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Electrospinning method: Prospects for current electronics products and applications

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Abstract

The production of fibers with diameters ranging from nanometers to micrometers can be achieved through electrospinning, a simple and versatile method that has been widely researched and developed. This method has diverse applications in various fields, including electronics. This article presents an overview of electrospinning, covering its history, principles, and applications in different fields. The focus of this review is on the potential applications of electrospun fibers in the electronics industry, such as transparent conductive films, energy storage and conversion devices, and e-textiles. We discuss the different materials used, the methods employed, and the various applications of electrospun fibers in electronics, while also highlighting the challenges and limitations of this approach for electronics applications. Our analysis reveals that electrospun fibers possess unique properties that make them attractive to produce highly efficient and cost-effective electronic devices. However, further research is required to optimize the electrospinning process and develop more efficient and reliable electrospun fibers for use in electronics applications.

Keywords: Electrospinning, Electro spun, Electronics, Fibers, E-textiles.

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1. Introduction

Electrospinning is a versatile and simple method for producing fibers with diameters ranging from nanometers to micrometers. The method was first reported in 1934 by Formhals, who used it to produce fine polymer fibers by applying a high voltage to a droplet of polymer solution [1]. Since then, electrospinning has been extensively studied and developed, and has found applications in a variety of fields, including biomedical engineering, energy storage and conversion, environmental remediation, and electronics. In the electronics industry, electro spun fibers have the potential to revolutionize the production of a range of devices, including energy storage and conversion devices, transparent conductive films, and e-textiles [2]. Electro spun fibers offer unique properties, such as high surface area-to-volume ratio, high porosity, and tunable morphology and composition, which make them attractive for these applications. In this paper, we aim to explore the potential of electrospinning for producing fibers for use in electronic devices. Specifically, we hypothesize that electro spun fibers can be used to produce highly efficient and cost-effective energy storage and conversion devices, transparent conductive films, and e-textiles. We will also discuss the challenges and limitations of electrospinning for these applications and suggest possible solutions.

2. Literature Review

Electrospinning has been widely explored for various electronics applications. In terms of materials, electrospinning has been used to produce fibers from a range of polymers, including polyacrylonitrile (PAN), polyvinyl alcohol (PVA), and polycarbonate (PC) [3]. The electro spun fibers can also be functionalized by incorporating metal nanoparticles, carbon nanotubes, and graphene, among others, to enhance their electrical and mechanical properties [4]. In terms of methods, electrospinning can be carried out in either a batch or continuous mode, and the process parameters, such as solution concentration, applied voltage, and flow rate, can be adjusted to control the fiber morphology and properties [5]. Various techniques, such as post-treatment, can also be employed to further modify the properties of the electro spun fibers. In the field of energy storage and conversion devices, electro spun fibers have been used as electrode materials in supercapacitors, batteries, and fuel cells [6]. The high surface area and porosity of the electro spun fibers allow for a high surface area-to-volume ratio, which is essential for enhancing the electrochemical performance of these devices [7]. The electro spun fibers were also used as templates for the synthesis of metal oxide and carbon-based materials, which could further improve the energy storage and conversion properties. Transparent conductive films (TCFs) are also a potential application of electro spun fibers in electronics [8]. By incorporating conductive materials, such as silver nanoparticles, into the electro spun fibers, a highly conductive and transparent film can be produced. This has potential applications in touch screens, solar cells, and flexible electronics. Indium tin oxide (ITO) is the most used material for TCFs, but it has limitations such as high cost and brittleness [9]. Electro spun fibers were investigated as an alternative material for TCFs. It was found that the fibers had high transparency and conductivity, and could be deposited onto flexible substrates, making them suitable for use in bendable electronic devices. Finally, electrospun fibers have also been explored for use in e-textiles. The high flexibility and breathability of the electrospun fibers make them an attractive material for producing wearable electronics, such as sensors and energy harvesters. E-textiles are wearable electronic devices that integrate electronics with textiles. Electrospun fibers were investigated for their potential use in e-textiles. It was found that the fibers could be easily integrated into textiles, and could be used to produce sensors, actuators, and energy harvesting devices [10]. Despite the potential of electrospinning for electronics applications, there are some challenges and limitations that need to be addressed. These include the low production rate, limited scalability, and difficulty in achieving uniform fiber morphology. Further research is needed to optimize the electrospinning process and to develop more efficient and reliable electrospun fibers for use in electronics applications.

3. Materials and methods

The electrospinning system as show as **Figure 1** consists of a high-voltage power supply, a syringe pump, a spinneret, and a collector. The syringe is loaded with a polymer solution or a mixture of polymers dissolved in a solvent. The polymer solution is then extruded through the spinneret at a controlled rate using the syringe pump. A high voltage is applied to the spinneret, which creates an electric field that draws the polymer solution towards the collector, where it solidifies into a fiber [11]. A wide variety of materials can be used for electrospinning, including polymers, ceramics, and metals. In electronics applications, conductive polymers and materials with high surface area-to-volume ratios are often used. Examples of commonly used polymers include polyacrylonitrile (PAN), polyvinyl alcohol (PVA), and polyethylene oxide (PEO). Metal and ceramic nanoparticles can also be incorporated into polymer solutions to produce composite fibers with unique properties. Several parameters can affect the morphology and properties of electrospun fibers, including solution viscosity, conductivity, surface tension, and solvent evaporation rate. The applied voltage and the distance between the spinneret and the collector also affect the fiber morphology. By adjusting these parameters, it is possible to control the diameter, alignment, and porosity of the resulting fibers [12]. To investigate the properties and potential applications of electrospun fibers in electronics, a series of experiments can be designed and conducted. The polymer solution is prepared by dissolving the polymer or a mixture of polymers in a suitable solvent. The solution is then electrospun using a specific set of parameters to produce fibers with desired morphologies. The resulting fibers are characterized using techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR). The data collected from the experiments are analyzed using statistical methods to determine the effect of different parameters on fiber morphology and properties. Regression analysis can be used to identify the most significant factors affecting fiber diameter and alignment. The properties of electrospun fibers, such as conductivity and porosity, can also be analyzed using appropriate techniques. These data can then be used to optimize the electrospinning process and to design more efficient and reliable electrospun fibers for electronics applications [13].

4. Several common electrospinning methods

4.1. Single Jet Electrospinning

Single Jet Electrospinning: This is the most basic electrospinning method, where a polymer solution is fed through a single nozzle and a high voltage is applied to the solution. As the voltage is increased, the polymer solution is charged, and a Taylor cone is formed at the tip of the nozzle. As the voltage continues to increase, a jet of polymer solution is ejected from the Taylor cone, and the solvent evaporates, leaving behind a solid fiber [14].

4.2. Coaxial Electrospinning

Coaxial Electrospinning: This method involves using two concentric needles to electrospin two different solutions simultaneously. The inner needle is used to deliver the core material, while the outer needle is used to deliver the shell material. The two solutions are electrospun simultaneously to produce a fiber with a core-shell structure [15].

4.3. Emulsion Electrospinning

Emulsion Electrospinning: This method involves using an emulsion as the spinning solution. An emulsion is a mixture of two immiscible liquids, such as oil and water, stabilized by an emulsifying agent.

The emulsion is electrospun to produce fibers with a core-shell structure [16].

4.4. Needleless Electrospinning

Needleless Electrospinning: This method does not use a needle to electrospin fibers. Instead, a high voltage is applied to a spinning solution that is sprayed through a small orifice. The solvent evaporates, leaving behind a solid fiber [17].

4.5. Multi-Jet Electrospinning

Multi-Jet Electrospinning: This method involves using multiple nozzles to electrospin fibers simultaneously. This can increase the production rate of electrospun fibers [18]. These are just a few of the common electrospinning methods used in scientific research. Each method has its advantages and disadvantages, and the choice of method depends on the specific application and the properties of the polymer solution.

5. Morphologies electrospun fiber based on different electrospinning method

Different electrospinning methods can lead to varying morphologies in electrospun fibers. Some common morphologies observed in electrospun fibers based on these methods are presented below. Single Jet Electrospinning: The fibers produced by this method are typically smooth and cylindrical with a uniform diameter. However, if the polymer solution is too concentrated or the electrospinning conditions are not optimized, beading or branching of the fibers may occur, resulting in a non-uniform fiber structure [19].

5.1. Coaxial Electrospinning

The core-shell structure of the fibers produced by this method can vary depending on the flow rate and the concentration of the core and shell solutions. The core and shell can be uniform or exhibit a concentration gradient, resulting in a variety of core-shell morphologies [20].

5.2. Emulsion Electrospinning

The fibers produced by this method often have a core-shell structure, with the core being the dispersed phase of the emulsion and the shell being the continuous phase. The morphology of the fibers can vary depending on the type of emulsifying agent used and the concentration of the emulsion [21].

5.3. Needleless Electrospinning

The fibers produced by this method often exhibit a highly porous morphology, with a large surface area-to-volume ratio. The porosity can be controlled by adjusting the electrospinning parameters, such as the voltage and distance between the spinneret and the collector [22].

5.4. Multi-Jet Electrospinning

The fibers produced by this method can have a range of morphologies depending on the number and arrangement of the nozzles. The fibers can be aligned or randomly oriented, and can have a uniform or non-uniform diameter [23].

In summary, the morphology of electrospun fibers can vary depending on the electrospinning method used, and can be controlled by adjusting the electrospinning parameters such as solution concentration, flow rate, and applied voltage. Tengzhou X. et al., reported that electrospun nanofibers can exhibit various morphologies, such as cobweb, hollow, core-shell, randomly distributed, aligned, patterned, composite, pine needle, and hollowed-out nanofibers [24].

6. Method

6.1. Single Jet Electrospinning

Single jet electrospinning as show as Figure 2 can produce various types of structures for electrospun fibers, depending on the processing conditions and the material properties. The structures of electrospun fibers can be categorized into four types: solid, porous, core-shell, and hollow. Solid fibers have a uniform morphology with a solid cross-section, and they are commonly produced using polymer solutions with low viscosities and high surface tension [25]. Porous fibers have an interconnected porous structure, which is beneficial for applications such as filtration, tissue engineering, and drug delivery [26]. Porous fibers can be produced by controlling the solvent evaporation rate, the concentration of the polymer solution, and the diameter of the spinneret. Core-shell fibers have a coaxial structure, where a core material is surrounded by a shell material. These fibers can be produced by using a dual-coaxial spinneret, where two solutions are electrospun simultaneously from the same spinneret, with the core solution flowing through the innermost needle and the shell solution flowing through the outer needle [27]. Hollow fibers have a tubular structure with an empty central lumen. These fibers can be produced by using a single coaxial spinneret, where a polymer solution is electrospun through an outer needle, and a solvent is introduced through the inner needle, which is removed after spinning [28]. Overall, the structure of the electrospun fibers produced by single jet electrospinning can be controlled by adjusting the process parameters and the material properties to meet specific application requirements.

6.2. Emulsion Electrospinning

Emulsion electrospinning as show as Figure 3 can produce a variety of structures for electrospun fibers depending on the processing conditions and material properties [29]. Emulsion electrospinning is a technique where a polymer solution is emulsified in an immiscible solvent to form droplets, which are then electrospun into fibers. Solid fibers have a uniform morphology with a solid cross-section, and are commonly produced using emulsion electrospinning techniques. The size and distribution of the droplets can be controlled by adjusting the emulsion processing parameters, such as the type and concentration of the emulsifier, the emulsification speed, and the emulsification time [30]. Porous fibers have an interconnected porous structure, which is useful for applications such as filtration, tissue engineering, and drug delivery. Porous fibers can be produced by emulsion electrospinning using a water-in-oil emulsion, where the droplets are composed of a polymer solution and water [31]. After electrospinning, the water can be removed by evaporation, leaving behind a porous structure.

Core-shell fibers have a coaxial structure, where a core material is surrounded by a shell material. These fibers can be produced by using an emulsion electrospinning setup, where two immiscible polymer solutions are emulsified together to form droplets with a core-shell structure, which are then electrospun into fibers [32]. Hollow fibers have a tubular structure with an empty central lumen. These fibers can be produced by using an emulsion electrospinning setup, where the droplets are composed of a polymer solution and a volatile solvent. After electrospinning, the solvent can be removed by evaporation, leaving behind a hollow structure [33]. Overall, the structure of the electrospun fibers produced by emulsion electrospinning can be controlled by adjusting the process parameters and the material properties to meet specific application requirements. The advantages of emulsion electrospinning include the ability to produce fibers with complex structures and the possibility of encapsulating different materials within the fibers for advanced applications.

6.3. Needleless Electrospinning

Needleless electrospinning as show as **Figure 4** can produce a variety of structures for electrospun fibers depending on the processing conditions and material properties [34]. The structures of electrospun fibers can be categorized into four types: solid, porous, core-shell, and hollow. Solid fibers have a uniform morphology with a solid cross-section, and are commonly produced using needleless electrospinning techniques such as electrospinning from a flat substrate or electrospinning using a rotating drum [35]. Porous fibers have an interconnected porous structure, which is beneficial for applications such as filtration, tissue engineering, and drug delivery. Porous fibers can be produced by adjusting the processing conditions such as the solvent evaporation rate, the concentration of the polymer solution, and the distance between the spinneret and the collector [36]. Core-shell fibers have a coaxial structure, where a core material is surrounded by a shell material. These fibers can be produced by using a concentric tube electrospinning setup, where two solutions are electrospun simultaneously from different concentric tubes, with the core solution flowing through the innermost tube and the shell solution flowing through the outer tube. Hollow fibers have a tubular structure with an empty central lumen. These fibers can be produced by using a coaxial tube electrospinning setup, where a polymer solution is electrospun through an outer tube, and a solvent is introduced through the inner tube, which is removed after spinning. Overall, the structure of the electrospun fibers produced by needleless electrospinning can be controlled by adjusting the process parameters and the material properties to meet specific application requirements.

6.4. Multi-Jet Electrospinning

Multi-jet electrospinning as show as **Figure 5** can produce a variety of structures for electrospun fibers depending on the processing conditions and material properties. The structures of electrospun fibers can be categorized into four types: solid, porous, core-shell, and hollow. Solid fibers have a uniform morphology with a solid cross-section and can be produced by multi-jet electrospinning using polymer solutions with low viscosities and high surface tension. Porous fibers have an interconnected porous structure, which is useful for applications such as filtration, tissue engineering, and drug delivery. Porous fibers can be produced by adjusting the processing conditions such as the solvent evaporation rate, the concentration of the polymer solution, and the diameter of the spinneret [36]. Core-shell fibers have a coaxial structure, where a core material is surrounded by a shell material. These fibers can be produced by using a multi-jet coaxial electrospinning setup, where two or more solutions are electrospun simultaneously from different coaxial needles [37]. Hollow fibers have a tubular structure with an empty central lumen. These fibers can be produced by using a multi-jet concentric electrospinning setup, where multiple solutions are electrospun simultaneously from different concentric needles, with a solvent introduced through the innermost needle. Overall, the structure of the electrospun fibers produced by multi-jet electrospinning can be controlled by adjusting the process parameters and the material properties to meet specific application requirements. The advantage of multi-jet electrospinning is the ability to produce complex structures by combining different materials, which makes it a promising technique for advanced applications in various fields, such as biomedicine and energy storage.

7. Morphologies

7.1. Cobweb Nanofiber

Electrospun cobweb structure refers to the unique morphology of ultrafine fibers produced by cobweb electrospinning, which resembles a spider's cobweb. The electrospinning process used to produce the cobweb structure involves using a low concentration of polymer solution and a high applied voltage, which results in the formation of a fine, interconnected web-like structure. The cobweb structure consists of randomly oriented, ultrafine fibers that are intertwined and interconnected with each other, forming a porous and flexible network [38]. The interconnected fibers in the cobweb structure have a high surface area to volume ratio, which makes them useful for a variety of applications such as filtration, sensing, and tissue engineering. The electrospun cobweb structure has unique properties compared to other electrospun fiber structures, such as higher porosity, surface area, and mechanical flexibility [39]. This makes it an attractive material for a variety of applications, such as drug delivery, wound healing, and energy storage. However, it is important to note that controlling the formation of the electrospun cobweb structure can be challenging and requires precise control over processing parameters such as concentration, viscosity, and applied voltage.

7.2. Hollow Nanofiber

Hollow electrospun fibers, also known as core-shell electrospun fibers, have a unique structure consisting of a hollow core surrounded by a shell of electrospun fibers. This structure can be achieved by electrospinning a polymer solution containing a sacrificial material as the core, which is later removed by dissolution or burning. Hollow electrospun fibers have attracted significant attention due to their unique properties, such as high surface area to volume ratio, tunable porosity, and the ability to encapsulate and release bioactive molecules [40].

Below are some possible uses of hollow electrospun fibers, which will be explained in detail. The hollow core of electrospun fibers can be used to encapsulate and deliver drugs or other bioactive molecules. The shell can be designed to control the release rate and duration of the drug, providing a sustained and controlled drug delivery system [41]. The unique properties of hollow electrospun fibers make them ideal for tissue engineering applications. They can be used as scaffolds for tissue regeneration, with the hollow core providing space for cell growth and proliferation, and the shell providing mechanical support [42]. Hollow electrospun fibers can be used as electrodes in energy storage devices, such as batteries and supercapacitors. The high surface area to volume ratio of the fibers enhances the electrochemical performance of the device [43]. The high surface area of electrospun fibers can be used to detect and sense various analytes. By functionalizing the surface of the fibers with specific receptors, they can be used as biosensors for various applications, such as environmental monitoring and medical diagnostics. Overall, the unique structure and properties of hollow electrospun fibers make them a promising material for a variety of applications in the fields of medicine, energy, and sensing.

7.3. Core-shell Nanofibers

Core-shell electrospun fibers have a unique structure consisting of a core material surrounded by a shell of electrospun fibers. This structure can be achieved by electrospinning a polymer solution containing a core material, followed by electrospinning a shell material around the core. Core-shell electrospun fibers have attracted significant attention due to their unique properties, such as high surface area to volume ratio, tunable porosity, and the ability to encapsulate and release bioactive molecules [44]. Below are some possible uses of core-shell electrospun fibers, which will be explained in detail. The core of electrospun fibers can be used to encapsulate and deliver drugs or other bioactive molecules, while the shell can be designed to control the release rate and duration of the drug. This provides a sustained and controlled drug delivery system [45]. Core-shell electrospun fibers can be used as scaffolds for tissue regeneration. The core material can provide space for cell growth and proliferation, while the shell can provide mechanical support and control the release of growth factors [46]. The high surface area and tunable porosity of core-shell electrospun fibers make them ideal for separation and filtration applications [47]. By controlling the core and shell materials, the fibers can be designed to selectively capture and remove specific molecules or particles. The high surface area and ability to encapsulate bioactive molecules make core-shell electrospun fibers useful for sensing applications. By functionalizing the surface of the fibers with specific receptors, they can be used as biosensors for various applications, such as environmental monitoring and medical diagnostics [48]. Core-shell electrospun fibers can be used as electrodes in energy storage devices, such as batteries and supercapacitors [49]. The high surface area and unique structure of the fibers enhance the electrochemical performance of the device. Overall, core-shell electrospun fibers have a wide range of potential applications in the fields of medicine, energy, separation, and sensing.

7.4. Randomly Distributed Nanofibers

Randomly distributed electrospun fibers have a structure where fibers are randomly oriented and distributed within a non-woven fabric. This structure is achieved by electrospinning a polymer solution onto a substrate, resulting in a mat of randomly oriented and interconnected fibers. Randomly distributed electrospun fibers have a wide range of potential applications due to their unique properties, including high surface area, tunable pore size, and high porosity [50]. Below are some possible uses of randomly distributed electrospun fibers, which will be explained in detail. The high porosity and interconnected structure of randomly distributed electrospun fibers make them ideal for wound dressings [51]. The fibers can be designed to mimic the extracellular matrix of skin tissue, promoting cell attachment and proliferation [52]. Randomly distributed electrospun fibers can be used for air and liquid filtration applications. The high surface area and tunable pore size of the fibers make them effective at capturing and removing small particles and pollutants [53]. Randomly distributed electrospun fibers can be used as scaffolds for tissue engineering applications [54]. The fibers provide a high surface area for cell attachment and proliferation, while the interconnected structure allows for nutrient and waste exchange. Randomly distributed electrospun fibers can be used as electrodes in energy storage devices, such as batteries and supercapacitors [55]. The high surface area and interconnected structure of the fibers enhance the electrochemical performance of the device. The high surface area of randomly distributed electrospun fibers makes them effective catalysts for various chemical reactions [56]. By functionalizing the surface of the fibers with specific catalytic materials, they can be used to promote various chemical reactions. Overall, the unique properties of randomly distributed electrospun fibers make them a promising material for a variety of applications in the fields of medicine, energy, and catalysis.

7.5. Aligned Nanofibers

Aligned electrospun fibers have a structure where the fibers are aligned in a parallel orientation. This structure can be achieved by electrospinning a polymer solution onto a rotating or stationary collector, resulting in a mat of fibers that are aligned in a specific direction. Aligned electrospun fibers have attracted significant attention due to their unique properties, such as high mechanical strength, anisotropic conductivity, and the ability to mimic the extracellular matrix of various tissues [57]. Below are some possible uses of aligned electrospun fibers, which will be explained in detail. Aligned electrospun fibers can be used as scaffolds for tissue engineering applications [58]. The aligned fibers mimic the natural orientation of collagen fibers in various tissues, such as muscle, nerve, and bone, promoting cell attachment, proliferation, and differentiation. Aligned electrospun fibers can be used for the regeneration of damaged tissues, such as spinal cord injuries, where nerve guidance channels made of aligned fibers can help in axonal regeneration [59]. Aligned electrospun fibers can be used for wound healing applications [60]. The aligned fibers can be designed to mimic the extracellular matrix of skin tissue, promoting cell attachment and proliferation. Aligned electrospun fibers can be used as electrodes in energy storage devices, such as batteries and supercapacitors [61].

The aligned fibers provide high mechanical strength and anisotropic conductivity, which enhances the electrochemical performance of the device. Aligned electrospun fibers can be used as sensing elements in various applications, such as strain sensors, biosensors, and environmental sensors [62]. The aligned fibers provide a high surface area for sensing and can be functionalized with specific receptors for various sensing applications. Overall, aligned electrospun fibers have a wide range of potential applications in the fields of medicine, energy, and sensing, among others. The unique properties of aligned electrospun fibers make them an attractive material for various applications that require high mechanical strength, anisotropic conductivity, and a biomimetic structure.

7.6. Patterned Nanofibers

Patterned electrospun fibers have a structure where the fibers are arranged in a specific pattern or geometry, such as grids, circles, stripes, and spirals. This structure can be achieved by using a template or mask during electrospinning, which controls the deposition of the polymer solution onto the substrate, resulting in a patterned mat of fibers. Patterned electrospun fibers have attracted significant attention due to their unique properties, such as tunable mechanical properties, controlled drug release, and enhanced cell adhesion and alignment. Below are some possible uses of patterned electrospun fibers, which will be explained in detail. Patterned electrospun fibers can be used as scaffolds for tissue engineering applications [63]. The patterned fibers can be designed to mimic the natural architecture of various tissues, such as cardiac, vascular, and nerve tissues, promoting cell attachment, proliferation, and differentiation. Patterned electrospun fibers can be used for controlled drug release applications [64]. The patterned fibers can be functionalized with specific drugs or growth factors, and the release rate can be controlled by the patterned structure. Patterned electrospun fibers can be used as sensing elements in various applications, such as biosensors and environmental sensors [65]. The patterned fibers can be functionalized with specific receptors for various sensing applications. Patterned electrospun fibers can be used for microfluidic applications, such as microchannels and microreactors [66]. The patterned fibers can be used to control the flow and mixing of fluids within the microdevices. Patterned electrospun fibers can be used as electrodes in energy storage devices, such as batteries and supercapacitors [67]. The patterned fibers provide a high surface area and tunable mechanical properties, which enhances the electrochemical performance of the device. Overall, patterned electrospun fibers have a wide range of potential applications in the fields of medicine, energy, and sensing, among others. The unique properties of patterned electrospun fibers make them an attractive material for various applications that require controlled structure and function.

7.7. Composite Nanofiber

Composite electrospun fibers have a structure where two or more different materials are combined to form a single fiber [68]. This structure can be achieved by electrospinning a polymer solution that contains multiple components, such as nanoparticles, nanofibers, or biomolecules, resulting in a composite mat of fibers. Composite electrospun fibers have attracted significant attention due to their unique properties, such as tunable mechanical, electrical, and biological properties. Below are some possible uses of composite electrospun fibers, which will be explained in detail. Composite electrospun fibers can be used as scaffolds for tissue engineering applications [69]. The composite fibers can be designed to mimic the natural composition and structure of various tissues, such as bone, cartilage, and skin, promoting cell attachment, proliferation, and differentiation. Composite electrospun fibers can be used for targeted drug delivery applications [70]. The composite fibers can be functionalized with specific drugs or biomolecules, and the release rate can be controlled by the composition and structure of the fibers. Composite electrospun fibers can be used for membrane applications, such as water filtration and gas separation [71]. The composite fibers can be designed to have specific pore sizes and surface chemistries, which enhances the filtration and separation performance. Composite electrospun fibers can be used as electrodes in energy storage devices, such as batteries and supercapacitors [72]. The composite fibers can be designed to have specific surface areas and electrical conductivities, which enhances the electrochemical performance of the device. Composite electrospun fibers can be used as sensing elements in various applications, such as biosensors and environmental sensors [73]. The composite fibers can be functionalized with specific receptors and nanoparticles for various sensing applications. Overall, composite electrospun fibers have a wide range of potential applications in the fields of medicine, energy, and sensing, among others. The unique properties of composite electrospun fibers make them an attractive material for various applications that require tunable structure and function.

7.8. Pine Needle Nanofibers

Pine needle is a natural and renewable resource that can be used as a raw material for electrospinning. Pine needle extract contains bioactive compounds, such as phenolic compounds, flavonoids, and terpenoids, which have potential applications in various fields, including medicine, food, and cosmetics. Below are some possible uses of pine-needle electrospun fibers, which will be explained in detail. Pine needle extract contains bioactive compounds that exhibit antibacterial and antioxidant properties. Pine needle electrospun fibers can be used as a wound dressing material to prevent infection and promote wound healing [74]. Pine needle extract contains antioxidant compounds that can be used to prevent food spoilage and extend the shelf life of food products. Pine needle electrospun fibers can be used as a food packaging material to enhance the quality and safety of food products [75]. Pine needle extract contains bioactive compounds that exhibit anti-aging and skin-whitening properties. Pine needle electrospun fibers can be used as a cosmetic material, such as a facial mask, to improve skin texture and reduce pigmentation [76]. Pine needle extract contains bioactive compounds that can be used to remove heavy metals and organic pollutants from wastewater. Pine needle electrospun fibers can be used as a water filtration material to enhance the efficiency and effectiveness of the remediation process [77]. Pine needle extract contains bioactive compounds that exhibit electrochemical properties.

Pine needle electrospun fibers can be used as a material for energy storage devices, such as batteries and supercapacitors, to enhance the electrochemical performance of the devices [78]. Overall, pine needle electrospun fibers have a wide range of potential applications in various fields, including medicine, food, cosmetics, environmental remediation, and energy storage.

7.9. Hollowed-out Nanofibers

Hollowed-out electrospun fibers are fibers with a hollow core, which can be achieved by electrospinning a polymer solution containing a sacrificial template material that can be removed after the electrospinning process. The resulting hollowed-out electrospun fibers have unique properties and potential applications in various fields. Below are some possible uses of hollowed-out electrospun fibers, which will be explained in detail. Hollowed-out electrospun fibers can be used for drug delivery applications [79]. The hollow core of the fiber can be loaded with drugs or other bioactive molecules, and the release rate can be controlled by the size and structure of the core. Hollowed-out electrospun fibers can be used as scaffolds for tissue engineering applications [80]. The hollow core of the fiber can be used to promote cell infiltration and nutrient transport, and the shell of the fiber can be designed to mimic the composition and structure of various tissues. Hollowed-out electrospun fibers can be used as sensing elements in various applications, such as environmental sensors and biomedical sensors [81]. The hollow core of the fiber can be functionalized with specific receptors and nanoparticles for various sensing applications. Hollowed-out electrospun fibers can be used as electrodes in energy storage devices, such as batteries and supercapacitors [82]. The hollow core of the fiber can increase the surface area of the electrode and enhance the electrochemical performance of the device. Hollowed-out electrospun fibers can be used as catalyst supports for various catalytic reactions [83]. The hollow core of the fiber can increase the accessibility of the catalyst to the reactants and enhance the catalytic activity of the material. Overall, hollowed-out electrospun fibers have a wide range of potential applications in various fields, including medicine, energy, sensing, and catalysis. The unique properties of hollowed-out electrospun fibers make them an attractive material for various applications that require a high surface area and tunable structure and function.

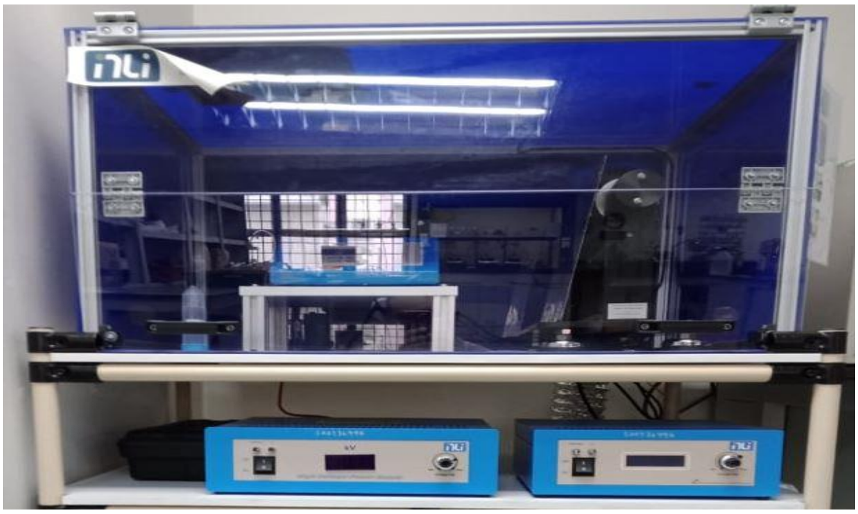

Figure 1: Electrospinning system.

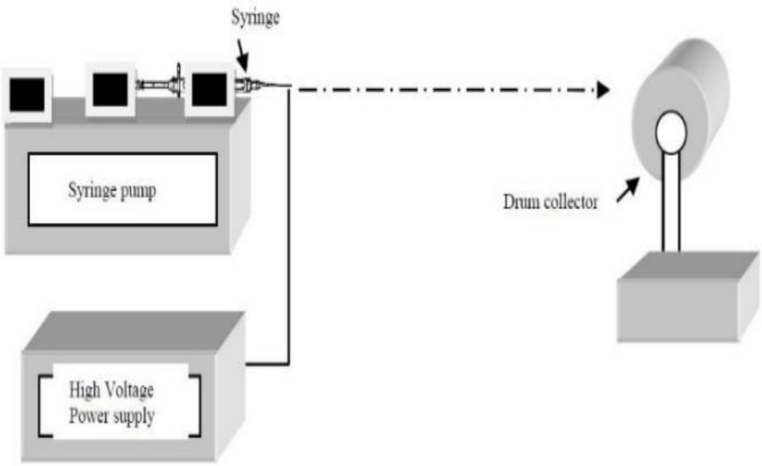

Figure 2: Single Jet Electrospinning.

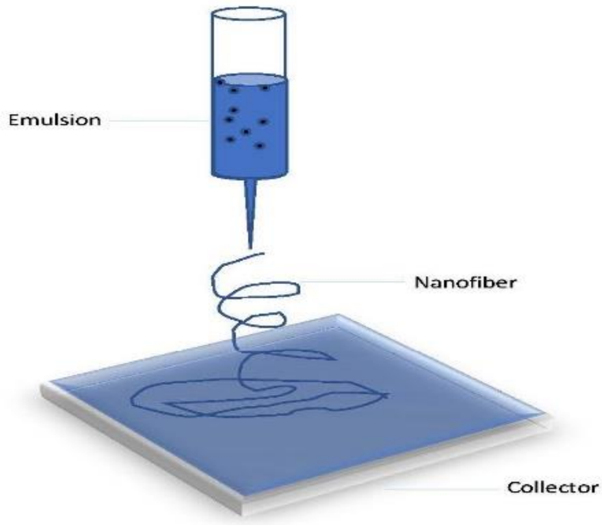

Figure 3: Emulsion Electrospinning.

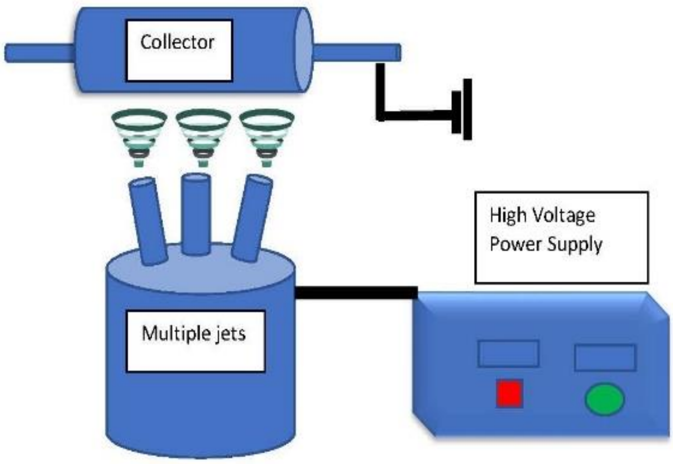

Figure 4: Needless Electrospinning.

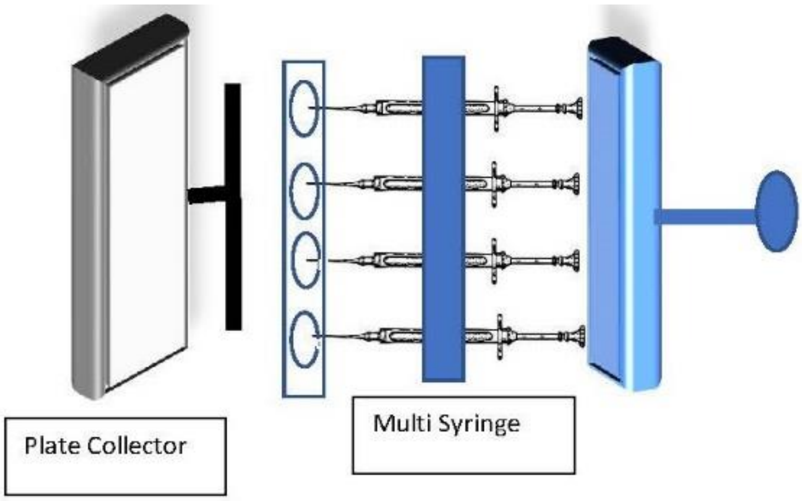

Figure 5: Multi-Jet Electrospinning.

Table 1: Electrospun morphology and structure based on common electrospinning method.

Electrospinning Method	Electrospun Morphology	Electrospun Structure
Single Jet Electrospinning	smooth and cylindrical with a uniform diameter non-uniform fiber structure	Solid Porous core-shell hollow
Coaxial Electrospinning	uniform or exhibit a concentration gradient	core-shell
Emulsion Electrospinning	vary depending on the type of emulsifying agent	core-shell
Needleless Electrospinning	porous morphology, with a large surface area-to-volume ratio	solid, porous, core-shell, and hollow
Multi-Jet Electrospinning	aligned or randomly oriented	solid, porous, core-shell, and hollow

Table 2: Electronic and other application based on electrospun structure.

Electrospun structure	Electronic Application	Other Application
Cobweb	energy storage	filtration, sensing, tissue engineering,
hollow	Energy storage, Sensing	Drug delivery, Tissue engineering,
core-shell	Sensing Energy storage	Drug delivery, Tissue engineering, Separation and filtration,
randomly distributed	Energy storage	Wound dressings Filtration Tissue engineering Catalysis
aligned	Energy storage Sensors	Tissue engineering Regenerative medicine Wound healing
patterned	Sensors	Tissue engineering Drug delivery Microfluidics Energy storage
composite	Energy storage Sensors	Tissue engineering Drug delivery Membranes
pine needle	Energy storage	Antibacterial and antioxidant wound dressing Food packaging Cosmetics Environmental remediation
hollowed-out	Sensors Energy storage	Drug delivery Tissue engineering Catalysis

8. Conclusions

Electrospun fibers produced from the electrospinning method possess unique properties that make them attractive for producing highly efficient and cost-effective electronic devices. Single jet, Emulsion, Needleless and multi jet electrospinnig method can produce various types of structures for electrospun fibers, depending on the processing conditions and the material properties. Other applications, such as medicine, energy, separation, and water treatment, also have bright perspectives from electrospun fibers.

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