Chapter

Electrospinning: The Technique and Applications

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Abstract

Electrospinning is a useful and convenient method for producing ultrathin fibers. It has grabbed the scientific community's interest due to its potential to produce fibers with various morphologies. Numerous efforts have been made by researchers and industrialists to improve the electrospinning setup and the associated techniques in order to regulate the morphology of the electrospun fibers for practical applications. Porous, hollow, helical, aligned, multilayer, core-shell, and multichannel fibers have been fabricated for different applications. This chapter aims to provide readers with a clear understanding of the electrospinning process: its principle, methodology, materials, and applications. The chapter begins with a brief introduction to the history of electrospinning, followed by a discussion of its principle and the basic components of electrospinning setup. The parameters that affect the electrospinning process such as operating parameters and the properties of the material being electrospun are discussed briefly. An overview of the different types of electrospinning technique, capable of producing nanofibers with different morphologies, is also presented. Afterward, the applications of electrospun nanofibers, including their use in biomedical applications, filtration, energy sectors, and sensors applications are discussed succinctly. The perspectives on the challenges, opportunities, and new directions for future development of electrospinning technology are also offered.

Keywords: electrospinning, electrospun fiber, coaxial electrospinning, tri-axial electrospinning, core-shell fiber, spinneret

1. Introduction

Electrospinning (electrostatic fiber spinning) has been developed as a sophisticated, modern, and versatile technique since the late 1990s due to its ease of generating nanofibers with a range of materials. It uses an electric field to produce microscopic threads with diameters as small as nanometers (nm). Tissue engineering, filtration, energy, biotechnology, and sensors are just a few of the fields where electrospun fiber membranes find extensive applications [1–5].

1.1 History of electrospinning

In nature, fibers can be found in the shape of elongated objects or continuous filaments. Spiders have relied on webs of fiber matting to catch food in the wild. Silk

fibers with sizes ranging from 2 to 5 meters make up the webs. Silkworms are also known for their capacity to produce silk strands in large quantities. Rayon is the name given to the earliest man-made textiles created from cotton or wood cellulose fibers. DuPont developed nylon as the first commercially feasible synthetic fabric in 1938, and it immediately sparked a popular interest [6–10].

A variety of techniques have been used to manufacture synthetic polymer fibers. The most common procedures are wet, dry, melt, and gel spinning. During the wet spinning process, a spinneret is immersed in a chemical bath. A polymer solution is extruded from a spinneret into a chemical bath, and then the polymer is precipitated out due to the chemical reaction or dilution effect to generate fibers through solidification. During dry spinning, a polymer solution is extruded into the air through a spinneret, and fibers are generated as a result of solvent evaporation from jets aided through a stream of hot air. For melt spinning, a polymer melt is extruded from the spinneret to produce fibers upon cooling. Gel spinning is used to generate fibers with high mechanical strength or other distinctive properties through spinning a polymer in the gel state followed by drying in air and then cooling in a liquid bath. In the gel spinning process, jets are mainly made under external shearing forces and/or mechanical drawing while passing through spinnerets, and fibers are generated upon solidification of the jets as a result of drying or precipitation. The fibers obtained by spinning have diameters in the range of 10–100 micrometers (μm) [11–15].

In 1887, fibers were made from a viscoelastic liquid in the presence of an external electric field as reported by Charles V boys. He used a setup that consisted of an insulated dish connected with an electric supply. He demonstrated that viscoelastic liquid could be drawn into fibers when it moved to the edge of the dish [16]. Electrospinning is a well-known technique now, for the production of continuous ultrathin fibers with diameters ranging from 10 nm to 100 μm. In 1600, William Gilbert introduced the concept of electrospinning. In his study, cone-shaped water droplet formation was observed in the presence of an electric field [4]. In 1747, Abbe Nollet demonstrated the earliest known electrospraying experiment, in which water could be sprayed as aerosol while passing through an electrostatically charged container that was placed on the ground. Both electrospinning and electrospraying are dependent on the use of a high voltage to eject viscous and viscoelastic liquid jets. During electrospinning, the jets eject polymer solution continuously to produce fibers instead of breaking into droplets as with electrospraying. In 1902, John Cooley and William Morton were granted two patents on electrospinning, in which they described a prototype of an electrospinning setup [4, 17]. In 1914, John Zeleny had reported that he was working on the treatment of liquid drop at the end of capillaries. In this study, he tried to find a mathematical model of liquids under electrostatic forces. Formhals tried to produce electrospun fibers in the 1930s, but the system had some disadvantages such as drying, due to the distance between nozzle and collector [18, 19]. In 1940, he improved and modified the device to overcome the drawback. Between 1964 and 1969, Sir Geoffrey Ingram Taylor developed the theoretical underpinning of electrospinning, and his research helped advancement in electrospinning by modeling the hopper form in which liquid drops were formed by the electric field. His collaboration with JR Melcher led to expanding the "leaky dielectric model" for conducting liquids. In early 1990s, some research groups, remarkably those led by Darrel Reneker and Gregory Rutledge, reinvented the electrospinning technique. These groups demonstrated that many different organic polymers could be electrospun into the nanoscale. For the first time, Darrel Reneker used high voltage to charge the polymer dispersion to produce fine fibers with a diameter of less than 5 μm [4, 20–22].

This technique became a very popular and a good choice for producing continuous and long fibers with diameters ranging from micrometer to nanometer. Meanwhile, new methods were developed to control the alignment and structure of electrospun nanofibers, which created new opportunities in energy-related and biomedical applications. After that, many other new methods were developed for aligning the nanofibers to improve several properties of nanofibers such as size, structure, morphology, composition, porosity, and conductivity. One such method is coaxial electrospinning to produce continuous core-sheath and hollow nanofibers [2, 23–27].

2. Electrospinning setup

Electrospinning is a voltage-driven technology that uses an electro-hydrodynamic process, in which a high voltage is applied to the polymer solution and then a liquid droplet is electrified to generate a jet, followed by elongation and stretching to produce fibers. The diameter of these fibers ranges from nanometers to a few micrometers (μm). One of the primary advantages of electrospinning is its adaptability in processing, which allows it to create fibers with a variety of configurations and morphological structures [19, 28]. **Figure 1** represents the schematic diagram of the basic electrospinning set-up. The basic electrospinning setup consists of mainly three parts: (1) a high voltage power supply, (2) a spinneret (metallic needle), and (3) a grounded collector [7, 29–31]. The metallic collectors are generally of three types, namely stationary flat plates, spinning drums, and rotating disc, as shown in **Figure 2**.

2.1 Principle

To understand the basic principle of the electrospinning process, consider a spherically charged droplet of a low-molecular-weight conducting liquid that is placed in a vacuum. The liquid droplet experiences two forces: (1) disintegrative repulsive

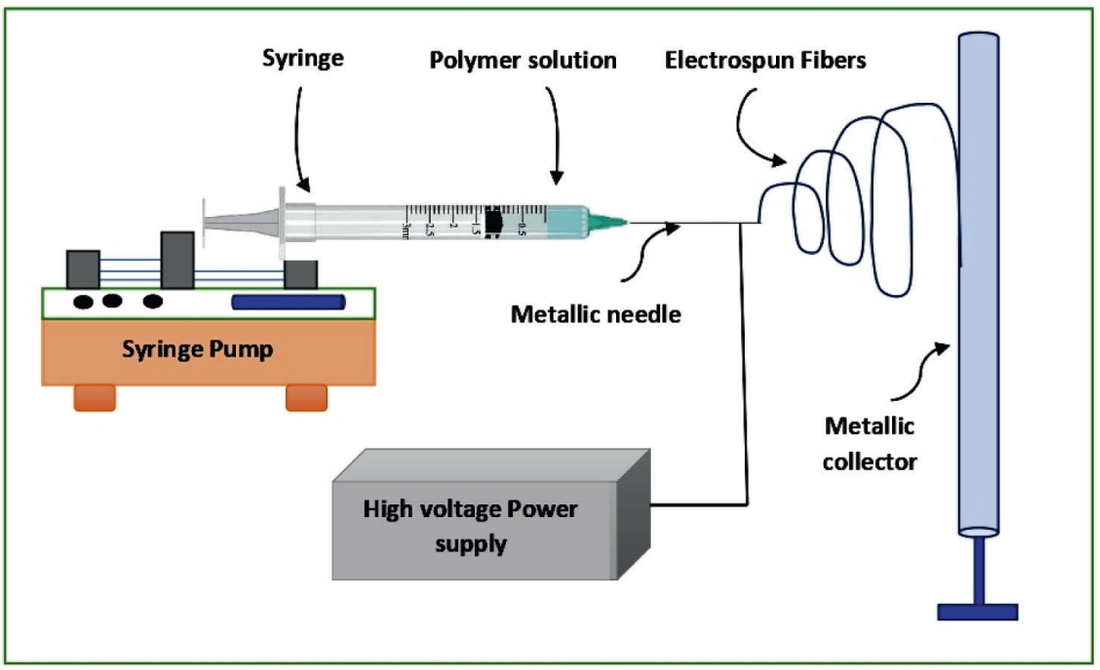

Figure 1.
Basic setup of electrospinning [28].

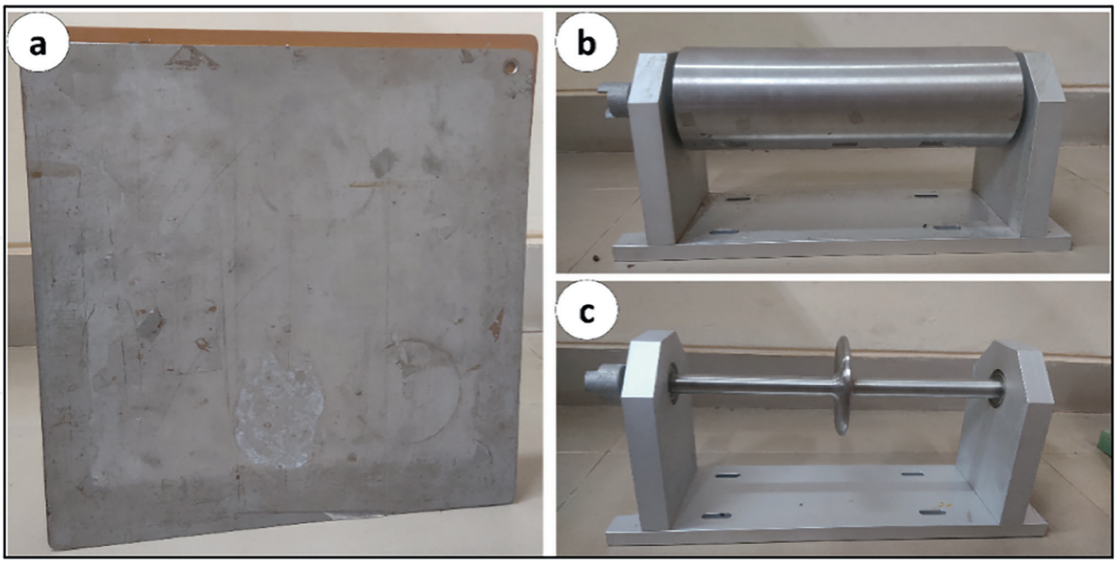

Figure 2.
Metallic collectors. (a) Stationary flat plate, (b) drum collector, and (c) rotating disc.

force and (2) surface tension that tries to hold the liquid droplet in a spherical shape. During the electrospinning process, a high electric voltage is applied to the liquid droplet from polymer melt/solution at the tip of the spinneret. When the high voltage is continuously increased, the liquid droplet will start to elongate into a conical shape known as a "Taylor cone." The elongation starts when the electrostatic repulsion overcomes surface tension. The charged liquid jet is directed toward the metallic collector once the Taylor cone has been produced. The liquid mentioned here can be melt polymer, polymer solution, or an emulsion. Solid fibers will develop as the melt cools down or solvent evaporates from the whipping action that happens throughout the flight time from the Taylor cone to the collector, depending on the liquid viscosity. As a result, the collector is covered with a non-woven fiber mat [32–35].

3. Parameters that affect the electrospinning process

The electrospinning process depends on operating parameters, material parameters, and ambient parameters that affect the morphology of fiber. The operating parameters consist of the applied voltage or electric field, the flow rate of polymer melt/solution, the distance between the tip of the metallic needle and collector, and the diameter of the needle. A small change in the operating parameters can lead to a significant change in the morphology of fiber [23, 26, 36–39].

3.1 Operating parameters

3.1.1 Applied voltage

The applied voltage determines the amount of charges carried by the jet, the degree of electrostatic repulsion among the charges, and the strength of interactions between the jet and the external electric field. Higher voltage facilitates the formation of thinner fibers, but it can also result in more fluid being ejected, resulting in thicker diameter fibers [36, 40].

3.1.2 Flow rate

It is necessary to adjust the flow rate of the spinning liquid for a particular voltage in order to maintain a stable Taylor cone during the electrospinning process. A uniform Taylor cone can produce uniform fibers with narrow dispersion during electrospinning. As the flow rate increased, the amount of material passing through the tip increased, resulting in the formation of fiber with a high diameter. At a very high flow rate, the polymeric jet becomes unstable due to the effect of gravitational force and tends to electrospray [40].

3.1.3 The distance between the tip of the metallic needle and the collector

The distance between the tip and the collector can also influence the diameters and shape of nanofibers; however, the effect is not as strong as the other factors. In the electrospinning process, a minimum distance is necessary to allow enough time for solvent evaporation before the fiber reaches the collector. Thinner fibers have resulted from longer distances. When the distance was too great or too small, beads would form [4, 7, 25].

3.1.4 Diameter of the needle

Nanofibers, electrospun with small needle diameters, are thinner, smoother, and bead-free and have greater fiber porosity than nanofibers electrospun with large needle diameters. As aforementioned, higher applied voltage, smaller spinneret diameter, and lower flow rate resulted in thinner electrospun nanofibers [4, 33, 36].

3.2 Material parameters

The material properties that affect the electrospinning process and fiber morphology involve polymer concentration, the viscosity of the solution, the surface tension of the polymer melt/solution, and other properties related to the solvent as well as the polymer itself [4, 7, 25].

3.2.1 Polymer concentration

Among the material properties, the polymer concentration plays the most significant role in stabilizing the fibrous structure because it influences the other properties such as viscosity of the solution, surface tension, and conductivity of the material [4, 7, 25].

3.2.2 Viscosity

The viscosity of the polymer solution has a significant impact on the diameter and shape of the electrospun fiber. It is controlled by polymer properties including molecular weight and polymer solution concentration. When the concentration of polymer in a solution is raised, the viscosity of the solution rises. If the viscosity is too high, then it will be difficult to pump the solution via the syringe pump, or the solution may dry at the needle tip before electrospinning can begin. Higher viscosity results in the increased diameter fibers and lower deposition region [4, 7, 25].

3.2.3 Surface tension

Surface tension is the attraction between molecules in a liquid that is influenced by intermolecular interactions. During electrospinning, the charges on the polymer solution must be high enough to overcome the solution's surface tension. When a high voltage is applied, the polymer jet begins to form from the needle's tips and elongates and stretches toward the collector, breaking up into minute droplets due to the solution's lower surface tension, which is known as electrospraying. Surface tension causes bead formation when the polymer concentration is low. If the surface tension is low, the formation of the jet begins at a lower voltage. The surface tension of polymer solution can be changed by varying solvents and by adding surfactants [26, 41].

3.2.4 Conductivity

During electrospinning, the charged liquid (melt/solution) stretches to form fibers due to charge repulsion. The jet carries more charges as the electrical conductivity of the solution rises, reducing the diameter of the electrospun fiber. A small amount of polyelectrolyte (salts) can be introduced to eliminate fiber bead formation since it raises more charges and helps to elongate the jet to produce fibers. The electrospinning of polymer solution is difficult at very high voltages, while fiber formation is impossible when the solution has no conductivity [4, 7, 25].

3.2.5 Solvent properties

For electrospinning, solvent choice is critical, since the process is influenced by the solvent's evaporation rate (which is determined by the solvent's vapor pressure) and permittivity [4, 7, 25].

3.2.5.1 Vapor pressure

The volatility or vapor pressure of the solvent determines the evaporation rate and, as a result, the solidification rate of the jet. High volatility is not suitable for spinning fibers because the jet may solidify immediately after leaving the spinneret. If the volatility is too low, the fibers will still be wet when deposited onto the collector. The solvent volatility modifies the surface fiber morphology and nano-membrane structure [4, 7, 25].

3.2.5.2 Permittivity

The permittivity of a solvent has a substantial impact on the electrospinning process and fiber morphology. The bead formation and diameter of the electrospun fiber are reduced when a solution with a greater permittivity is used. Higher permittivity increases bending instability and the traversed jet path of the electrospinning jet, resulting in smaller fiber diameter and a larger deposition area. Solvents such as N, N-dimethylformamide (DMF) can be used to increase the permittivity of polymer solutions [4, 7, 25].

3.3 Ambient parameters

The interaction between the surrounding environment such as the temperature and humidity of the surrounding and the electrospinning jet may alter the electrospinning

process and fiber morphology. The temperature is inversely proportional to the viscosity of the solution. So, the temperature may affect the properties of the electrospinning solution. Humidity may affect the porosity of fiber because humidity influences solvent evaporation [4, 7, 25].

4. Types of electrospinning

Electrospinning technique is divided into two categories based on the electrospinning setup: needle-based electrospinning and needleless electrospinning. Furthermore, needle-based electrospinning is classified into electrospinning using single nozzle, coaxial, tri-axial, and multichannel spinnerets. Electrospinning may also be categorized based on the state of the spinning material. Thus it is divided into three categories: melt electrospinning, emulsion electrospinning, and solution electrospinning.

4.1 Needle-based electrospinning

In needle electrospinning, a needle-like spinneret is utilized and a sharp "cone shape" arises at the needle tip under the influence of the electric field.

4.1.1 Single nozzle

Single nozzle electrospinning is the simplest and basic form of the technique in which only one needle is used as the spinneret as shown in **Figure 1**.

Side-by-side electrospinning is a modification of the basic single nozzle electrospinning. The side-by-side electrospinning process employs two parallel syringes to produce fibers with Janus structure as shown in **Figure 3**. The same voltage is applied to both solutions, and the fiber is usually separated due to repulsion between the two solutions. Producing a Janus structure is extremely difficult due to repulsion, and as a result, just a few studies have been conducted on this topic.

4.1.2 Coaxial electrospinning

A coaxial needle, made up of two concentric hollow needles, is used to produce a coaxially electrified jet for coaxial electrospinning. A simple approach to fabricate a coaxial needle is to insert a small (inner) needle into a larger (outer) needle in a coaxial

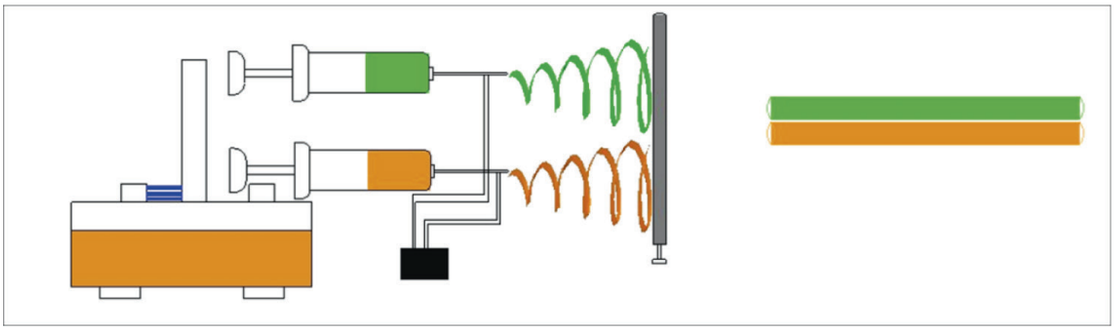

Figure 3.
Side-by-side electrospinning setup.

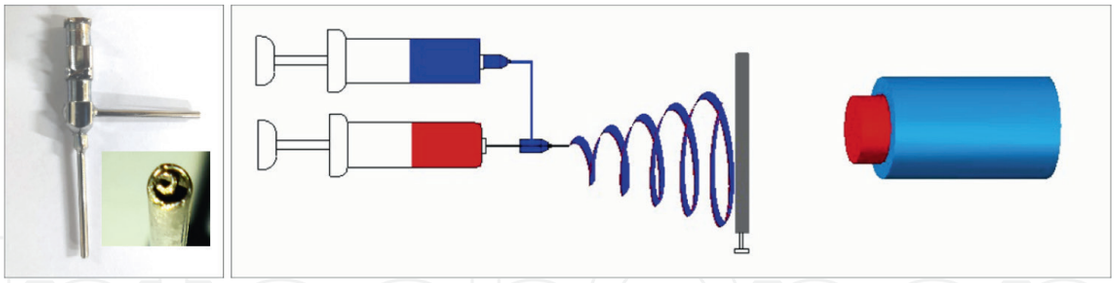

Figure 4.
Coaxial spinneret and coaxial electrospinning setup.

configuration. Using two syringe pumps, the outer and inner needles are subsequently filled with two solutions with independently controllable flow rates. When the core and shell solutions meet at the coaxial needle's exit end, in the presence of an external electric field, the shell solution wraps around the core solution to produce a compound Taylor cone, followed by the ejection of a coaxial jet. Finally, core-shell nanofibers with different core and shell compositions were fabricated, as shown in **Figure 4**.

In the fabrication of core-shell nanofibers, the properties of the inner and outer solutions, as well as the electrospinning parameters, all play important roles. For maintaining the smooth flow of jets, the inner and outer solutions, in particular, should have proper viscosities. Furthermore, the flow rates of the two solutions must be carefully controlled to ensure that the inner solution is completely wrapped by the outside solution. The flow rates may also be adjusted to change the diameter of the nanofibers and the shell thickness.

Coaxial electrospinning is used to fabricate core-shell nanofibers with better control over the compositions for different applications. It also allows for the fabrication of nanofibers from unspinnable liquids, as they may be used as the inner fluid although being controlled by the outer fluid. Hollow nanofibers with adjustable wall thickness can be fabricated by selectively removing the core from as-spun core-shell nanofibers. The core-shell morphology of coaxial electrospun fibers offers the possibility of multifunctional materials, with various functional components put into the two compartments of the concentric structure [24, 34, 42–54].

4.1.3 Tri-axial electrospinning

The trilayer spinneret and tri-axial electrospinning are shown in **Figure 5**. It consists of three concentric metal capillaries. Tri-axial electrospinning is often used to construct a three-layer system with a drug-loaded core, a hydrophobic middle layer, and a hygroscopic exterior layer, as seen in the **Figure 5**. It is vital to avoid merging between the spinning solutions in order to generate high-quality multi-compartment fibers. This means that either the compartmentalized solutions must be immiscible or all of the solutions must evaporate the solvent at the same rate: if one of the liquids evaporates quicker than the others, the compartments will separate. So, the spinneret needs to be designed according to the application. A properly designed spinneret may be utilized to control the behavior of fluids in an electrical field as well as act as a template for constructing the right nanofiber structures [11, 55–57]. Lallave and coworkers [58] were the first to report tri-axial electrospinning. They employed a tri-axial arrangement of ethanol, lignin, and glycerine (from outermost to innermost layer) with ethanol sheath flow to avoid solidification of the Taylor cone and glycerine as a template fluid.

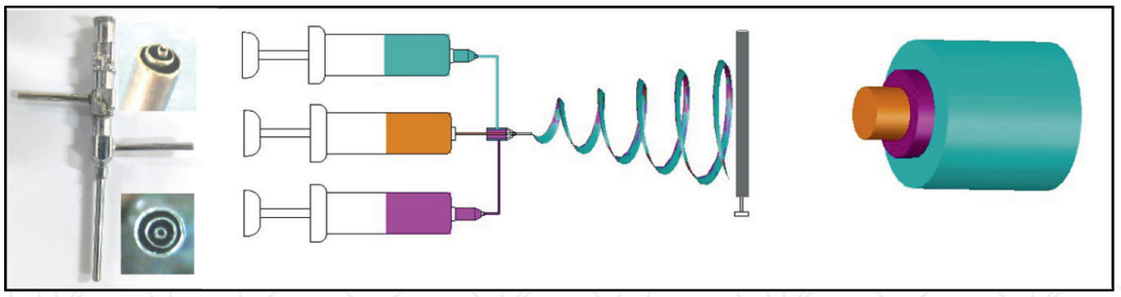

Figure 5.
Tri-axial spinneret and tri-axial electrospinning setup.

4.1.4 Multichannel electrospinning

In the simplest example of multichannel electrospinning, three metallic capillaries are inserted in a syringe at the three vertices of an equilateral triangle as shown in **Figure 6**. Zhao et al. [59] for the first time presented a multifluid compound jet electrospinning approach that can easily and quickly produce bio-mimic hierarchical multichannel microtubes. Multi-axial electrospinning was used to create a biomimetic system. They used numerous inner axial paraffin oils in a $Ti(OiPr)_4$ solution, then removed the organics to construct a multilayer channel.

4.2 Needleless electrospinning

In needleless electrospinning, several cones are spun without the need for a needle or a tiny open structure. The jet initiation in needleless electrospinning is a self-organized process that happens on a free liquid surface and is not driven by capillary forces. It is based on the use of an external agitation force to concentrate the electric field on the free liquid surface to the intensity necessary to initiate a Taylor cone [60–63].

4.3 Melt electrospinning

Solvent removal, recycling, environmental concerns, and toxicity associated with the usage of solvents are all avoided with melt electrospinning. The melted polymer is injected into the capillary tube. The operation must be carried out in a vacuum, therefore the capillary tube, the charged melt fluid jet's passage, and the metal collector must all be enclosed in a vacuum. Melt electrospinning has the advantage of producing extremely homogeneous fibers with very little variation in fiber diameter. Aside from these benefits, there are drawbacks due to the

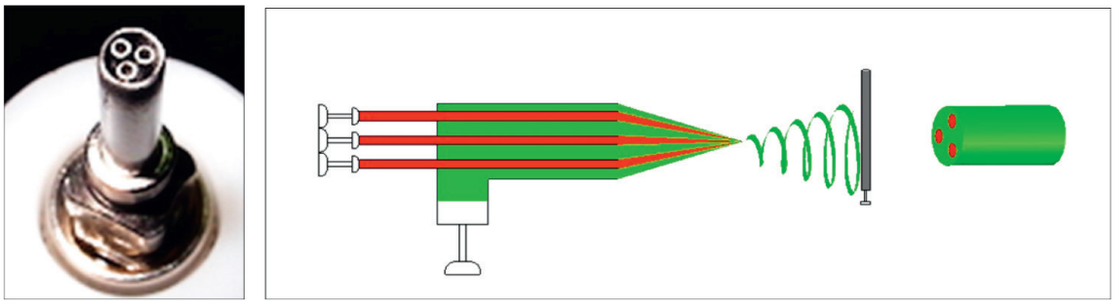

Figure 6.
Multichannel spinneret and multichannel electrospinning setup.

specialized equipment required, as well as the high viscosity and low electrical conductivity of polymer melt. In comparison to electrospinning from a polymer solution, despite the benefits afforded by melt electrospinning, the technology has not achieved more popularity and has not been frequently employed. This is mostly owing to the high viscosity, high process temperatures, and the inability to create nanometer-sized fibers [64–70].

4.4 Emulsion electrospinning

Emulsion electrospinning is a word that refers to two types of electrospinning. (1) the electrospinning of an emulsion through a single spinneret, whereby the emulsion structure allows reorganization to form a core-shell fiber, similar to coaxial electrospinning; (2) the electrospinning of an emulsion through multiple spinnerets, whereby the emulsion structure allows reorganization to form a core-shell fiber, allowing multiple jets to be formed and a higher production rate to be achieved. Emulsion electrospinning increases the loading capacity of drug-polymer systems with low compatibility or affinity, such as water-soluble drugs or proteins loaded in a hydrophobic polymer for longer release. When compared with traditional blending methods, emulsion eliminates the need for a common solvent for both the drug and the polymer. Emulsifiers such as surfactants are frequently used to encapsulate and stabilize the drug phase [24, 71–76].

4.5 Solution electrospinning

Solution electrospinning is the most commonly used method wherein the polymer to be electrospun is dissolved in an appropriate solvent at a suitable concentration. As already discussed, the solution viscosity, as well as other conditions, needs to be optimized carefully to obtain nanofibers with desirable properties [5, 30, 31].

5. Applications of electrospun fibers

Electrospinning is employed extensively in industrial applications because of the attractive properties of electrospun fibers. The unique properties of electrospun fibers may be summarized as follows. First, electrospun fibers have diameters ranging from micro to nanometers. Second, the fibers are porous and aligned. Third, the electrospun fibers have a large aspect ratio and a high surface-to-volume ratio. Fourth, electrospinning enables the production of fibers with an infinite number of chemical compositions, and fifth, it also allows the production of different types of morphology by modifying the spinneret. With the combination of these properties, electrospun fibers can be utilized in biomedical applications [12, 41, 43, 51, 54, 60, 77–84], filtration [39, 85–88], energy sectors [2, 89–93], sensors [5, 26, 94–97], textiles, catalysis [26, 98], and electrical applications [99, 100]. **Figure 7** shows the different types of nanofibers and their applications.

5.1 Biomedical applications

In biomedical applications, biocompatible polymers with bioadhesive and biodegradable properties are preferred. Material selection is critical in the production of these nanofibers because it affects their morphology, biocompatibility, mechanical

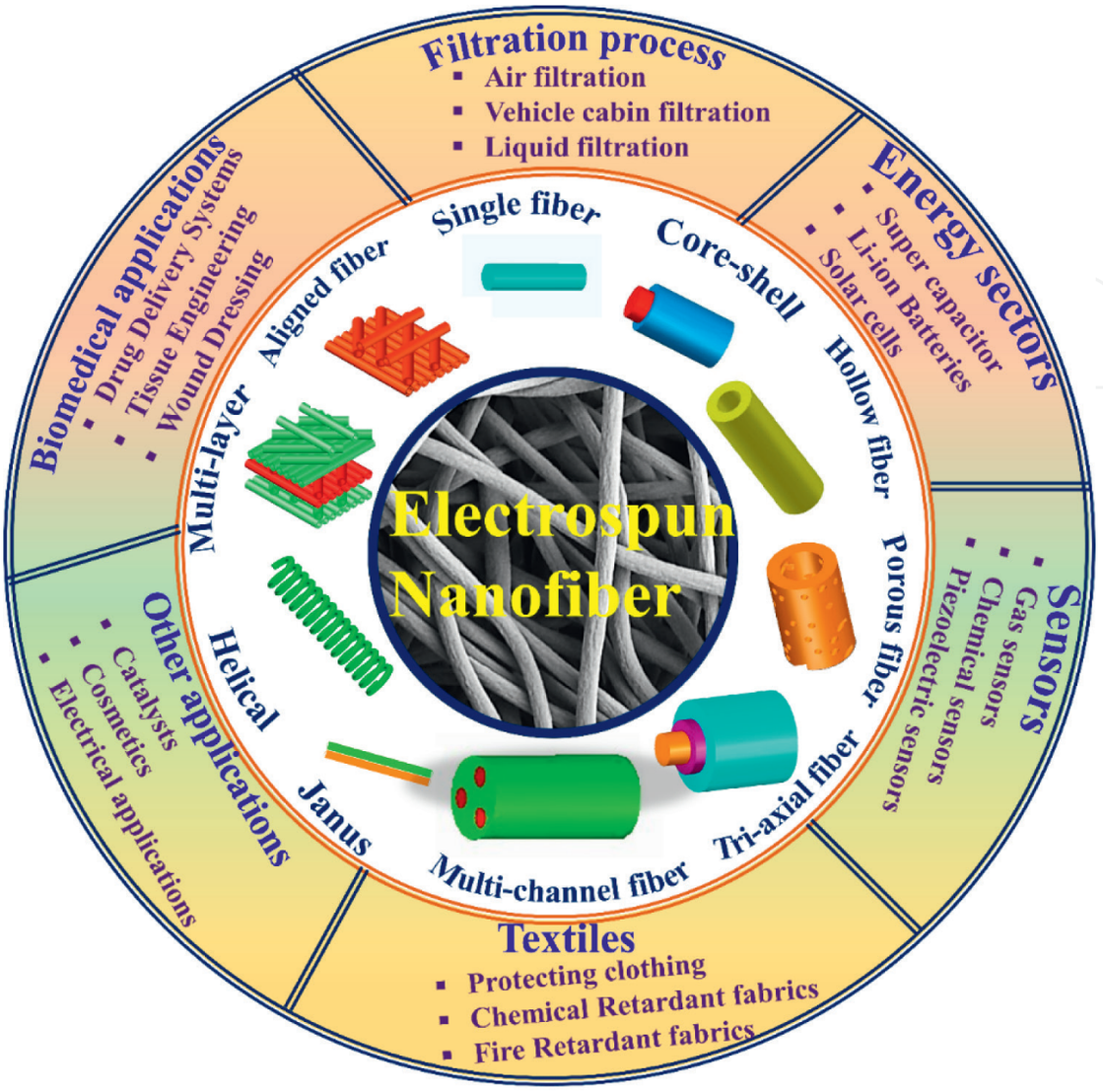

Figure 7.
Different types of electrospun nanofibers and their applications.

strength, degradation rate, and release profile, as well as their interactions with cells, which can result in a range of tissue responses.

Jalaja et al. [43] fabricated electrospun core-shell structured gelatin-chitosan nanofibers for biomedical applications. Chitosan as the shell can mimic the extracellular matrix while gelatin in the core can incorporate drugs and bioactive molecules. Singh et al. [54] fabricated core-shell nanofibers for biomedical applications using a novel coaxial airbrushing method as shown in **Figure 8**.

The core-shell nanofiber was fabricated using an air brush with a coaxial needle to flow two distinct polymeric solutions containing biomolecules [polyethylene oxide (PEO)/poly-DL-lactide/PCL (polycaprolactone)] in core and PCL/PEO is in shell. The great potential of coaxial electrospinning in biomedical field is evidenced by a large number of reports and reviews available in the literature on the topic [54].

5.1.1 Drug delivery systems

The single nozzle electrospinning produces fibers with a high surface area to volume ratio, and as a result, more amounts of drugs would be present at the fiber surface.

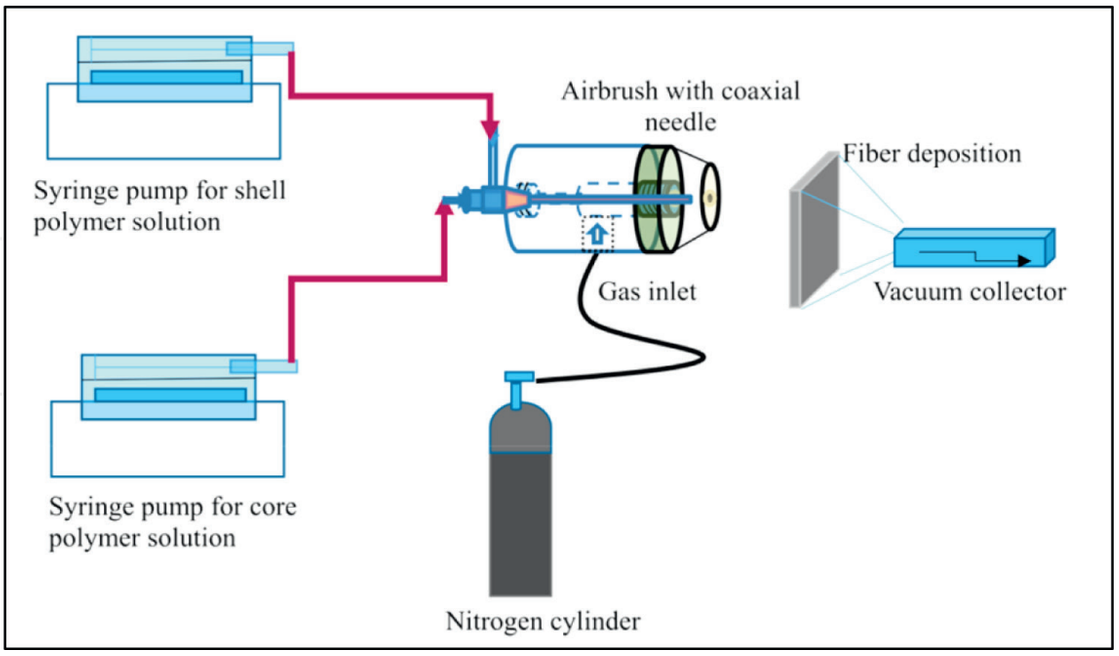

Figure 8.
Experimental setup for core-shell fiber preparation via coaxial airbrushing methods [54].

This frequently leads to a burst release, in which a large amount of the drug content is released into the solution quickly at the start of the process [11, 47, 84, 101, 102]. So, many researchers have relied on core-shell nanofibers to regulate the rate of drug release [34, 42, 45, 49, 103].

5.1.2 Tissue engineering

The interaction of cells and scaffolds for the secretion of extracellular matrix (ECM) and the development of new tissues are the core ingredients of tissue engineering. Biocomposite scaffolds were created to overcome restrictions such as inflammation, toxicity, and recognition caused by scaffold degradation. In tissue engineering, electrospun nanofiber scaffolds are used to replicate the function of the native extracellular matrix (ECM). Core-shell is a flexible approach with intriguing features for encapsulation of the active component, such as growth factors and drugs in the core of the fiber, which is advantageous in drug delivery and tissue regeneration [42, 48, 49, 53, 73, 81, 104–109].

5.1.3 Wound healing

Wound healing is a complicated and comprehensive process that includes four phases: hemostasis, inflammation, proliferation, and remodeling. These stages involve a coordinated and integrated process including extracellular matrix (ECM) mediators, cell growth factors, platelets, cytokines, and chemokines, among others. Ideal wound healing dressings are planned to be multifunctional and capable of delivering various drugs required at various phases of healing. There are various advantages of using electrospun nanofiber for wound dressing. First, the morphology and microstructures of electrospun nanofibers are similar to the natural ECM, which offers a perfect microenvironment for cell adhesion, proliferation, migration, and differentiation. Secondly, the electrospun nanofibers can simultaneously combine

the biocompatibility of natural polymers and the reliable mechanical strength of synthetic polymers. The rate and timing of drug release may be controlled by changing the fiber structure to promote effective wound healing. As a result, electrospun nanofibers have a lot of potential for developing improved bioactive wound dressings [26, 41, 47, 49, 53, 54, 66, 77, 78, 98, 108, 110, 111].

5.2 Applications in filtration process

Electrospun fibers are suitable for filtration due to the properties, particularly, controlled porosity and high surface area to volume ratio. The potential of electrospun fibers in air filtration process has been well investigated [39, 87, 88, 112, 113].

Controlling the porosity of the nanofiber mesh is crucial for air particle permeability and avoiding hazardous particulate matter including dust, pollen, and bacteria. The electrospun fibers possess layer-by-layer structure that provides many interaction sites for a high number of airborne particles. Because of their characteristics, electrospun nanofibers can be used for air filtration [4, 19, 31, 114]. Zhang et al. [14] fabricated electrospun ultrafine fibers for advanced face masks with capability to physically block viruses.

5.3 Applications in energy sectors

The one-dimensional electrospun nanofibers have nanostructured materials with a high aspect ratio, strong mechanical strength, and efficient electron transport, allowing for a wide range of applications in the energy sectors. Additional advantages of electrospun nanofibers include: (1) attractive properties (unidirectional electron flow, uniform porosity, excellent aspect ratio, high surface area, tunable wettability, fine flexibility, and high connectivity); (2) easily tunable morphologies and characteristics according to the precursor solution, processing settings, and setup geometries; (3) simple preparation procedures at the lab scale and feasibility to be made on an industrial basis from a variety of materials; (4) capability to act as free standing electrodes without the need of conductive agents and binders; (5) possibilities to further improve the properties with simple post-electrospinning procedures (solvothermal method, calcination, electrodeposition, chemical vapor deposition, etc.). As a result, electrospun 1D nanofibers have shown significant promise as suitable materials for supercapacitors [6, 30, 92, 115–117], Li-ion batteries [2, 7, 25, 29, 118–123], solar cells [2, 90, 124–128], etc.

5.3.1 Supercapacitors

Electrospun nanofibers are incredibly versatile in terms of forming unique structures that may be altered with defects, functional groups, and other active materials, which is crucial for overcoming the present challenges toward developing efficient supercapacitors. Several research articles and review papers have discussed the attempts to exploit the potential of electrospun nanofibers as components of supercapacitors [2, 6, 22, 30, 89, 92, 115, 117].

5.3.2 Li-ion batteries (LIBs)

LIBs have sparked academic and industry interest because of their long cycle life, high energy density, high operational voltage, and low self-discharge rate.

Many advancements in LIB technology would not have been possible without the development of nanocomposites and nanometer-thick coatings to increase ionic and electronic conduction channels and prevent undesirable and irreversible side reactions. Electrospun nanofibers have excellent electrical and ionic conductivity due to their tunable fiber diameter, high porosity, high specific surface area, and interconnected pore structure, which is useful for improving cyclability and rate capability. Electrospun carbon nanofiber anodes loaded with metal oxide have sparked attention as anode materials in LIBs due to their high theoretical capacity, longer cycle life, and quick recharging rates [2, 118–122, 129–132].

5.3.3 Solar cells

Many inorganic precursors may be electrospun with the help of carrier polymers and then annealed to produce inorganic fibers. This has sparked interest in dye-sensitized solar cells (DSSCs) and other solar energy-generating technologies [2, 124–128, 133, 134]. Nanofibers of TiO_2 have been produced, which are typically employed as the photo-sensitized anode in DSSCs. Nagata et al. [134] utilized coaxial electrospinning to fabricate solar cells using heterojunction polymer fibers.

5.4 Sensors

Sensors have long been a prominent research topic among all the applications of nanomaterials. A sensor is a device that can be detected, measured, and converted into meaningful output signals by following certain rules. In diverse sectors, sensors are also known as sensitive components, detectors, converters,

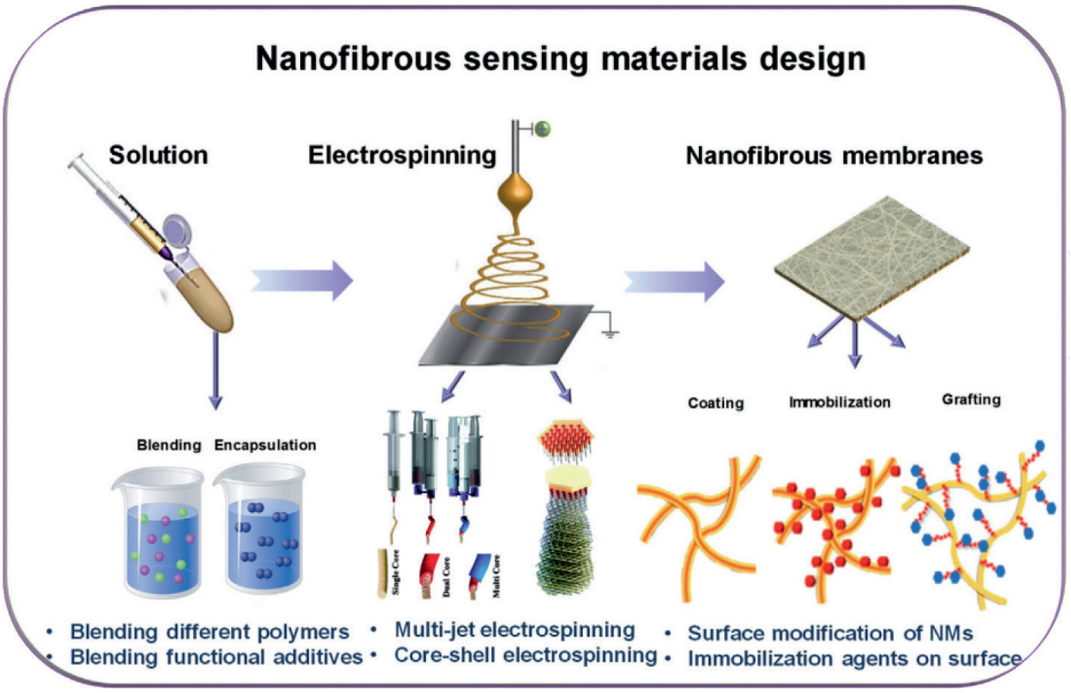

Figure 9.
Schematic illustration of the fabrication of sensing materials via electrospinning [5].

and so on [5, 26, 95–97]. Researchers have designed a number of unique methods for fabricating nanomaterials using conventional electrospinning to satisfy the sensor response unit's specifications as shown in **Figure 9** [5]. Many electrospun nanofiber-based nanomaterials are developed as gas sensors, chemical sensors, piezoelectric sensors [135, 136], and biosensors [137–140].

5.5 Textiles and other applications

Electrospun nanofibers are found to be potential alternative reinforcing choice for composites due to their superior mechanical as well as tunable chemical and physical properties. Despite the fact that electrospun nanofibers offer a number of desired features for usage as nano-fillers, little investigation into their application as prospective reinforcements has been done. The restriction is most likely due to their specific type of nano-fibrous architecture, which they may be made with. The electrospinning technology has been used to incorporate nanoparticles into composite nanofiber fabrics to impart new functions. Additional elements, such as metal nanoparticles, metal oxide nanoparticles, ionic liquids, and conductive polymers, might be included in these nano-fibrous structures to provide technical functions to an engineered fabric, such as electrical conductivity, strain resistance, and antibacterial qualities. The most often used nanomaterials are silver (Ag) and titanium dioxide (TiO_2), followed by silicon dioxide (SiO_2), carbon nanotubes (CNTs), and zinc oxide (ZnO), although a number of polymers are being studied for a range of prospective purposes. In textile applications, polymers such as polyester, polyamide, polyacrylonitrile (PAN), and polyethylene oxide (PEO) are often used. The composited nanofiber textiles with polymer and nanomaterial filler are expected to be light, strong, mechanically flexible, cost-effective, and simple to manufacture. In the case of food science applications, however, only food-grade polymers and safe, nontoxic solvents should be used to make nanofibers. As a result, natural polymers including collagen, gelatin, elastin, fibrinogen, and chitosan have been employed in electrospun technologies in a variety of applications [43, 77, 141]. Low basic weight, small fiber diameter, pore size, high surface area, and fiber chemistry are all critical in the selection of materials for specific applications. With better quality control of the electrospinning process, the fabrication of nanofiber-based textiles from electrospun nanofiber-based material might be widely commercialized [13, 79, 98, 142–144].

6. Summary and conclusion

Electrospinning allows for infinite combinations of chemical compositions, as defined by the periodic table, with morphologies and structures that may be controlled using solution and process parameters. This opens up a vast array of one-dimensional nanomaterials with various desired characteristics that might be used in a wide range of applications. This chapter explained the basic principles of electrospinning and information on how to carry it out. The history of electrospinning and principle, the configuration of electrospinning setup, parameters that influence the properties of electrospun fiber, various types of spinnerets to fabricate electrospun fibers, and their applications in diverse fields have been discussed in brief.

7. Future prospects

Significant development has been made in the field of electrospinning in the previous decade than ever before, and technical breakthroughs continue to evolve. Despite substantial advances, there are issues to be addressed in the future.

It's still difficult to synthesize uniform electrospun nanofibers with certain morphological, mechanical, and chemical properties that are tailored to specific end-user applications. Furthermore, a better understanding is needed to intelligently regulate the processing conditions and solution parameters to impact fiber mat characteristics for specialized applications. Natural polymers have poor chemical and mechanical qualities in some circumstances, and they are less widely employed in various applications than synthetic polymers. As a result, new hybrid polymer systems based on synthetic and natural polymers that are electrospinnable and have better functionalities are needed for a wide range of applications, particularly in biotechnology.

Several spinnerets have been proposed for mass production; however, some of them may not be suitable, and some of them still require additional experimental verifications in terms of fiber quality control and the electrospinning process. Electrospinning processes such as coaxial, tri-axial, multichannel, and side-by-side electrospinning have been found to be effective in customizing the physical properties of electrospun nanofibers. However, more research into the process control and mechanism for core-shell and multichannel morphologies of electrospun nanofibers is required. In comparison to solution electrospinning, melt electrospinning provides benefits such as the lack of harmful solvents and high production. To achieve theoretically expected strengths, however, tremendous measures are needed to minimize fiber diameters while simultaneously establishing a high degree of orientation in the structure. Needleless spinnerets offer considerable promise in electrospinning nanofibers on large scales, but needleless electrospinning of bicomponent nanofibers remains a difficulty. Although over 200 polymers have been successfully electrospun into nanofibers, there has been little research on the macromolecular orientation and crystalline structures of the resultant fibers. In addition, the influence of the crystalline phase and molecule orientation on mechanical properties remains unclear.

Application of electrospun nanofibers: Despite the fact that electrospun nanofibers have been shown to be a potential candidate for composite reinforcements, little study has been done on this subject due to their poor mechanical properties when compared with standard alternatives such as carbon or glass fibers. Adding nanoparticles as a post-treatment to electrospun nanofibers may be an acceptable approach to increase mechanical properties. One of the main hurdles to the advancement of electrospinning applications in tissue engineering is increasing scaffold thickness, pore size, and the difficulty to prepare identical scaffolds. The relationships between drug-controlled release profiles and nanofiber structures should be investigated in detail. To understand the drug transport mechanism and to predict drug release kinetics as a function of nanofiber structure, mathematical models of drug release from diverse nanofibers might be useful. Electrospun nanofibers offer a lot of potential in the energy sector, but there are still a lot of obstacles and opportunities to be explored in this field. "Bottleneck" difficulties in electrospun nanofibers such as poor conductivity, chemical structural instability, volume expansion, and kinetic hysteresis of active materials should be addressed in this research field. For filtering applications, further research might involve using different polymers and/or post-treatment procedures to control the formation of pores on fibers, as well as a better understanding of the transport process through fibers with microporous rough

surfaces. Electrospun nanofibers have been shown to exhibit remarkable properties for sensor applications. Further research into improving the surface area and pore sizes of nano-fibrous membranes is suggested to improve sensitivity. Furthermore, incorporating such nanomaterials into practical devices is difficult, as it necessitates materials with precise orientation, size, and repeatability in order to place them in specific positions and orientations.

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Conflict of interest

The authors declare that they do not have any conflict of interest.

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