial of CH and the rapid release of cinnamaldehyde [182]. Also, antibacterial PVP/cinnamon essential oil nanofibers have been produced using oil-in-water emulsion electrospinning to provide the framework for the development of novel nanofibrous biomedical materials [183]. In a study, an antibacterial nanofibrous scaffold of polyurethane (PU) and cinnamon extract has been fabricated by electrospinning for treating burn wound infections [184]. Other studies have shown that CH/gelatin electrospun nanofibers scaffold with cinnamon extract, with antibacterial activity, improves cellular attachment and growth. Also, it has been illustrated that cinnamon extract causes resistance to the degradation of biodegradable polymers [51]. In another study, it is found that encapsulating three distinct types of essential oils (peppermint, lemongrass, and cinnamon) in cellulose acetate electrospun nanofiber had antibacterial and noncytotoxicity properties that can be utilized for wound dressing [185].

8.1.39. Honey

It has been shown that PVA and honey as natural antibiotic electrospun nanofiber mats with dexamethasone sodium phosphate as an anti-inflammatory drug can improve the efficiency of wound dressing as well as the healing rate. It has been reported that electrospun fibers show a huge burst release at the beginning in a short period [186]. In another study, it has been illustrated that PET/CH/honey nanofiber mats show a high ability to absorb water and antibacterial activity, with no toxicity to the cells that can be used in wound dressing [187]. Sarhan and Azzazy proved that honey/PVA/CH nanofibers have strong antibacterial action against S. aureus but very low antibacterial behavior against E. coli and on cultivated fibroblasts, there were no cytotoxic effects [188]. In another research, it has been shown that an increment in the concentration of honey in honey/PVA/CH nanofibers leads to an increase in the mean diameter of these nanofibers as well as a decrease in the swelling and improvement in antibacterial activity [189]. In terms of WHL, PCL nanofiber scaffolds with manuka honey that have a high rate of water vapor transfer and high proliferation of fibroblasts, seem promising [190]. Elsewhere, electrospinning was used to make honey/CH/PVA-based nanofibers with half of the solvent replaced with Allium sativum extract and loaded with Cleome droserifolia extract as a potential antibacterial wound dressing that is biocompatible. This nanofiber mat has been demonstrated to have low swelling abilities and great weight loss, as well as antibacterial activity against S. aureus, high content of cell survival and proliferation, as well as quick WHL rates [191]. Jaganathan et al. used electrospinning technology to successfully synthesize a new PU-based bio-nanofibrous dressing infused with honey and Carica papaya extracts for the treatment of burn injuries [192]. They showed that nanofibrous porous shape may simulate native extracellular matrix structure while also allowing for efficient nutrient penetration. Also, outstanding water absorption abilities, availability of carbohydrates, proteins, and vitamins derived from honey and Carica papaya, lead to the regeneration process. They fabricated manuka honey/silk fibroin composite electrospun nanofiber matrices, which is another potential option for wound dressing with outstanding biocompatibility, antimicrobial action, and WHL enhancement [193].

In another work, honey was mixed with PVA electrospun nanofibers and shown to have antioxidant, antibacterial, and anti-inflammatory effects which are principal to be preserved in the wound microenvironment [194]. Honey combined with a PVA scaffold has been shown to inhibit proteases in chronic wounds and promote WHL owing to the effective osmolality impact [195]. In another study, it has been shown that electrospun nanofiber honey and Nepeta dschuparensis plant loaded in PVA/CH has a positive effect on burn WHL [196]. Honey can be integrated into poly (1,4 cyclohexane dimethylene isosorbide terephthalate) electrospun nanofibers for possible wound dressing uses [197]. It has also been demonstrated that honey decreases hydrophobicity, and these mats have good elastic properties and tensile strength at the optimum honey content. As a biocompatible and antibacterial wound dressing, electrospun nanofiber mats of cellulose acetate mixed with manuka honey with acceptable mechanical characteristics, high porosity, strong antioxidant capacities, and high cytocompatibility have been developed [198]. In a research, honey/sodium alginate/PVA nanofibrous membranes were synthesized using all-aqueous electrospinning, and it was discovered that these mats have antibacterial properties, good biocompatibility, and antioxidant activity. It is reported that increasing honey concentration reduces swelling ratio and increases weight loss that can be a good contender for a wound-healing dressing [199]. In another study it has been proved that Curcumin honey-loaded multilayer PVA/cellulose acetate electrospun nanofibrous mats offer antioxidant and antibacterial properties, as well as good absorption and wound exudate transfer control [200]. Honey/tripolyphosphate/CH electrospun nanofibers loaded with capsaicin and gold nanoparticles demonstrated to have antibacterial properties, cell survival, proliferative impact, and wound closure capacity [18]. Sharaf and El-Naggar synthesized WHL mats of cellulose acetate nanofiber loaded with honey bee propolis extract. They discovered that these mats exhibited strong antibacterial

capabilities as well as a sustained and regulated release at neutral pH [201]. In another research, using a mixture of honey, curcumin, and gelatin, a nanofibrous membrane with antibacterial, antioxidant, cytocompatible, biodegradable, and high swelling characteristics was fabricated, resulting in rapid wound closure [202]. Honey can be inserted into an ethylcellulose/gum tragacanth electrospun nanofibrous mat to show suitable antioxidant activity, antibacterial properties, enhanced degradation ability, strong mechanical characteristics, appropriate cell attachment, proliferation, and growth against NIH-3 T3 fibroblast cells [203]. Jaganathan et al. proved that PU electrospun nanofibers containing propolis, honey, and sesame oil have improved mechanical strength, reduced surface roughness, reduced toxicity to red blood cells, and increased cell survival when compared to pure PU nanofibers [204].

8.1.40. Curcumin

Electrospun curcumin-loaded cellulose acetate nanofibers demonstrate the ability to scavenge free radicals and no effect on normal human dermal fibroblasts, allowing them to be employed in wound treatment [50, 205]. According to the findings of a study, the curcumin-loaded PCL nanofibre matrix is bioactive and is promising material for wound dressing with gradual curcumin (CUR) release, cytocompatibility, anti-oxidant, and anti-inflammatory effects [206]. It has been shown that CUR-loaded electrospinning PLA composite membrane shows anticoagulant characteristics, and the anticoagulant activity improves as the CUR content rises. This makes it a good candidate for drug-eluting stents for the treatment of in-stent restenosis following stent implantation [207, 208]. It has been proved that the biological activity of PLA electrospun nanofibers loaded with CUR reveals to be significantly CUR concentration-dependent [209]. CUR induces C2C12 cell growth at optimal concentrations, whereas larger concentrations have lethal effects on the cells. Also, these scaffolds increase the pace of wound closure. In another study, a zein–CUR electrospun nanofiber scaffold is developed for biomedical applications with a large pore size and a high surface-area-to-volume ratio, all of which are beneficial for cell adhesion, growth, and proliferation [210]. It has been shown that this material not only shows no cytotoxicity but also shows antioxidant characteristics with controlled drug release patterns and selective degradation. In another study it has been shown that CH/PLA nanofibers loaded with CUR had no toxicity to L-929 fibroblasts and show enhanced WHL [211]. Electrospun nanofiber PCL-PEG loaded with CUR has been demonstrated in a research to exhibit anti-inflammatory action toward RAW264.7 murine macrophages, antibacterial effect versus Staphylococcus aureus, and helps wound closure with cell proliferation [212]. A combination of PEG in PCL has also been found to increase porosity in the nanofibers, as well as enhanced biocompatibility. Fu et al. found that electrospun nanofiber scaffolds made of CUR and PCL-PEG-PCL (PCEC) exhibit substantial anti-oxidant activity, minimal cytotoxicity, sustained CUR release, and effective behavior to WHL [213]. According to the Yakub et al. research, CUR loaded CoPLA/PEG demonstrates antioxidant and anticoagulant activity, that can be utilized for wound dressings [214]. Also, CoPLA/CUR mats have been found to have a better antibacterial effect than CoPLA/PEG/CUR mats; however, adding PEG to mats promotes hydrophilization. CUR-loaded silk fibroin/P(LLA-CL) nanofibrous scaffolds were synthesized in an investigation, and it was discovered that CUR has a long-term release [215]. The addition of CUR to nanofibrous scaffolds significantly increased their antioxidant and antibacterial properties. CUR-loaded PCL/gum tragacanth electrospun nanofiber scaffolds with good biological properties were produced in another study that allows controlled CUR release for a long period for diabetic WHL [216, 217]. The addition of CUR and gum tragacanth generates a hydrophilic surface that is ideal for cell adhesion and growth. CUR incorporated with gum tragacanth-PVA electrospun nanofiber has also been found to have strong biological characteristics, making it a viable option for the treatment of cancer, hyperplastic scar healing [218]. It is found that the addition of CUR to PCL-gelatin electrospun nanofibers results in a hydrophilic surface, excellent antibacterial characteristics, and postpone nanofiber degradation, all of which are useful for wounds that take a long time to heal [219]. CUR loaded in poly(2-hydroxyethyl methacrylate) electrospun nanofibers have been proven to have strong cell adhesion, antimicrobial characteristics, and a regulated and continuous release rate of CUR, making them suitable for use as a gauze patch in skin WHL [220]. In another research, it has been shown that CUR loaded in polylactide/PVP electrospun has antibacterial characteristics, anticoagulant action, and inhibits platelet adherence and aggregation on the mats' surface that can be used in wound dressing where blood coagulation is not required [221]. In comparison to poly (lactic acid)/CUR electrospun nanofibers, Perumal et al. discovered that CUR incorporated in electrospun nanofibers of a blend of poly (lactic acid) and hyperbranched polyglycerol promotes the cell viability, adhesion, and proliferation, making them suitable for wound dressing [222]. The addition of PVP to the cellulose acetate and CUR mixture results in enhanced hydrophilicity of the fibers and faster CUR release [223]. It has been shown that the use of dual-spinneret electrospinning allows for the creation of fibers with a more complicated structure, making it easier to control the CUR release profile and thus the antibacterial characteristics of the materials produced. Aytac and Uyara developed core-shell nanofibers with a CUR/cyclodextrin inclusion complex as the core and PLA as the shell [224]. They showed that Hydrophobic medicines, e.g., CUR, could be placed in the core structure as an inclusion complex with cyclodextrins, resulting in delayed-release and high-water solubility. CUR induced electrospun nanofibers of cellulose acetate phthalate has sluggish sustained diffusion of the loaded CUR that can be used as a regulated transdermal delivery method for medicines that are susceptible to degradation when taken orally and need long-term systemic administration within the skin [225]. Using a crosslinked PVA/PEG film supports the membrane and a CUR-loaded electrospun PLA nanofiber mat. Moradkhannejhad et al. synthesized a nanofibrous composite for wound dressing [226]. Their data demonstrated that the hydrophilic characteristics of the membrane, together with the porosity of the nanofiber mat and a controlled release of CUR, can ensure a moist environment for WHL by allowing gas exchange and exudate absorption. CUR loaded poly(3-hydroxy butyric acid-co-3-hydroxy valeric acid) (PHBV) electrospun nanofibers has been found in another study to enhance cell adhesion and proliferation in L929 murine fibroblasts, which can be utilized in WHL applications [227]. In another study, it has been foud that antioxidant materials such as allicin, CUR, piperine, polydatin, and quercetin loaded in poly(-caprolactone) electrospun nanofiber scaffolds, show good cytocompatibility and mechanical behavior with human adipose-derived mesenchymal stem cells, and can be used in a practical treatment method for WHL [228]. Somewhere else, CUR was loaded in poly(L-lactic acid) electrospun nanofiber mats [229]. Their findings showed that the antioxidant activity of as-released CUR was reduced

with increasing immersion duration, which might be related to CUR's poor stability. Also, they showed that by increasing submersion time, neither water retention nor weight loss of mats in PBS containing Tween 80 and methanol was substantially different. These compounds promote cell adhesion and proliferation, making them highly applicable for wound dressing.

8.1.41. Caffeic acid

Researchers have chemically immobilized caffeic acid on the surface of electrospun PLLA fibers to improve the hydrophilicity and antioxidant behavior of the resulting fibrous layers [230]. The fibrous membrane shows no cytotoxicity to human dermal fibroblasts (HDFa) and murine dermal fibroblasts (L929) and highly supported cell proliferation, which makes it a good candidate for wound dressings.

8.1.42. Gum tragacanth

According to a study, electrospun nanofiber of gum tragacanth and PVA for wound dressing exhibit strong antibacterial properties against Gram-negative bacteria and cause human fibroblast cells to adhere and proliferate [231]. It is also found that electrospun nanofiber poly (ε-caprolactone) and gum tragacanth exhibit hydrophilicity, degradation behavior, good mechanical, and excellent cell morphology on nanofibers, which can be used to produce skin scaffolds or wound dressing [232].

8.1.43. Memecylon edule

In a study, Jin et al. discovered that human dermal fibroblast proliferation on PCL and memecylon edule electrospun nanofibers was 31% higher than proliferation on PCL nanofibers after 9 days of cell culture. This proves that these nanofibers can be applied as substrates for skin tissue engineering [31].

8.1.44. Capparis spinosa

Incorporating Capparis spinosa L. extracts into PLA electrospun nanofiber membranes enhances air permeability, moisture permeability, mechanical characteristics, and oxidation resistance [233]. It also leads to hydrophilic and antibacterial nanofiber membranes that may be utilized in wound treatment.

8.1.45. Urtica dioica

It has been demonstrated that the electrospun hybrid scaffolds of PCL/urtica dioica/ZnO nanoparticles exhibit antibacterial characteristics and excellent cell viability, making them appropriate for wound dressing applications [234]. Urtica dioica reduces nanofiber diameter, which in turn increases tensile strength and water absorption ability.

8.2. ELENs for tissue engineering application

8.2.1. Aloe vera (AlVer)

Shanmugavel and his colleagues demonstrated the significant use of natural biomaterials such as silk fibroin and AlVer in polymeric electrospun nanofibrous scaffolds with hydroxyapatite surface precipitation to control and enhance basic biological functions such as adhesion, proliferation, and differentiation of adipose-derived stem cells for bone repair and regeneration [235]. Elsewhere, using a blend solution of water-soluble AlVer and PCL in Trifluoroethanol, nanofibrous membranes of PCL/AlVer were successfully fabricated [236]. For guided tissue regeneration, PCL/AlVer fibers showed strong morphological uniformity, structural stability, sufficient porosity, satisfactory mechanical properties, and cellular compatibility. Ranjbar-Mohammadi created composite scaffolds from PCL/gum tragacanth/AlVer nanofibers with random topography. They found that AlVer reduced the diameter of PCL and PCL/gum tragacanth nanofibers and increased the hydrophilic properties of these scaffolds [237]. In vitro cell culture experiments on electrospun PCL/gum tragacanth/AlVer nanofibers revealed higher proliferation and proper cellular phenotype, indicating the feasibility of using gum tragacanth/PCL/AlVer scaffolds as a regenerative method for healing various skin disorders and application in skin tissue engineering. In another research, researchers found that incorporating AlVer into electrospun scaffolds increased fibroblast proliferation compared to PCL and Gelatin-PCL scaffolds, suggesting that it can be used for skin tissue engineering [238]. In another research, Shabannejad et al. created nanofibrous scaffolds with PCL-PVA/AlVer for skin regeneration [239]. They discovered that increasing AlVer concentration reduced nanofiber diameter and PCL-PVA/AlVer scaffolds facilitated cell proliferation. According to their findings, coating nanofibers with AlVer gel does not influence the morphology and diameter of electrospun fibers [240]. Its appearance on the scaffold also improved its biocompatibility, which increased the number of cells adhering to the scaffold in the early stages and then increased the stem cells' growth and proliferation rate, making them a possible candidate for bone tissue engineering (BTE) applications. The hybrid nanofibrous scaffolds of a synthetic polymer PCL blended with biopolymers AlVer, silk fibroin, and CUR can be used as an alternative material for tissue engineering applications [241]. Another study used a mixture of Magnesium ferrite, PCL, and AlVer into electrospun nanofibers [242]. The obtained nanofibers showed high structural integrity, morphological uniformity, cellular compatibility, and magnetic strength for tissue regeneration.

8.2.2. Azadirachta indica (neem)

Electrospinning with sunflower and neem oil results in a novel composite of polyurethane-based bone scaffold [243]. The addition of some portions of sunflower oil caused the scaffold to become hydrophobic, which can be modified by adding neem oil, restoring its wettability to the required range for BTE. In another investigation, PU has been loaded and electrospun with both neem oil and corn oil, resulting in a material with good physio-chemical and biological properties for BTE [244].

8.2.3. Baicalein

Bachimam et al. developed a nanofiber-based bone tissue-mimicking scaffold containing baicalein, Hyaluronic acid, PEO, and PVA. They discovered that baicalein molecules were entrapped inside the nanofiber structure, hence these scaffolds could be used to treat bone cancer [245].

8.2.4. Centella asiatica

It is found that loading asiaticoside into PLGA nanofibers during electrospinning reduces inflammatory cell infiltration and shifts macrophage phenotype to M2 within the embedded scaffold nanofibers, dramatically improving the host inflammatory response to asiaticoside-PLGA nanofibers [246].

8.2.5. Emo oil

Nejati et al. found that combining PCL/collagen/emu oil + adipose-derived stem cells/glial cell line-derived neurotrophic parameter scaffold can improve certain pathways involved in the reconstruction of spinal cord injury, suggesting that combination therapy might be more efficient [247].

8.2.6. Equisetum arvense

In a study focused on BTE applications, PLA composite nanofibrous scaffolds incorporating Equisetum arvense herbal extract were successfully fabricated [248]. The in vitro release profile of the Equisetum arvense extract in PBS showed an initial burst release followed by a slower, sustained release. Additionally, the composite nanofibrous scaffold containing the herbal extract presented wonderful cell attachment, enhanced proliferation, as well as promoted osteogenic differentiation of adipose tissue-derived mesenchymal stem cells. This was evidenced by increased cell viability, alkaline phosphatase activity, and mineralization content.

8.2.7. Green seaweed ulva rigida

Ulva rigida, a marine sulfated polysaccharide, was electrospun into fibrous matrices combined with the biodegradable PCL. It was shown that ulva rigida containing PCL, which has a lengthy biodegradation time of up to 18 months, can result in a long-term drug release [149].

8.2.8. Calendula officinalis

Pedram Rad et al. synthesized Calendula officinalis-loaded PCL/zein/gum arabic composite scaffolds utilizing suspension, multilayer, and two-nozzle electrospinning techniques [249]. The resulting nanofibrous composite scaffolds exhibited moderate degradability and controlled release of Calendula officinalis. These scaffolds are considered promising biomaterials for applications in skin tissue engineering. According to the findings of a study, ethanolic extract of calendula officinalis could greatly boost the hydrophilicity of PCL nanofibers, hence increasing cell adhesion to PCL mats [250]. As a result, it can be employed as an effective transport of tenocyte cells to the wounded tendon tissue region.

8.2.9. Urtica dioica

Urtica dioica can be incorporated into a silk fibroin nanofibrous scaffold to boost the osteogenic ability of the nanofibers and give an appropriate quantity of Urtica dioica to the cells over time in BTE as a prospective matrix [251]. Urtica dioica has been shown to increase the production of osteogenic variability genes such as ALP, Runx2, Col I, and OCN, as well as mineralization, in a dose-dependent way.

8.2.10. Thyme

In a study, silk fibroin was mixed with gelatin and electrospun to create a nanofibrous matrix for the delivery of antibacterial drugs, specifically thyme essential oil and doxycycline monohydrate, in skin tissue engineering. It was found that thyme essential oil loaded into the nanofibers exhibited a lower burst release, a longer release period, and a larger inhibitory zone against bacteria compared to doxycycline monohydrate [252].

8.2.11. Curcumin

Curcumin (CUR) loaded poly (ε-caprolactone) electrospun nanofiber was produced by Jain et al., who proved that continuous release of the phytochemical lowers cell proliferation and enhances osteogenesis, making it suitable for BTE [253]. Because of the delayed release and little amount of CUR required to stimulate cell proliferation, a study showed that polydioxanone (PDO) electrospun fiber loaded with optimal CUR concentration suited for tissue repair applications [254]. In another work, functionalized electrospun poly(N-vinyl-2-pyrrolidone) fibers were used as a free-standing framework to immobilize CUR-PVP capped gold nanoparticles conjugates [255]. The findings revealed that these composites have a two-stage release, with a minor burst release during the early period of 2 h, followed by a sustained release over 48 h, and are sufficiently biocompatible to support cell growth over three days, making them a potential substrate for sustained release drug delivery and tissue engineering applications. In another study, it was found that addition of CUR-containing CH nanoparticles and gelatin to PCL electrospun fiber mats improved its hydrophilicity, wettability, and degradability while lowering its mechanical properties [256]. It has also been shown that it promoted cell attachment and proliferation, within the human endometrial stem cells (EnSCs), could be a good scaffold for epidermis tissue engineering. It is also found that when CUR forms an inclusion compound with cyclodextrin, its dissolution rate is higher than that of CUR alone [257]. The compound was also loaded in PCL nanofibers that demonstrated the controlled release of CUR, which can be used for various applications, e.g., tissue engineering and DDS.

8.2.12. Gum tragacanth

It is found that composite scaffolds made of gum tragacanth and PLLA with aligned topography have higher proliferation, high neurite outgrowth, better cell differentiation, and an excellent cellular phenotype than randomly oriented nanofibers. This makes them suitable for application in peripheral nerve regeneration [258]. Studies have proved that the release rate of tetracycline hydrochloride loaded in polylactic glycolic acid and gum tragacanth blend nanofibers increases with a higher gum tragacanth ratio, attributed to the enhanced hydrophilicity of the electrospun nanofibers [259]. Polylactic glycolic acid and gum tragacanth core-sheath nanofiber membranes have also been found to release tetracycline hydrochloride for longer than blend nanofibers, with a smaller burst release of the medication that can be employed as a drug delivery method for periodontal disorders. Zarekhalili et al. created nanofibrous scaffolds comprising PCL, PVA, and gum tragacanth using a co-electrospinning technique with antibacterial characteristics, no toxicity, and cell proliferation that can be utilized for skin tissue engineering applications [260]. Their data depicted that adding PVA and gum tragacanth improves the hydrophilicity of nanofibrous scaffolds.

8.2.13. Gum arabic

Pedram Rad et al. synthesized an electrospun nanofibrous scaffold from corn protein (zein), gum arabic, and PCL that has an acceptable degradation rate, high hydrophilicity, acceptable mechanical properties, adequate porosity for cell proliferation, growth, infiltration, adhesion, and antibacterial properties that can be utilized for skin tissue engineering applications and WHL [261]. According to their results, the presence of PCL in the blends improved mechanical characteristics,

the addition of gum arabic caused an increment in hydrophilicity, and the addition of zein caused mitigated degradation behavior.

8.2.14. Honey

It is reported that an electrospun nanofiber scaffold of honey and S-nitroso-N-acetyl-penicillamine into polylactic acid has synergistic effects of honey and S-nitroso-N-acetyl-penicillamine that causes high antibacterial properties with excellent cytocompatibility which effectively simulates the natural ECM and is therefore appropriate for applications in soft tissue engineering, such as skin and cartilage regeneration [262].

8.3. ELENs for food industrial application

8.3.1. AlVer

Torres-Giner et al. [263] encapsulated AlVer using both synthetic polymers, including PVP and PVA, and naturally occurring polymers, i.e., barley starch, whey protein concentrate, and maltodextrin by electrospinning for bioactive packaging. They discovered that, under ideal processing conditions, synthetic polymers created fiber-like structures, while naturally occurring polymers produced capsules. Another group of researchers found that AlVer skin extract could be effectively encapsulated in PEO electrospun nanofibers and used in active food packaging to reduce oxidation of packaged food during storage [264].

8.3.2. Amaranth

Amaranth protein isolate-based ultrathin structures have been synthesized for the first time using electrospinning by Aceituno-Medina et al. [265]. These materials have a lot of potential for encapsulating bioactive for utilization in functional foods. The morphology of the resulting structures was primarily influenced by the solvent and the protein concentration used in them. They proved that pullulan was essential for fiber growth, but it blends with higher protein contents, and a certain amount of surfactant was needed to obtain defect-free fibers, a finding that was linked to the α-helical conformation of the protein chains, as determined by FTIR [266]. According to the findings of a review, nisin was entrapped in an active form in amaranth/pullulan electrospun nanofibers [267]. At pH of 3.4 and 6.1, the release of nisin from amaranth/pullulan nanofibers was controlled by diffusion, with the solubility of the polysaccharide pullulan exceeding 65 and 90%, respectively, after 100 hours [268]. The nisin molecules bound to the fibers' surface were released first, followed by the fibers' swelling, which increased the solubility of the pullulan, resulting in pores, which favor the release of nisin molecules trapped within the fiber's inner structure. Nanofibers shield the nisin in this manner, reducing its contact with food components while preserving its antimicrobial function. The microbiological protection of nisin active electrospun fibers makes them a potentially valuable technology for extending the shelf life of food products.

8.3.3. Catechin

Electrospinning is used for nanoencapsulation of catechin in an Azivash gum-PVA polymeric matrix, serving as an active coating on polymer surfaces to protect sensitive bioactive compounds in foods from oxidation [269, 270]. The release profiles showed approximately 50% and 70% of the total catechin released in simulated gastric and intestinal fluids, respectively. In addition, distinct catechin release rates were observed in simulated low-fat and high-fat food media, with the release rate in high-fat media being twice as slow as in low-fat media due to differences in polarity.

In another research developed, flexible electrospun biocomposites were developed using plasticized PLA-PHB blends modified with CH or catechin, creating biodegradable films suitable for applications such as agricultural mulch and food packaging [271]. Additionally, in the food packaging sector, biodegradable antioxidant bilayer films were successfully fabricated. These films consist of a compression-molded PHBV layer and an inner antioxidant layer made from plasticized PLA-PHB electrospun fibers loaded with catechin [272].

8.3.4. Black pepper oleoresin

Intending to improve the water-resistance and mechanical efficiency of high oxygen barrier gelatin films of interest in active food packaging applications, gelatin films were coated with electrospun PCL containing black pepper oleoresin. For at least the first 10 days after processing, the black pepper oleoresin is released as an antimicrobial active ingredient.

Intending to improve the water resistance and mechanical efficiency of gelatin films, which are valued for their high oxygen barrier properties in active food packaging, gelatin films were coated with electrospun PCL infused with black pepper oleoresin [273]. The black pepper oleoresin, serving as an antimicrobial agent, is released effectively for at least the first 10 days post-processing.

8.3.5. Clove

Clove oil-loaded CH nanoparticles were effectively incorporated into gelatin nanofibers through electrospinning for use in antibacterial food packaging [274]. Sensory evaluation findings indicated that the gelatin nanofibers containing clove oil-loaded CH nanoparticles preserved the color and taste of cucumbers for over four days.

8.3.6. Cress seed

In a study, cress seed mucilage–PVA nanofibers were electrospun under various conditions for a variety of applications, including distribution systems and packaging film fabrication [275]. To increase the spinnability of cress seed mucilage, PVA was used.

According to SEM analysis, the best electrospun nanofibers exhibited an average diameter ranging from 95 to 278 nm. Additionally, varying concentrations of vitamin A were incorporated into cress seed mucilage/PVA blends and successfully electrospun [276]. The release of vitamin A from the nanofibers was found to be faster in simulated intestinal fluid compared to simulated gastric fluid.

8.3.7. Basil seed

Using an electrospinning technique, different concentrations of hesperetin were successfully encapsulated using basil seed mucilage/PVA nanofibers. Nanocarriers with high-temperature tolerance and slow-release rates in acidic conditions were found to have the necessary properties for use in food systems [277].

8.3.8. Flaxseed

Researchers have found that flaxseed mucilage has no spinnability and electrospinning cannot be used to produce nanofiber [64]. As a result, PVA can be applied to the solution as a co-material, and a flaxseed mucilage/PVA nanofiber can be formed. Seed mucilage, with its

biosafety, biocompatibility, biodegradability, and low cost, can be considered a completely green compound, with more hope of performance than synthetic products in the food industry, such as distribution mechanisms and encapsulation for bioactive compounds.
A study revealed that CH-flaxseed mucilage nanofibers, produced through electrospinning, hold promise for use in the food packaging industry, particularly for encapsulating and enabling the sustained release of Ziziphora clinopodioides essential oil and sesame oil [278]. Additionally, flaxseed oil was successfully encapsulated within electrospun flaxseed mucilage nanofibers, with oxidation indices indicating that the stability of the encapsulated flaxseed oil was significantly enhanced compared to unprotected oil [279].

8.3.9. Plantago major seed

According to the research, Plantago major mucilage can be used as a new source for blending with PVA to manufacture nanofiber for the medical and food industries [280]. Furthermore, a Plantago major mucilage/PVA-based scaffold has been suggested as a good candidate for cell culture and has the ability to be commonly used in biomedical applications.

8.3.10. Garcinia

PVP/Garcinia mangostana extract composite nanofiber mats can be fabricated through an electrospinning process, making them a potential antioxidant material for applications in the food and pharmaceutical industries. The composite nanofiber mats exhibited strong antioxidant properties, indicating that exposure to high voltage during electrospinning had minimal impact on their antioxidant activity [281].

8.3.11. Moringa

It has been demonstrated that encapsulating Moringa oleifera extract with gelatin is achievable using the electrospinning process while the antioxidative capabilities of its phenolic chemicals in the extract are not harmed [282]. In a study, Moringa oil/CH nanoparticles can be embedded in gelatin nanofibers that have been developed to protect the cheese from Listeria monocytogenes and Staphylococcus aureus [283]. Moringa oil can be incorporated in CH nanoparticles to increase the stability and extend the activity duration of the oil. In another study, electrospinning technology was utilized to produce nanofibers from a blend of water-soluble protein powder extracted from Moringa stenopetala seeds and PVA, targeting applications in water treatment [284].

8.3.12. Orange essential oil

The coaxial electrospinning approach has been used to produce composite zein prolamine as sheath and orange essential oil as core membranes [285]. These fibrous composites have been shown to have antibacterial properties in E. coli, thus they could be used as a food packaging material for bioactive food preservation, such as extending the shelf life of fruits and hence ensuring their sustainability. In a study, gelatin nanofibers were fabricated as applicable materials for nanoencapsulation of orange essential oil using electrospinning [286]. Both gelatin and gelatin-cross-linked tannic acid have been found to provide adequate controlled release of orange essential oil while also significantly increasing its storage stability, suggesting that they could be used as a promising delivery system for value-added enriched or fortified food products.

8.3.13. Zataria

Cinnamon zeylanicum and Zataria multiflora essential oils were combined with Soy Protein Isolate-gelatin nanofibers to produce antibacterial nanofibers, which could be promising for extending the shelf life of food and being used in the production of active food packaging [287].

8.3.14. Araucaria angustifolia (Pinhão)

Pinho coat extract has been encapsulated into starch electrospun fibers, which demonstrated rapid but modest phenolic chemical release in vitro in both hydrophilic and hydrophobic conditions, that it can be used as an efficient antioxidant ingredient in the food product [288].

8.3.15. Pomegranate

According to a study, active nanofibers of CH/PEO/Pomegranate peel extract successfully prevented E.coli development on beef samples held at 4 and 25 °C for 7 and 10 days, respectively, demonstrating that this mat is an excellent food wrapping material for preserving and extending the shelf life of meat without sacrificing its sensory properties [289]. In another research, an electrospinning procedure has been used to manufacture a PVA film containing pomegranate peel extract and sodium dehydroacetate as active packaging. Results have shown that pomegranate peel extract and sodium dehydroacetate have a synergistic antibacterial action when used together against E. coli and S. aureus [290]. Another study found that ethanolic pomegranate peel extract encapsulated in gelatin electrospun nanofiber improves the bioavailability of bioactive components in ethanolic pomegranate peel extract, which could be useful for a variety of applications in biomaterials, pharmaceutical, or food industries [291].

8.3.16. Rubus strigosus

The anthocyanin-rich red raspberry extract has been incorporated into electrospun soy protein isolate fibers with the least quantity of PEO for fiber production to suppress microbial development and oxidation, they might be utilized as natural food preservatives [292].

8.3.17. Rose hip seed

In a study, electrospinning was used to create coaxial electrospun fibrous zein prolamine/rosehip seed oil films to extend the shelf life of fruit [293]. The data depicted that rosehip seed oil can be consistently encapsulated inside a zein prolamine fiber matrix.

8.3.18. Saffron

Core/shell nanofibers of tragacanth/zein as shell and saffron extract as core have been made using coaxial electrospinning [294]. It has been illustrated that the saffron extract was well encapsulated in nanofibers, and there was no chemical interaction between the constituents, and it has thermostability that can be used in a variety of food products, including chewing gum and tea bags.

8.3.19. Tea tree

Plasma-treated PEO nanofiber membranes containing a tea tree oil/Beta-cyclodextrin inclusion complex have been demonstrated to extend the shelf life of beef, indicating that it might be used in active food packaging [295]. Results have shown that the antibacterial agent release efficiency from PEO nanofibers was enhanced after cold nitrogen plasma treatment. As a result, the synthesized tea tree oil

liposomes/CH nanofibers can help increase the shelf life of chicken meat by preventing microbiological contamination by Salmonella [296]. In another research, electrospinning was used to create antibacterial, mechanical, and moisture-protective nanofibers based on tea tree essential oil and PU [297]. These nanofibers could potentially extend the shelf life of fruits, but they could also be used in other applications requiring antimicrobial activity, such as filters and medical applications.

8.3.20. Litsea cubeba

For biomedical and food packaging applications, the inclusion complex of Litsea cubeba essential oil encapsulated in cyclodextrin has been electrospun onto nanofibers made from dandelion polysaccharide, a natural product [298]. These nanofibers exhibit a high drug release rate and demonstrate antibacterial activity against Staphylococcus aureus.

8.3.21. Urtica dioica

PCL nanofibers with Urtica dioica have been electrospun and implanted in whey protein isolate as bioactive coverings to protect fresh rainbow trout fillets [299]. It has been shown that the developed bioactive coatings have a longer release time, indicating that the bioactive compounds may permeate into the food product and its media in a controlled manner, providing significant antimicrobial and antioxidant activity and potentially extending the shelf life and quality of the fish fillets by up to 15 days.

8.3.22. Thyme

Thyme essential oil/β-cyclodextrin–ε polylysine nanoparticles and gelatin have been used as antibacterial nanofibers in the creation of functional food packaging [300]. The antibacterial activity of the thyme essential oil/β-cyclodextrin ε polylysine nanoparticles incorporated in gelatin nanofibers against Campylobacter jejuni on chicken has been shown. Lin et al. [301] used cold plasma to modify the substrate of thyme essential oil/silk fibroin nanofibers, which demonstrated antibacterial properties against Salmonella Typhimurium and might be used to preserve poultry meat. It has been shown that surface treatment increases the quantity of thyme essential oil released from thyme essential oil/silk fibroin nanofibers, resulting in increased antibacterial activity. Using nozzle-less electrospinning, CH/gelatin nanofibers with thyme essential oils have been proven to show antimicrobial activity against Clostridium perfringens which can be substituted with Sausage nitrite [302]. Thyme essential oil has been loaded onto porous PLA nanofibers electrospun and coated with PVA/PEG mixture for humidity-controlled thyme essential oil release for antibacterial active packaging that is humidity regulated [303]. Also, it has been shown that the loading efficiency of thyme essential oil is enhanced because of the porosity of nanofibers. In another study, it has been illustrated that electrospun nanofibers produced from starch and thyme essential oil exhibit thermal stability and antioxidant activity, making them suitable for application in food products subjected to heat processing [304]. Also, thyme essential oil-loaded PLA/guar gum nanofibers show good biocompatibility, and antioxidant and antimicrobial properties that can be an ideal option for application in active food packaging [305]. It has been shown that the use of thyme essential oil improves the flexibility and hydrophobicity of the surface.

8.3.23. Vanillin

Electrospinning has been used to synthesize PVA nanofibers with a vanillin/cyclodextrin complex formation for extended storage life and high-temperature stability for volatile Flavors [306]. Compared to α-cyclodextrin and β-cyclodextrin, it has been reported that γ-cyclodextrin stability and gradual release of vanillin, lead to greater contact strength between vanillin and the c-cyclodextrin hole. Also, it has been demonstrated that complex formation can improve vanillin's weak antioxidant properties [307]. Another study found that the rate of vanillin release from almond gum/PVA/vanillin nanofibers via diffusion mechanism in simulating saliva is greater than the other media and was rather constant under dry ambient conditions and this composite had high thermal resistance [308, 309]. Research has shown that electrospun PVA nanofibrous films with immobilized ethyl vanillin are mechanically stable [310].

8.3.24. Cinnamon

It has been shown that the nanofibres made of CH/PVA/β-cyclodextrin with essential oils of cinnamon and oregano demonstrate outstanding antibacterial activity and could be used in the creation of active packaging systems [311]. Cinnamon essential oils/β-cyclodextrin microcapsules demonstrate better antibacterial efficiency than oregano essential oils/β-cyclodextrin microcapsules. In a study, the antibacterial activity of the cinnamon essential oil/β-cyclodextrin inclusion complex in PLA nanofibers was investigated. It was suggested that it can be used in active food packaging to extend the shelf life of pork [312]. Also, it has been shown that the thermal stability and antimicrobial activity of cinnamon essential oil were greatly enhanced by creating a cinnamon essential oil/β-cyclodextrin inclusion complex. It was shown that when an essential oil is combined with other antimicrobial chemicals, the necessary dose of essential oil is reduced while the antibacterial action is maintained. That's why the combination of cinnamon essential oil with lysozyme was applied to fabricate PVA/β-cyclodextrin/cinnamon essential oil/lysozyme electrospun nanofilm that can be used in active food packaging [313].

Elsewhere it has been shown that the PVA/cinnamon essential oil/β-cyclodextrin nanofibrous film shows good antibacterial activity and thermal stability and may be employed in active food packaging to extend strawberry shelf life [314]. In a study, cinnamon essential oil was embedded in CH nanoparticles, followed by electrospinning as PLA/CH-cinnamon essential oil composite nanofibers. It was shown that these composites have antibacterial properties, good stability, and beneficial sustained release of cinnamon essential oil for active food packaging [315]. In another study, electrospinning was used to fabricate cinnamon essential oil/β-cyclodextrin proteoliposomes into PEO nanofibers for antibacterial packaging to the shelf life of beef [316]. It was found that the antibacterial efficacy of cinnamon essential oil/β-cyclodextrin proteoliposomes against Bacillus cereus was improved. In another study, it has been reported that an inclusion complex with cyclodextrins considerably enhanced the solubility content as well as the dissolving rate of pure cinnamon essential oil [317]. elsewhere, using the electrospinning approach, cinnamon essential oil nanophytosomes have been inserted into cross-linked PVA nanofibers that have low cell toxicity, and high antibacterial properties, and can be used in packing perishable food products [318].

8.3.25. Curcumin

Curcumin (CUR) has been encapsulated and released through electrospun fiber structures made of amaranth protein isolate and the carbohydrate polymer pullulan, which may be utilized in the food industry. It has been shown that CUR is released in a regulated and sustained manner [319]. It is also shown that surfactants such as Tween 80, SDS, and CTAB can alter the release, and antioxidant and antibacterial properties of encapsulated CUR by changing the structure of gelatin nanofibers [1]. These findings suggest a novel method for producing gelatin nanofibres with food-grade surfactants for the controlled release of CUR, which might have interesting uses in the food sector as a nutraceutical carrier. Other research has been illustrated that CUR loaded in zein electrospun nanofiber can be used in food packaging since it shows antibacterial activity against S. aureus and E. coli at which the efficiency increased with the increase of CUR content [320]. It is also shown that Fickian diffusion was the most common method of releasing CUR from fibers, and the first-order model and the Hixson-Crowell model could both accurately explain this diffusion behavior. Wang et al. fabricated a bioactive nanofibril film using electrospinning with antibacterial and antioxidative properties from CUR, konjac glucomannan, and zein, which may be used in food packaging [321]. Akman et al. fabricated gliadin nanofibers containing CUR that can be used in the food industry [322]. The CUR in vitro release study showed two phases of release, with a fast release step occurring initially and a regulated release step occurring afterward. Moreover, it is shown that CUR's bioactive characteristics, such as antioxidant and antibacterial activity, were significantly increased when it was encapsulated in the nanofibers. According to a study for orally quick dissolving strips as dietary supplements, CUR/hydroxypropylgamma-cyclodextrin is significantly more efficient than CUR/hydroxypropyl-beta-cyclodextrin in improving the solubility and antioxidant effects of CUR in CUR/cyclodextrin fibers [323].

8.3.26. Egg

By electrospinning cellulose acetate and egg albumen solutions, edible nanofibrous thin films have been developed for the first time [324]. Results have shown that Egg albumen, due to insufficient entanglement and high surface tension cannot form nanofibers on its own. However, by incorporating cellulose acetate and a surfactant, the blend's electrical conductivity and surface tension were reduced. This enables the successful formation of nanofibers.

8.3.27. Fish oil

It has been reported that fish oil can be effectively encapsulated within electrospun zein fibers, enhancing the stability of the lipid. It is shown that electrospun zein fibers are useful for expanding the nutritional value of enriched or fortified foods by encapsulation and loading [325]. Using whey protein isolate or fish protein hydrolysate as emulsifiers, PVA nanofibers containing fish oil have been produced [326]. The results indicated tiny droplets of fish oil encapsulated in fibers, but the fibers had low oxidative stability. In another study, coaxial electrospinning was used (fish oil and zein as a core and PVP as a sheath) to encapsulate fish oil [327]. This coaxial electrospun nanofibrous mat, which has good oxidative stability and release characteristics, can be used as a nutritional supplement. Findings revealed that the addition of ferulic acid to electrospun zein fibers enhanced the oxidative stability of encapsulated fish oil, but did not affect the fish oil's release behavior [328]. With monoaxial emulsion electrospinning, Liu et al. synthesized a fish oil-vitamin C/gelatin core-shell nanofibrous membrane that is a potential edible film for the delivery of hydrophilic and hydrophobic nutrients [329].

8.3.28. Oregano essential oil

Oregano essential oil, rosemary extract, and green tea extract encapsulated in PHBV electrospun nanofiber film have been found to exhibit thermal stability up to 200 °C and reduce hydrophobicity [330]. Findings revealed that PHBV nanofiber films with oregano essential oil have the best antibacterial and antioxidant characteristics, making them suitable for food packaging.

8.3.29. Grape seed

It is found that grape seed extract encapsulated in electrospun nanofibers of rye flour, whey protein concentrate, and PEO has strong antioxidant activity and improved thermal stability, making it a viable material for food packaging [331]. Microwave heating pretreatment to solutions is more successful than conventional heating in terms of producing uniform and beadless nanofibers in a shorter processing time. In another investigation, it has been shown that covering PVA electrospun nanofiber loaded with grape seed oil was shown to be extremely efficient against fast oxidation in fish meat and kashar cheese held at 4 ± 1 °C, in addition to microbiological limitations [332].

8.4. ELENs for protective textile, filter, and sensor application

8.4.1. AlVer

AlVer and PVA electrospun nanofibers are reported to be smooth and bead-free. Finer fibers were collected at higher Aloe vera concentrations. Furthermore, as the concentration of AlVer increased, the amount of OH-1 also rose. This leads to a greater ability of the material to absorb moisture. Hence, it is confirmed that AlVer has a very slow release behavior. Since AlVer/PVA electrospun nanofibers have excellent antimicrobial activity, they are ideally suitable for the preparation of COVID-19 safety clothing (gowns, face masks, etc.) [333].

8.4.2. Baicalein

In a study, baicalein was successfully incorporated into PVA nanofibers using the electrospinning technique. The addition of baicalein to the PVA/baicalein composite enhanced its UV light-blocking properties and improved its antibacterial activity [334].

8.4.3. Clove

Acaricidal nylon 66 fabrics embedded with clove oil-loaded microcapsules were produced to target D. farinae, offering potential for acaricidal effects, reducing allergen levels, and alleviating clinical symptoms of house dust mite allergies in home environments [335].

8.4.4. Garcinia

Garcinia mangostana has been successfully integrated into electrospun PAN fiber mats applied to make face masks, respirators, and air-conditioning filters. Researchers showed that Garcinia mangostana had burst release characteristics at first, accompanied by a steady rise in the total amount of Garcinia mangostana produced and that the release

feature of Garcinia mangostana increased with increased Garcinia mangostana-loading material in the fibers [336].

8.4.5. Oregano oil

Biocompatible and antibacterial nanofibers made from concentrated collagen hydrolysate and infused with thyme or oregano essential oils have been successfully created via electrospinning. These nanofibers hold potential for applications in wound dressings, tissue engineering, and protective clothing [337]. The essential oils in new collagen nanofibers have demonstrated antibacterial efficacy against S. aureus, E. coli, Pseudomonas aeruginosa, and Candida albicans, as well as no cytotoxicity in certain concentrations.

8.4.6. Tea tree

The electrospinning technology has been applied to construct CH/PEO nanofiber mats containing tea tree oil liposomes for use as a long-term antibacterial nonwoven material [338]. It has been shown that it possessed strong fluid absorption and water vapor permeability, as well as outstanding mechanical strength and flexibility, thanks to their enormous porosity.

8.4.7. Thyme

In a research, nanofiber mats were created by electrospinning nylon-6/polyamidoamine dendritic polymer second-generation/thyme essential oils. According to the antibacterial influence of thyme essential oils, they can be used as an appropriate adsorption layer, particularly in smart face masks. It has been also shown that the use of polyamidoamine dendritic polymer (PAMAM) for encapsulated thyme essential oils causes the prolonged release of the material [339, 340].

8.4.8. Cinnamon

To make core/sheath-structured nanofibers, researchers employed an oil-in-water emulsion using cinnamon oil and PVA. They showed that the nanofiber has acaricidal activity against home dust mites (Dermatophagoides farinae) and antibacterial activity against S. aureus and a group of fungi that can cause respiratory and skin infections and release indefinitely functional substances over 28 days that can be used in ecologically friendly and multipurpose home fabrics [341].

8.4.9. Curcumin

A zein electrospun nanofiber loaded with CUR and crosslinked with citric acid (CA) was developed as a membrane for Fe^{3+} sensing in aqueous samples by naked-eye detection in a research [342]. It has been shown that as a response of the CUR-Fe^{3+} complexation, the color of the membrane changed from yellow to brown, and the degree of the color change increased as the quantity of Fe^{3+} rose.

8.5. ELENs for anti-cancer application

8.5.1. Angelica gigas

Nam et al. extract was loaded into PVA nanofibers in a sample. Using electrospinning, a fast-dissolving mat with an average diameter of 170 nm and entrapment efficiency greater than 80% was fabricated. Its anti-proliferative effect on oral squamous cell carcinoma cells suggests it may be a promising candidate for oral cancer therapy [343].

8.5.2. Chrysin

Research shows that CUR and Chrysin incorporated into PLGA/PEG nanofibers will improve the mechanical properties of the nanofibers and lower the initial burst discharge of the drug-loaded in nanofibers, thus increasing the anticancer efficiency of the drugs [344].

8.5.3. Green tea

Scientists have proved that PCL/MWCNTs (multi-walled carbon nanotubes) composite nanofibers containing green tea polyphenols have a lot of potential in cancer treatment since they have few adverse effects on normal body tissues [345]. They also suggested that by supplying MWCNTs and changing the green tea polyphenols content, both the in vitro breakdown of the fibers and the green tea polyphenols release can be regulated.

8.5.4. Oregano essential oil

Electrospinning can be used to produce oregano essential oil loaded into a mixture of PLCL/silk fibroin nanofibrous [346]. It has been demonstrated that oregano essential oil can sustain its release from polymers for over two days, and the resulting composite not only exhibits antioxidant properties but also demonstrates cytotoxic effects against tumor cell lines.

8.5.5. Curcumin

Electrospun curcumin loaded PCL-PEG-PCL (PCEC) nanofibers demonstrate anticancer activity and no cytotoxicity, suggesting that this composite might be effective in the treatment of brain cancer patients following surgery [347]. In a research, in vitro drug release and cytotoxicity tests have been shown that the PLLA electrospun nanofiber loaded with CUR is a potential substratum for anti-cancer drug delivery [348]. PVA containing β-cyclodextrin–CUR complex electrospun nanofibers were produced in a study. The incorporation of CUR into nanofibers was found to enhance both the thermal stability and the controlled release properties of CUR [349]. These nanofibers have the potential to be used in drug delivery, WHL, and as promising materials for cancer treatment. AlVer/CUR incorporated PCL nanofiber membranes have been shown to have anti-cancer behavior against human breast cancer (MCF7) and lung cancer (A459) cells with long sustained release of the natural medication, which can be administered in the form of a localized medical device, such as a drug-eluting stent or patch implant, which is effective against cancer therapy [350]. In a research, CUR incorporated in PLGA electrospun nanofibers have been demonstrated to have a continuous release of CUR with no burst release and to be effective against skin cancer cell lines [351]. It has also been proven that by increasing hydrophilicity of the polymer, the CUR loading efficiency decreases, but the drug release rate increases. In another research, it has been found that CUR loaded in PVP electrospun nanofiber shows anticancer activity and bioavailability [352]. Elsewhere it has been shown that electrospun micro-fibrous membranes of poly(L-co-D, L-lactic) acid/PVP/CUR have antibacterial, antifungal, and cytotoxic properties against HeLa and Graffi cancer cells that can be used in implants with antitumor properties [353]. Researchers proved that the hydrophobic/hydrophilic character of the polymer matrix components determined the CUR release profile, and the addition of PVP led to CUR release from the fibers. Also, they showed that CUR's physicochemical and therapeutic characteristics were maintained after UV-Vis irradiation indicating that the fibrous biomaterials can be UV-Vis sterilized. Bulbula et al. showed that CUR-loaded polycaprolactone/polyethylene oxide electrospun fibrous membranes combined with halloysite nanotubes (HNT) and 3-aminopropyltriethoxysilane (APTES) can be used in

controlled drug delivery systems, notably as an anticancer carrier [354]. They discovered that the modified HNT with APTES has a considerably greater CUR loading capacity and a delayed-release profile and that the PCL/PEO-CUR/HNT-APTES membrane is highly toxic against MCF-7 cell lines.

9. Electrospun nanofibers with natural extracts in large-scale production

It is implied that using natural polymers with plant extracts is often cheaper than synthetic polymers like PLA or PCL, especially in regions where these plants are abundant [355, 356]. For example, chitosan derived from seafood waste reduces raw material costs while supporting circular economy principles [356]. On the other hand, variability in plant extract quality and seasonal availability may increase processing costs for standardization, which requires investment in purification technologies [355].

Large-scale electrospinning setups like industrial roll-to-roll systems have been successfully applied for air filtration membranes that demonstrate the feasibility for food packaging applications [356, 357]. Also, it should be noted that natural extracts may require stabilizers to prevent degradation during processing. This may add ~15–20% to material costs [355, 356]. However, natural polymer-based nanofibers exhibit lower environmental impact than petroleum-derived synthetics, with reduced carbon emissions during production [356, 357]. Also, Table 2 dictates the most recent studies about ELENs.

Table 2. Studies in the field of electrospinning with natural ingredients.

Electrospun matrix	Natural extract	Additional medication	Structure	Application	Year	Ref.
PLA	Achillea lycaonia	-	Blend	Wound healing	2019	[81]
PVA/PVP/PEG/PAA	Aloe vera	-	Blend	Wound healing	2013	[83, 84]
PVA/PAA	Aloe vera	Ciprofloxacin HCI	Blend	Wound healing	2013	[85]
PCL	Aloe vera	-	Blend	Wound healing	2015	[86]
PLACL/silk fibroin	Aloe vera	-	Blend	Wound healing	2014	[88]
PCL/silk fibroin	Aloe vera	Hydroxyapatite	Blend	Tissue engineering	2014	[235]
PLGA	Aloe vera	-	Blend	Wound healing	2017	[89]
PVA	Aloe vera	-	Blend	Wound healing	2017	[90]
PCL	Aloe vera	-	Blend	Tissue engineering	2016	[236]
PVP-PVA-starch-whey protein-maltodextrin	Aloe vera	-	Blend	Food industrial	2017	[263]
PCL-chitosan/polyethylene oxide (PEO)	Aloe vera	-	Layer by layer (LBL)	Wound healing	2017	[91]
PCL/gum tragacanth	Aloe vera	-	Blend	Tissue engineering	2018	[237]
PLLA	Aloe vera	-	Coating	Wound healing	2017	[92]
PCL/gelatin	Aloe vera	-	Blend	Tissue engineering	2018	[238]
PVA/chitosan	Aloe vera	-	Blend	Wound healing	2017	[93]
Silk fibroin-PVA	Aloe vera	Vitamin E	Core-sheath	Wound healing	2018	[94]
PCL	Aloe vera	Tetracycline hydrochloride	Blend	Wound healing	2019	[95]
PLGA	Aloe vera	-	Blend	Wound healing	2019	[49]
PCL/PVA	Aloe vera	-	Blend	Tissue engineering	2020	[239]
PVA/PLGA	Aloe vera	-	Blend	Wound healing	2021	[96]
PHBV	Aloe vera	-	Coating	Tissue engineering	2020	[240]
PEO	Aloe vera	-	Blend	Food industrial	2020	[264]
PVP	Aloe vera-Aloe vera acetate	-	Blend	Wound healing	2019	[97]
Zein/PCL/collagen	Aloe vera	Zinc oxide nano particles	Blend	Wound healing	2020	[98]
PCL/silk fibroi	Aloe vera/curcumin	-	Blend	Tissue engineering	2014	[241]
PVA	Aloe vera	-	Blend	Protective clothing	2020	[333]
PVA	Aloe vera	-	LBL	Wound healing	2021	[99]
PCL	Aloe vera	Magnesium ferrite	Blend	Tissue engineering	2017	[242]

Table 2. Continued.

Electrospun matrix	Natural extract	Additional medication	Structure	Application	Year	Ref.
PCL-PLLA-PLGA	Aloe vera rich with alloin	-	LBL	Wound healing	2020	[79]
PCL/chitosan	Aloe vera	-	Blend	Wound healing	2020	[100]
PCL/chitosan/keratin-PEO	Aloe vera	-	Core-sheath	Wound healing	2019	[101]
PCL/gelatin	Aloe vera /hypericum perforatum oil	-	Blend	Wound healing	2021	[102]
PVA/PVP/gelatin	Aloe vera/Ajwain essential oil	-	Core-sheath	Wound healing	2021	[103]
Protein isolate amaranth/pullulan	Amaranth	-	Blend	Food industrial	2013	[265, 266]
Protein isolate amaranth/pullulan	Amaranth	Nisin	Blend	Food industrial	2019	[267, 268]
PVA	Angelica gigas	-	Blend	Anticancer	2017	[343]
Silk fibroin/gelatin	Astragaloside	-	Blend	Wound healing	2019	[105, 106]
PVA/chitosn	Azadirachta indica	-	LBL/blend	Wound healing	2019	[107, 108]
PU	Sunflower oil/ neem oil	-	Blend	Tissue engineering	2018	[243]
PVA	Baicalein	-	Blend	Anti UV/antibacterial	2011	[334]
Hyaluronic acid/PEO/PVA	Baicalein	-	Blend	Tissue engineering	2020	[245]
Silk fibroin/PVP	Baicalein	-	Blend	Wound healing	2017	[109]
PVA	Baicalein	-	Blend	Medicine/food	2021	[110]
Azivash gum/PVA	Catechin	-	Blend	Food industrial	2021	[269, 270]
PCL	Catechin	-	Blend/add	Wound healing	2012	[111]
PLA/poly(hydroxybutyrate)	Catechin	-	Blend/add	Food industrial	2016	[271]
PLA/poly(hydroxybutyrate)	Catechin	-	Blend	Food industrial	2019	[272]
PLGA	Catechin	-	Core-sheath	Wound healing	2018	[112]
PCL	Biophytum sensitivum	-	Blend	Wound healing	2013	[113]
PCL	Black pepper oleoresin	-	LBL	Food industrial	2018	[273]
PCL/PVA/gelatin	Bromelain	Salvianolic acid B	Core-sheath	Wound healing	2017	[114]
Chitosan	Bromelain	-	Blend	Wound healing	2019	[115]
Cellulose triacetate	Bromelain	-	Blend/crosslink	Medical application	2020	[116]
PLA	Candeia (eremanthus erythropappus)	-	Blend	Antibacterial	2015	[117]
Gelatin	Centella asiatica	-	Blend/crosslink	Wound healing	2008	[118]
Cellulose acetate	Centella asiatica	-	Blend	Wound healing	2008	[119]
Gelatin/PVA	Centella asiatica	-	Blend	Wound healing	2017	[120]
Alginate/PVA/chitosan	Centella asiatica	-	Core-sheath	Wound healing	2016	[121]
PLGA	Centella asiatica	-	Blend	Tissue engineering	2020	[246]
PHBH	Centella asiatica/ propolis	-	Blend	Antibacterial	2019	[122]
PVA/PCL/chitosan/sodium tripolyphosphate	Centella asiatica	-	LBL	Wound healing	2020	[123]
PCL/PEG	Chrysin	-	Blend	Wound healing	2017	[124, 125]

Table 2. Continued.

Electrospun matrix	Natural extract	Additional medication	Structure	Application	Year	Ref.
PLGA/PEG	Chrysin/curcumin	-	Blend	Anticancer	2020	[344]
PCL/PEG	Chrysin/curcumin	-	Blend	Wound healing	2019	[126]
PCL/gelatin	Chrysin	-	Blend	Wound healing	2020	[127]
PCL	Clerodendrum phlomidis	-	Blend	Wound healing	2019	[128]
Gelatin	Clove	-	Blend	Food industrial	2018	[274]
PCL/gelatin	Clove	-	Blend	Wound healing	2019	[129]
Nylon 66	Clove	-	Crosslink	Protective clothing	2017	[335]
PCL/gelatin	Coconut oil	-	Blend	Wound healing	2022	[132]
PLA/PVP	Copaiba	-	Solution blow spinning/blend	Biomedical	2015	[133]
PVA	Coptidis rhizoma	-	Blend	Wound healing	2019	[134]
PVA	Coptis chinensis	-	Blend	Medical/cosmetic	2018	[135]
PVA	Cress seed	Vitamin A	Blend	Food industrial	2018	[275, 276]
PVA	Basil seed	Hesperetin	Blend	Food industrial	2019	[277]
PVA	Flax seed	-	Blend	Food industrial	2018	[64]
Chitosan	Flax seed/ziziphora clinopodioides/ sesame	-	Blend	Food industrial	2021	[278]
Flax seed	Flax seed oil	-	Emulsion	Food industrial	2019	[279]
PVA	Plantago major seed	-	Blend	Food industrial/biomedical	2019	[280]
PU	Emu oil	-	Blend	Wound healing	2012	[136]
PCL/collagen	Emu oil	-	Blend	Biomedical	2017	[137]
PCL/PEG	Emu oil	-	Blend	Wound dressing	2017	[138, 139]
PCL/collagen	Emu oil	-	Blend	Tissue engineering	2020	[247]
PLA	Equisetum arvense	-	Blend	Tissue engineering	2017	[248]
PVA	Mangosteen	-	Blend	Medical	2008	[140]
PLLA	Garcinia cowa	-	Blend	Wound healing	2014	[141, 142]
Chitosan/PVA	Mangosteen	-	Blend	Wound healing/medical	2015	[143, 144]
PVP	Garcinia mangostana	-	Blend	Food and pharmaceutical industries	2017	[281]
Polyacrylonitrile (PAN)	Garcinia mangostana	-	Blend	Filter	2018	[336]
Silk fibroin/PEO	Grape seed	-	Blend	Wound healing	2016	[145]
PLA/PEO	Grape seed	-	Blend	Wound healing	2019	[146]
Gelatin	Grape seed	-	Blend	Wound healing	2014	[147]
PVA/PEO	Green seaweed ulva rigida	-	Blend	Biomedical	2011	[148]
PCL/PEO	Green seaweed ulva rigida	-	Blend	Wound healing/tissue engineering	2015	[149]
PVA	Green seaweed ulva rigida	-	Blend	Biomedical	2021	[150]
PCL/MWCNTs (multi-walled carbon nanotubes)	Green tea	-	Blend	Anticancer	2011	[345]

Table 2. Continued.

Electrospun matrix	Natural extract	Additional medication	Structure	Application	Year	Ref.
PEO/chitosan	Green tea	-	Blend	Wound healing	2015	[151]
PVP	Green tea	-	Blend	Anti oxidant	2018	[152]
Polystyrene/pluronics	Tea	Ag nanoparticles	Blend	Medical/catalyst	2015	[153]
PCL/zein/gum arabic	Calendula officinalis	-	Blend/LBL/multi nozzle	Tissue engineering	2019	[249]
PCL	Calendula officinalis	-	Blend	Tissue engineering	2015	[250]
PCL	Gymnema sylvestre	-	Blend	Wound healing	2015	[220]
PCL/gelatin	Gymnema sylvestre	-	Blend	Wound healing	2019	[155]
PCL	Hypericum perforatum	-	Blend	Wound healing	2017	[156]
PCL/PEG	Hypericum perforatum	-	LBL	Wound healing	2019	[157]
PLLA/PEO/chitosan	Hypericum perforatum	-	LBL	Wound healing	2021	[158]
Zein	Hypericum perforatum	Montmorillonite	LBL	Wound healing	2020	[159]
PAN	Lavender	-	Blend	Antibacterial	2014	[160]
Sodium alginate/PEO	Lavender	-	Blend	Wound healing	2016	[161]
Polyurethane (PU)	Lavender	Ag nanoparticles	Blend	Wound healing	2019	[162]
PVA/PEO	Lawsonia inermis (henna)	-	Blend	Antimicrobial	2013	[163]
Chitosan/PEO	Lawsonia inermis (henna)	-	Blend	Wound healing	2017	[164]
Gelatin/oxidized starch	Lawsonia inermis (henna)	-	Blend	Wound healing	2018	[165]
PLLA/gelatin	Lawsonia inermis (henna)	-	Blend	Wound healing	2018	[166]
Gelatin	Moringa oleifera	-	Blend	Food industrial	2017	[282]
PAN	Moringa oleifera	-	Blend	Wound healing	2018	[167]
Gelatin	Moringa	-	Blend	Food industrial	2019	[283]
PVA	Moringa stenopetala seed protein	-	Blend	Water treatment	2018	[284]
PU	Murivenna oil	-	Blend	Wound healing	2020	[168]
PU	Corn and neem oil	-	Blend	Tissue engineering	2018	[244]
Zein prolamine	Orange essential oil	-	Core-sheath	Food industrial	2017	[285]
Gelatin	Orange essential oil	-	Blend	Food industrial	2018	[286]
PLCL/silk fibroin	Oregano essential oil	-	Blend	Anticancer	2019	[346]
Collagen hydrolysate	Oregano/thyme essential oil	-	Blend	Protective clothing/tissue enginnering/wound healing	2020	[337]
PLCL/silk fibroin	Oregano essential oil	-	Blend	Wound healing	2020	[170]
Eudragit E100	Oregano ethanolic extract	-	Blend	Oral drug system	2019	[171]
Chitosan/PVA/gelatin	Zataria	-	Blend	Wound healing	2019	[47]

Table 2. Continued.

Electrospun matrix	Natural extract	Additional medication	Structure	Application	Year	Ref.
Soy protein isolate/gelatin	Zataria/cinnamon	-	Blend	Food industrial	2021	[287]
Cellulose acetate/gelatin	Zataria multiflora	-	Soaking technique	Wound healing	2020	[48]
PVA/pineapple nanofiber	Stryphnodendron adstringens	-	Blend	Medical	2013	[173]
Starch	Araucaria angustifolia	-	Blend	Food industrial	2020	[288]
Chitosan/PEO	Pomegranate	-	Blend	Food industrial	2020	[289]
Honey/PVA	Pomegranate	Bee venom	Blend	Wound healing	2020	[174]
PVA	Pomegranate	-	Blend	Food industrial	2019	[290]
Soy protein isolate/PEO	Rubus strigosus	-	Blend	Food industrial	2013	[292]
Zein prolamine	Rose hip seed oil	-	Core-sheath	Food industrial	2016	[293]
Zein/tragacanth	Saffron	-	Core-sheath	Food industrial	2019	[294]
PEO	Tea tree oil	-	Blend	Food industrial	2018	[295]
PLA	Tea tree oil/manuka oil	-	Blend	Antibacterial	2017	[175]
Chitosan	Tea tree oil	-	Blend	Food industrial	2018	[296]
Chitosan/PEO	Tea tree oil	-	Blend	Antimicrobial nonwoven	2019	[338]
PU	Tea tree oil	-	Blend	Food industrial/filter/medical	2020	[297]
Dandelion polysaccharide	Litsea cubeba essential oil	-	Blend	Food industrial/medical	2019	[298]
PCL/PVP	Tecomella undulata	-	Blend	Wound healing	2011	[177]
PCL	Urtica dioica	-	Blend	Food industrial	2017	[299]
Silk fibroin	Urtica dioica	-	Blend	Tissue engineering	2019	[251]
PCL/PVA	Thyme	-	Core-sheath	Wound healing	2018	[178]
Silk fibroin/gelatin	Thyme	Doxycycline monohydrate	Soaking	Tissue engineering	2018	[252]
Gelatin	Thyme	-	Blend	Food industrial	2018	[300]
PVP/gelatin	Thyme	-	Emulsion	Antibacterial	2019	[179]
Silk fibroin	Thyme	-	Blend	Food industrial	2019	[301]
Chitosan/gelatin	Thyme	-	Blend	Food industrial	2019	[302]
PLA	Thyme	-	Soaking	Food industrial	2021	[303]
Nylon-6/polyamidoamine dendritic	Thyme	-	Blend	Face mask	2020	[339, 340]
Potato starch	Thyme	-	Blend	Food industrial	2020	[304]
PLA/guar gum	Thyme	-	Blend	Food industrial	2021	[305]
Zein/PEO	Thyme	-	Blend	Wound healing	2020	[180]
Almond gum/PVA	Vanillin	-	Blend	Food industrial	2016	[308, 309]
Chitosan/PVA	Cinnamon/oregano essential oils	Cyclodextrin	Blend	Food industrial	2018	[311]
Chitosan/PEO	Cinnamaldehyde	-	Blend	Antibacterial	2014	[182]
PLA	Cinnamon essential oils	Cyclodextrin	Blend	Food industrial	2016	[312]
PVA	Cinnamon essential oils	Cyclodextrin/lysozyme	Blend	Food industrial	2017	[313]
PVA	Cinnamon essential oils	Cyclodextrin	Blend	Food industrial	2016	[314]

Table 2. Continued.

Electrospun matrix	Natural extract	Additional medication	Structure	Application	Year	Ref.
PVP	Sophora flavescens	-	Blend	Antibacterial filter	2015	[176]
PVA	Vanillin	Cyclodextrin	Blend	Food industrial	2012	[306]
PLA	Cinnamon essential oils	Chitosan	Blend	Food industrial	2017	[315]
PEO	Cinnamon essential oils	Cyclodextrin proteoliposomes	Blend	Food industrial	2017	[316]
PVP	Cinnamon essential oils	-	Emulsion	Antibacterial	2019	[183]
PVA	Cinnamon essential oils	-	Blend	Food industrial	2019	[318]
PU	Cinnamon extract	-	Blend	Wound healing	2021	[184]
Chitosan/gelatin	Cinnamon extract	-	Blend	Biomedical	2021	[51]
PVA	Cinnamon oil	-	Core-sheath	Protective textile	2020	[341]
PVA	Honey	Dexamethasone sodium phosphate	Blend	Wound healing	2013	[186]
PET/chitosan	Honey	-	Blend	Wound healing	2014	[187]
Chitosan/PVA	Honey	-	Blend	Wound healing	2015	[188, 189]
PCL	Honey	-	Blend	Wound healing	2015	[190]
Chitosan/PVA	Honey/allium sativum/cleome droserifolia	-	Blend	Wound healing	2016	[191]
PU	Honey/carica papaya	-	Blend	Wound healing	2016	[192]
Silk fibroin	Honey	-	Blend	Wound healing	2017	[193]
PVA	Honey	-	Blend	Wound healing	2018	[194]
Chitosan/PVA	Honey/nepeta	-	Blend	Wound healing	2020	[196]
Poly(1,4-cyclohexane dimethylene isosorbide terephthalate)	Honey	-	Blend	Wound healing	2017	[197]
PVA	Honey	-	Blend	Wound healing	2020	[195]
Cellulose acetate	Honey	-	Blend	Wound healing	2020	[198]
Sodium alginate/PVA	Honey	-	Blend	Wound healing	2019	[199]
PVA/cellulose acetate	Honey/curcumin	-	LBL	Wound healing	2020	[200]
Chitosan/tripolyphosphate	Honey/capsaicin	Gold nanoparticles	Blend	Wound healing	2020	[18]
Cellulose acetate	Honey bee propolis extract	-	Blend	Wound healing	2018	[201]
Gelatin	Honey/curcumin	-	Blend	Wound healing	2021	[202]
Ethylcellulose/gum tragacanth	Honey	-	Blend	Wound healing	2021	[203]
PU	Honey/sesame oil/propolis	-	Blend	Wound healing	2019	[204]
Cellulose acetate	Curcumin	-	Blend	Wound healing	2010	[50, 205]
PCL	Curcumin	-	Blend	Wound healing	2009	[206]
PLA	Curcumin	-	Blend	Drug-eluting stents	2012	[207, 208]
PCEC	Curcumin	-	Blend	Anticancer	2011	[347]
Zein	Curcumin	-	Blend	Biomedical	2012	[210]
Chitosan/PLA	Curcumin	-	Blend	Wound healing	2013	[211]
PLLA	Curcumin	-	Blend	Anticancer	2012	[348]

Table 2. Continued.

Electrospun matrix	Natural extract	Additional medication	Structure	Application	Year	Ref.
PVA	Curcumin	B-cyclodextrin	Blend	Cancer treatment,wound healing	2013	[349]
PLA	Curcumin	-	Blend	Wound healing	2013	[209]
PCL	Curcumin/Aloe vera	-	Blend	Anticancer	2014	[350]
PLGA	Curcumin	-	Blend	Anticancer	2014	[351]
PCL/PEG	Curcumin	-	Blend	Wound healing	2014	[212]
PCEC	Curcumin	-	Blend	Wound healing	2014	[213]
Copla/PEG	Curcumin	-	Blend	Wound healing	2014	[214]
Silk fibroin/poly(L-lactic acid-co-e-caprolactone)	Curcumin	-	Blend	Wound healing	2014	[215]
Zein	Curcumin	-	Blend	Sensor	2014	[342]
PCL/gum tragacanth	Curcumin	-	Blend	Wound healing	2016	[216, 217]
Gum tragacanth/PVA	Curcumin	-	Blend	Wound healing, cancer treatment	2017	[218]
PCL/gelatin	Curcumin	-	Blend	Wound healing	2016	[219]
Poly(2-hydroxyethyl methacrylate)	Curcumin	-	Blend	Wound healing	2015	[220]
Amaranth protein isolate/carbohydrate polymer pullulan	Curcumin	-	Blend	Food industrial	2015	[319]
PVP	Curcumin	-	Blend	Anticancer	2015	[352]
PLA/PVP	Curcumin	-	Blend	Wound healing	2016	[221]
PCL	Curcumin	-	Blend	Tissue engineering	2016	[253]
PLA/hyperbranchedpolyglycerol	Curcumin	-	Blend	Wound healing	2017	[222]
Cellulose acetate/PVP	Curcumin	-	Blend/dual spinerete	Wound healing	2017	[223]
Poly dioxanone	Curcumin	-	Blend	Tissue engineering	2017	[254]
PLA	Cucumin	B-cyclodextrin	Core-sheath	Wound healing	2017	[224]
Gelatin	Curcumin	Tween80/SDS/CTAB	Blend	Food industrial	2017	[1]
Zein	Curcumin	-	Blend	Food industrial	2017	[320]
Cellulose acetate phthalate	Curcumin	-	Blend	Drug delivery	2022	[26]
PLA	Curcumin	-	Blend	Wound dressing	2017	[226]
Poly(N-vinyl-2-pyrrolidone)	Curcumin	Gold nanoparticle	Surface immobilization	Tissue engineering	2017	[255]
Poly(3-hydroxy butyric acid-co-3-hydroxy valeric acid) (PHBV)	Curcumin	-	Blend	Wound healing	2018	[227]
PCL/gelatin	Curcumin	Chitsoan nanoparticle	Blend	Tissue engineering	2020	[256]
PCL	Curcumin/allicin/ piperine/polydatin/ quercetin	-	Blend	Wound healing	2019	[228]
PCL	Curcumin	Cyclodextrin	Blend	Drug delivery/tissue engineering	2019	[257]
Konjac glucomannan/zein	Curcumin	-	Blend	Food industrial	2019	[321]
PLLA	Curcumin	-	Blend	Wound healing	2019	[229]
Gliadin	Curcumin	-	Blend	Food industrial	2019	[322]
PCL/PEO	Curcumin	HNT	Blend	Anticancer	2020	[354]
Cyclodextrin	Curcumin	-	Blend	Food industrial	2020	[323]

Table 2. Continued.

Electrospun matrix	Natural extract	Additional medication	Structure	Application	Year	Ref.
PLLA	Caffeic acid	-	Surface immobilization	Wound healing	2012	[230]
Cellulose acetate	Egg albumen	-	Blend	Food industrial	2010	[324]
Zein	Fish oil	-	Blend	Food industrial	2014	[325]
PVA	Fish oil	-	Emulsion	Food industrial	2016	[326]
PVP/Zein	Fish oil	-	Core-sheath	Food industrial	2017	[327]
Zein	Fish oil	Ferulic acid	Core-sheath/blend	Food industrial	2017	[328]
PVA	Gum tragacanth	-	Blend	Wound healing	2013	[231]
PCL	Gum tragacanth	-	Blend	Wound healing	2015	[232]
PLLA	Gum tragacanth	-	Blend	Regeneration nerve	2016	[258]
PLGA	Gum tragacanth	Tetracycline hydrochloride	Blend/core-sheath	Drug delivery	2016	[259]
PVA/PCL	Gum tragacanth	-	Co-electrospinning	Tissue engineering	2017	[260]
PCL/zein	Gum arabic	-	Blend	Tissue engineering	2018	[261]
PCL	Memecylon edule	-	Blend	Tissue engineering	2013	[31]
PCL/PLA	Thymol	-	Co-electrospinning	Wound healing	2013	[181]
PAN	Syzygium aromaticum (clove)	-	Blend	Antibacterial drug delivery	2014	[130]
Cellulose acetate (CA)	Cinnamon, lemongrass and peppermint	-	Blend	Wound healing	2015	[185]
Cellulose acetate (CA)	Rosemary/oregano oils	-	Blend	Antibacterial	2017	[172]
PHBV	Oregano essential oil/rosemary extract/green tea extract	-	Blend	Food industrial	2019	[330]
Chitosan/PEO	Aloe vera	-	Blend by changing the electrospinning equipment	Wound healing	2019	[104]
PLA	Capparis spinosa L. extracts	-	Blend	Wound healing	2021	[233]
Chitosan/PEO	Clove oil	-	Blend	Wound healing	2021	[131]
PEO/rye flour/whey protein	Grape seed extract	-	Blend	Food industrial	2021	[331]
PVA	Grape seed oil	-	Blend	Food industrial	2021	[332]
PEO	Moringa oleifera leaf extract	-	Blend/LBL	Wound healing	2020	[168]
Gelatin	Pomegranate peel	-	Blend	Food and pharmaceutical industrial	2021	[291]
PCL	Urtica dioica	Zno nanoparticles	Blend	Wound healing	2021	[234]
PLA	Honey	S-nitroso-N-acetyl-penicillamine	Blend	Tissue engineering	2021	[262]
Gelatin	Fish oil	Vitamin C	Core-shell	Food industrial	2021	[329]
PLA/PVP	Curcumin	-	Blend	Anticancer	2020	[353]

10. Conclusions and future insights

In conclusion, electrospinning has become a potent and adaptable method for creating nanofibers that are loaded with bioactive substances and natural extracts. Because these electrospun nanofibers can integrate natural substances with therapeutic qualities including antibacterial, antioxidant, and wound-healing activities, they show a wide range of potential applications across the biomedical, industrial, and food packaging sectors. It is possible to tune release kinetics and improve the functioning of these fibers for specific applications by carefully controlling the shape of the nanofibers and the drug-loading procedure.

The papers under evaluation show that extract-loaded electrospun nanofibers (ELENs) have developed significantly, showing promise for applications including cancer therapy, medication transport, and tissue engineering. Even with these developments, there is still a great deal of need for more study. Future research could concentrate on strengthening the electrospinning method scalability, improving the stability of natural chemicals during the process, and adjusting the release profiles for even more precise and long-lasting therapeutic benefits.

The industrial and consumer desire for natural, sustainable, and bio-based materials is driving significant growth in the electrospinning field. Interdisciplinary cooperation across materials science, biology, and engineering is probably going to be crucial to the future creation of novel ELEN applications. In light of the expectation that future research will further increase the significance of these nanofibers' influence on the industrial and biomedical domains, this review emphasizes the need for ongoing investigation into the production and uses of these materials.

CRediT authorship contribution statement

Rashid Forouzande: Writing – original draft.
Ali Akbar Gharehaghaji: Conceptualization, Supervision.
Dina Mohammadi: Visualization, Writing – review & editing.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Declaration of competing interest

The authors declare no competing interests.

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