

Electrospinning of Nanofibers and their Applications

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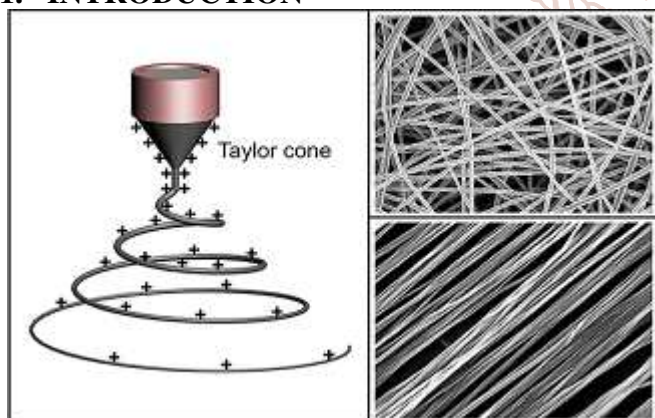
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ABSTRACT

Electrospinning is a versatile and viable technique for generating ultrathin fibers. Remarkable progress has been made with regard to the development of electrospinning methods and engineering of electrospun nanofibers to suit or enable various applications. We aim to provide a comprehensive overview of electrospinning, including the principle, methods, materials, and applications. We begin with a brief introduction to the early history of electrospinning, followed by discussion of its principle and typical apparatus. We then discuss its renaissance over the past two decades as a powerful technology for the production of nanofibers with diversified compositions, structures, and properties. Afterward, we discuss the applications of electrospun nanofibers, including their use as “smart” mats, filtration membranes, catalytic supports, energy harvesting/conversion/storage components, and photonic and electronic devices, as well as biomedical scaffolds. We highlight the most relevant and recent advances related to the applications of electrospun nanofibers by focusing on the most representative examples. We also offer perspectives on the challenges, opportunities, and new directions for future development. At the end, we discuss approaches to the scale-up production of electrospun nanofibers and briefly discuss various types of commercial products based on electrospun nanofibers that have found widespread use in our everyday life.

KEYWORDS: *electrospinning, nanofibers, electrospinning parameters, functional nanofibers, electrospun nanofibers*

1. INTRODUCTION



Graphical Abstract

Fibers, in the form of either continuous filaments or elongated objects, are ubiquitous in nature. For more than 140 million years, spiders have relied on webs of fibers to capture prey. The webs are constructed from silk fibers with diameters ranging from 2 to 5 μm . Silkworms are also well-known for their remarkable ability to produce silk filaments for the construction

of cocoons. These and many other natural systems have served as an important source of inspiration for the development of man-made fibers.¹⁻³ As a matter of fact, fibers have been a fundamental part of human life since the dawn of civilization. The history of fiber production by mankind can be traced back to prehistoric times. Fragments of cotton articles dating back to 5000 BC have been excavated, and silkworm cultivation began in 2700 BC for the production of silk fibers and textiles. Around 1300, the spindle was invented to fabricate fibers from wool and cotton for the production of fabrics and clothes, and this practice slowly evolved into the textile industry in the 1880s. Rayon, made of cotton or wood cellulose fibers, represents the first man-made fabrics. Although it was reported in 1891, it was not commercially marketed until 1911.⁴ About 50 years later, synthetic fibers were produced along with the development of chemistry and polymer science. As the first commercially viable synthetic fiber, nylon was

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introduced by DuPont in 1938, and it immediately caught the public's attention.^{5,6} Thereafter, many different types of polyesters and other synthetic polymers have been developed one after another for the manufacturing of synthetic fibers.⁷ The synthetic fibers significantly reduce the public's demand for natural fibers while greatly expanding the scope of applications.

Many methods have been developed for producing fibers from synthetic polymers, most notably, those based on wet, dry, melt, and gel spinning.^{8,9} Wet spinning involves a spinneret submerged in a chemical bath. When a polymer solution is extruded from the spinneret into the chemical bath, the polymer is precipitated out because of the dilution effect or chemical reaction, generating fibers through solidification. For dry spinning, a polymer solution is extruded into air through a spinneret and fibers are obtained as a result of solvent evaporation from the jets aided by a stream of hot air. During melt spinning, a polymer melt is extruded from a spinneret to generate fibers upon cooling. Gel spinning is used to produce fibers with high mechanical strength or other special properties by spinning a polymer in the "gel" state, followed by drying in air and then cooling in a liquid bath. During these spinning processes, jets are mainly formed under external shearing forces and/or mechanical drawing when passing through spinnerets, and fibers are formed upon solidification of the jets as a result of precipitation or drying. The jets are only stretched to a limited extent, corresponding to the formation of fibers with diameters typically in the range of 10–100 μm .^{8,9} Even with further mechanical drawing during the solidification process or after complete cooling of the jets, the resultant fibers still cannot reach the sub-micrometer scale.

In 1887, Charles V. Boys reported that fibers could be drawn from a viscoelastic liquid in the presence of an external electric field.¹⁰ He used an apparatus consisting of an insulated dish connected to an electrical supply. It was demonstrated that a viscous liquid (e.g., beeswax and collodion) could be drawn into fibers when it moved to the edge of the dish. Widely known as electrospinning now, this technique opens the door to the production of ultrathin fibers with diameters down to the nanometer scale. In general, electrospinning allows for the facile production of continuous fibers with diameters ranging from tens of nanometers to several micrometers.¹¹ Electrospun fibers with diameters down to 1 nm, and even below, have also been reported.¹² In literature, electrospun fibers are often referred to as nanofibers when their diameters are thinner than roughly 500 nm.

The concept of electrospinning was conceived in an earlier study conducted by William Gilbert in 1600, in which he observed the formation of a cone-shaped water droplet in the presence of an electric field.¹³ About one century later, Stephen Gray observed the electrohydrodynamic atomization of a water droplet from which a very fine stream was generated.¹⁴ In 1747, Abbé Nollet performed the earliest known electrospaying experiment, demonstrating that water could be sprayed as an aerosol when passing through an electrostatically charged vessel that was placed next to the ground.¹⁵ The behaviors of charged droplets were then systematically studied by Lord Rayleigh. In 1882, he theoretically estimated the maximum amount of charges that a liquid droplet could carry before liquid jets would be ejected from the surface.¹⁶ Electrospinning can be considered a variant of the electrospaying technique,¹⁷ both of which rely on the use of a high voltage to eject liquid jets. The major differences between electrospinning and electrospaying lie in the viscosity and viscoelasticity of the liquid involved and thus the behavior of the jet. During electrospinning, the jet can be kept in a continuous form to produce fibers instead of breaking into droplets (for the formation of particles) as with electrospaying.

In 1902, two patents on electrospinning were filed by John Cooley and William Morton, respectively,^{18,19} describing a prototype of the setup for electrospinning. Afterward, Anton Formhals filed a couple of additional patents in 1934 and 1944 to disclose the improvement in equipment, moving toward the commercialization of electrospinning for the fabrication of textile yarns.^{20,21} Electrospun nanofibers were first implemented in the Soviet Union in 1938 for the development of air filters, known as "Petryanov filters", for capturing aerosol particles. By 1939, this work had led to the establishment of a factory in Tver for the manufacturing of smoke filters with nanofiber-based mats as gas masks. During this period of time, a mechanistic understanding of electrospinning was slowly developed. Between 1964 and 1969, Geoffrey Taylor published a series of pioneering papers, showing how to mathematically describe and model the spherical to conical shape change of a polymer solution or melt droplet under the influence of a strong electric field.^{22–24} Specifically, as the strength of the electric field was increased beyond a critical level, the spherical droplet would gradually evolve into a cone (now commonly referred to as Taylor cone) and emanate a liquid jet. Afterward, the development of electrospinning technique experienced 20 years of stagnancy, as it did not receive much attention from academia or industry

during this period of time. This stagnancy can be largely attributed to the lack of characterization tools capable of accurately measuring the sizes of fibers with diameters down to the sub-micrometer range. Nevertheless, a variety of applications were proposed for electrospun fibers during this period of time, including their potential use as wound dressing materials as described by a patent filed in 1977.²⁵ In the early 1980s, Donaldson Co. Inc. in the U.S. began to produce and sell filters comprised of electrospun fibers for air filtration. However, the company did not disclose the makeup of their products in order to gain advantages over its competitors.

It was not until the early 1990s that several research groups, notably those led by Darrell Reneker and Gregory Rutledge, began to reinvent this technique.^{26–}

³² This was made possible by the increased accessibility of electron microscopes capable of resolving features down to the nanometer scale. These groups demonstrated that many different organic polymers could be electrospun into nanofibers. The term “electrospinning” was popularized for describing this technique. Their studies brought new life to electrospinning, and this technique eventually became the method of choice for producing long and continuous fibers with diameters down to the nanometer scale. At the beginning of this century, electrospinning started to receive increasing attention when its capability was further expanded by switching to new materials and formulations for the fabrication of composite and ceramic nanofibers.^{33–35}

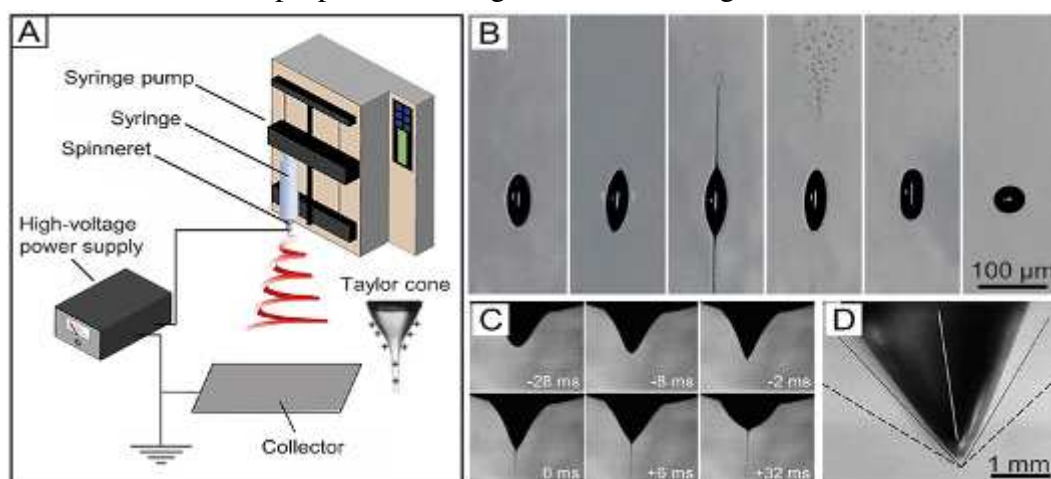
The ability to electrospin new materials quickly enabled new applications in catalysis, as well as energy harvesting, conversion, and storage, which were traditionally dominated by inorganic nanoparticles. In parallel, new strategies were also developed to control the structure and alignment of electrospun nanofibers, opening a world of opportunities in energy-related and biomedical applications. Notably, several methods for aligning the nanofibers were developed, demonstrating the feasibility to combine different properties arising

from the size, structure, composition, morphology, porosity, and assembly of nanofibers.^{35–38} At the same time, coaxial electrospinning was developed to produce continuous core–sheath and hollow nanofibers.³⁹ The fabrication of continuous yarns of electro-spun nanofibers was also reported.⁴⁰ brief summary of the major milestones for the development of electrospinning. These achievements make electrospinning a versatile and viable technology for the production of nanofiber-based materials to target a broad range of applications.

2. ELECTROSPINNING

2.1. Principle of Electrospinning

As illustrated, the basic setup for electrospinning is rather simple, making it accessible to almost every laboratory.^{41,42} The major components include a high-voltage power supply, a syringe pump, a spinneret (usually, a hypodermic needle with blunt tip), and a conductive collector. The power supply can be either direct current (DC) or alternating current (AC). During electrospinning, the liquid is extruded from the spinneret to produce a pendant droplet as a result of surface tension. Upon electrification, the electrostatic repulsion among the surface charges that feature the same sign deforms the droplet into a Taylor cone, from which a charged jet is ejected. The jet initially extends in a straight line and then undergoes vigorous whipping motions because of bending instabilities. As the jet is stretched into finer diameters, it solidifies quickly, leading to the deposition of solid fiber(s) on the grounded collector. In general, the electrospinning process can be divided into four consecutive steps: (i) charging of the liquid droplet and formation of Taylor cone or cone-shaped jet; (ii) extension of the charged jet along a straight line; (iii) thinning of the jet in the presence of an electric field and growth of electrical bending instability (also known as whipping instability); and (iv) solidification and collection of the jet as solid fiber(s) on a grounded collector.^{41,43,44} A more detailed discussion of these four steps is provided in the following subsections.



Electrospinning setup

Three parts make up a standard electrospinning setup: a high voltage supplier, a capillary tube containing a needle, and a collecting screen [10]. A typical electrospinning arrangement is shown in Figure 1a and b. Taylor asserts that a 6 kV applied voltage is necessary for the electrospinning process to begin [11]. However, the electrospinning procedure can be carried out at a lower applied voltage when a grounded target is placed closer to the spinneret [12].

Electrospinning Parameters

It is very important to understand the electrospinning working parameters, as they effect fiber morphologies. It is much easier and more possible to obtain desired fiber diameters and morphologies through control of these parameters. The ideal targets in electrospinning of a polymer into nanofiber are:

- A. The diameters of the fibers must be consistent and controllable
 - B. The fiber surface must be defect-free or defect-controllable
 - C. Continuous single nanofibers must be collectable
- Fiber diameter is among the most important quantities in electrospinning.

Another challenge is the uniformity of the fiber diameters. The occurrence of defects such as beads and pores is a major problem the pores in Poly-L-lactide (PLLA) fibers. The beaded fiber structure can be observed in Figure 8

Solution Parameters— viscosity, conductivity, molecular weight, molecular weight distribution, surface tension, polymer structure, solution properties

Process Parameters— applied electric field, tip to collector distance, feeding or flow rate, hydrostatic pressure in the capillary, plate movement

Ambient Parameters— humidity and temperature of the surroundings, solution temperature, air flow rate

Patterning of Nanofibers.

Nanofiber-based mats with patterned micro-and/or nanostructures are interesting for their high specific surface areas and roughness. The nanofiber-based mats can be patterned using two different approaches: bottom-up and top-down.

For the bottom-up approach, micropatterned architectures can be readily generated in the mats by controlling the properties of the electrospinning liquid and parameters for electrospinning. One typical example is the formation of unique ultrafine nanonets comprised of interlinked ultrathin nanowires in the as-spun nanofiber-based mat. As shown in nanonets

of ultrathin nanowires (ca. 30 nm) are stacked layer-by-layer and distributed in the mat of poly (acrylic acid) nanofibers. The nanonets are only formed under certain conditions, for example, electrospinning of a solution containing salts or involvement of fast phase separation between the polymer and solvent. Electrospinning under a relatively high voltage or low relative humidity may also result in the formation of nanonets. In another typical example, PVA nanofiber-based mat with a honeycomb-patterned architecture was fabricated by inducing the self-assembly of wet nanofibers on a collector Micropatterned architectures can also be readily generated through the use of micropatterned conductive templates as collectors, as discussed in . In this case, the electrical forces are the key factors in determining both the deposition and arrangement of nanofibers. The melt and near-field electrospinning techniques have also been demonstrated for patterning fibers through direct writing as discussed is and respectively. The drawbacks are the complicated setups and relatively large feature sizes.

Classification of electrospinning methods depending upon design of electrospinning setup.

Emulsion electrospinning.

This method provides us a chance to make a single fibrous scaffold out of two immiscible solutions when they are electrospun, the method specifies that the immiscible solutions are to be made into an emulsion by mixing strenuously after which the resulting colloid is packed into a syringe made out of glass and fitted with a power supply of high voltage and a needle. Fibers which are made out of this are difficult to produce as it involves a plethora of variables that are to be accounted for to create the emulsion. Nanoparticles and surfactants like sod. Dodecyl sulfate has been used for interface stabilization effectively.⁴² In this method, the core-shell containing functional materials like peptides, proteins, enzymes, and flavonoids are incorporated into a nanofiber. The setup of emulsion electrospinning is shown in. As far as emulsion material passes through the needle, due to the potential difference between the needle and collector plate results in the formation of nanofiber containing core-shells of emulsion droplets. The attenuation and deformation of this emulsion droplet occurred as a result of jet speed which drags the forces derived from its interaction with the surrounding air. Due to this, the solvent gets evaporated quickly and nanofiber with a core-shell containing fundamental material is formed.⁴²

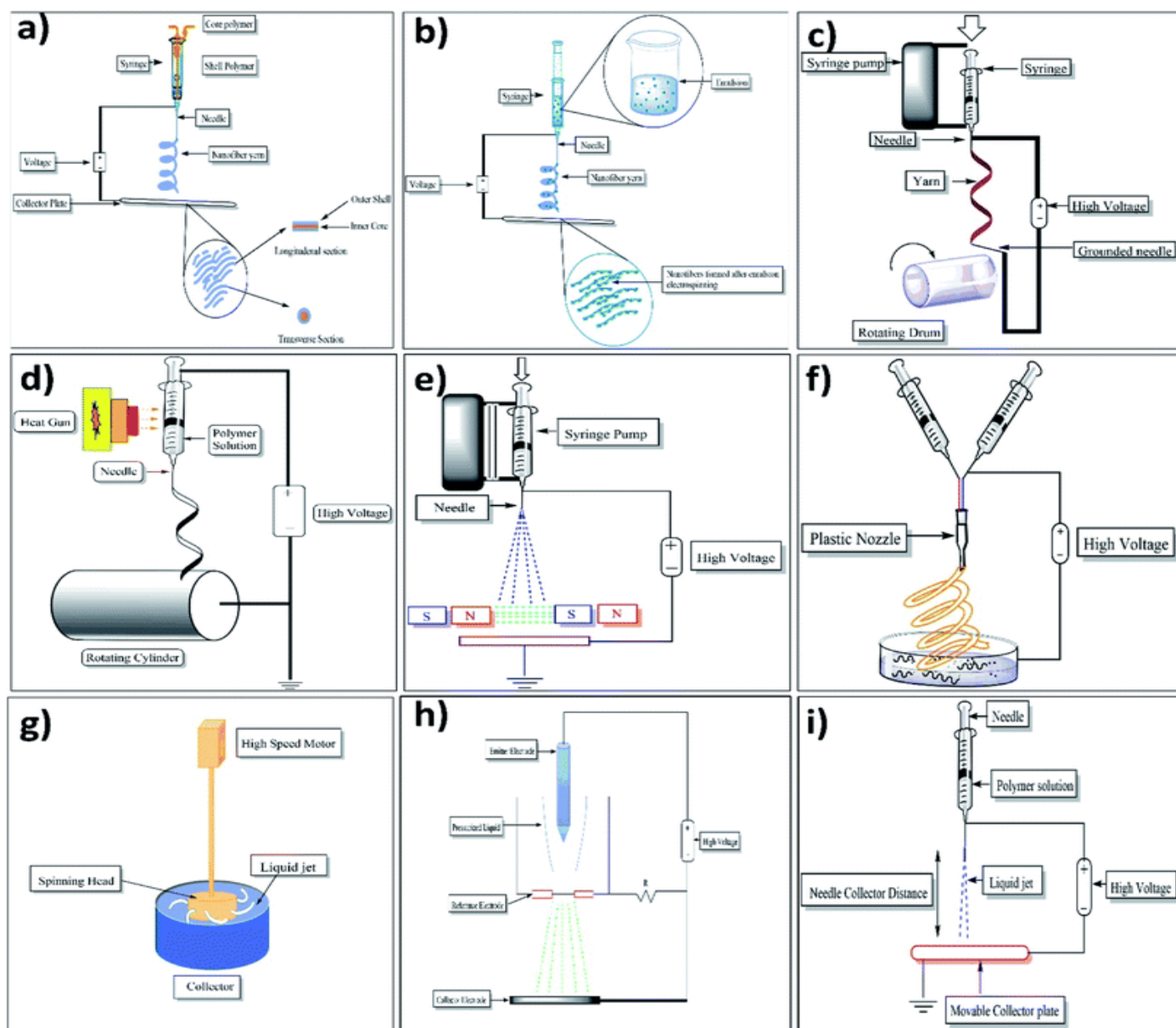


Fig. 5 Pictorial representation of setup used for fabrication of nanofibers by (a) emulsion electrospinning, (b) coaxial electrospinning, (c) roller electrospinning, (d) melt electrospinning, (e) magnetic-field facilitated electrospinning with two parallel permanent magnets, (f) bicomponent electrospinning, (g) force spinning, (h) charge injection method and (i) near-field electrospinning.

Coaxial electrospinning.

A technique that can be used to make core–shell (core–sheath) fibers by using spinneret in which there are two compartments (coaxial), where the shell/sheath (solution of polymer) and core (a solution of a compound) can be used as the precursors and co-spun, core–shell (2 different polymer solution can also be used). The fluids are independently driven using two compartments simultaneously in this method; the outer and inner solutions (precursors) reach the nozzle by passing from their capillaries and combining to produce droplets of composite. As both the solutions extrude through the jet, a nanofiber yarn is formed in which the core is surrounded by shell/sheath material as shown in . Most of the time shell is acts as a physical barrier to avoid the evaporation of core material.⁴³ Because of the electrostatic repulsive forces present in the middle of

the surface, the extension was seen in the shell liquid of composite droplets, resulting in viscid tension then the resulting tension was transmitted to the core layer, which was quickly stretched.^{44, 45}

Melt-blowing setup

It is a setup of single-step to produce materials on a micrometer and small scale. Once the polymer was melted, multiple nozzles are used to eject the jet of polymer simultaneously. After that, jets were enervated using the hot air stream (high velocity), resulting in a drastic decrease in the diameter of jets. Ultimately, a web of fibers that are fine, have a random position and are non-woven gets deposited on the collector.⁴⁶

Gas-assisted spinning

Also known as the spin blowing method gives a useful way to spin material that is considered poor

material for electrospinning.⁴⁷ Reyhaneh Aminyan *et al.* prepared fibers of 11% wt of aqueous a solution. The prepared fibers were kept under 20 kV voltage, followed by neutralization by 15 wt% NaOH solution, 20 rpm of the rotation speed of the collector with the fed rate of 20 $\mu\text{l min}^{-1}$ (chosen conditions were rationalized by the previous group's experiences). Then they crosslinked prepared fibers using 1,4-butanediol diglyceryl ether at 0.5, 0.4, and 0.3% wt for 3–7 min at the temperature of 130–1600 °C. The prepared cross-linked specimens were used to obtain results by conducting the swelling ratio analysis.⁴⁸

Low fiber productivity is the primary problem associated with the typical electrospinning procedure. To bettering the productivity of fibers by introducing the gas jet with the application of increased driving force around the solution of the polymer. Integrated fibers with a narrower diameter dispersity can be achieved using gas-assisted electrospinning.⁴⁸

Roller electrospinning

(*nano spider electrospinning*). This particular device consists of a tank, a ground collector, a supporting material, and a power supply of high voltage.⁴⁹ in this, to spin nanofibers a spinning roller electrode is half dipped into the polymer solution. An electrode (grounded) with non-woven material is fixed on the peak of the spine which makes a continuous nanofibers

Self-bundling electrospinning

Self-bundling electrospinning is rather a straightforward mechanism for creating continuously aligned electrospun fiber yarn. It has many things like a needle tip, a syringe pump, a generator (high-voltage), and a ground collector (rotating).⁵¹ To start the formation of a bundle, a ground tip that is twisted around the collector is used and then the bundling continues. The solution's conductivity (electrical) is contemplated to be a criterion of a significant impact.⁵²

Solvent-free electrospinning

Solvent-free electrospinning such as melt electrospinning, CO₂-assisted electrospinning, and anion-curing electrospinning are techniques and never use conventional solvents. It is used to highly utilize precursors and avoid solvent emission.⁵³

A. Melt electrospinning

The setup consists of a cylindrical collector, molten polymer, a needle, and a high-voltage power supply. For melting the polymer different techniques can be used such as electric heating, laser melting devices, heat guns, and heating ovens. Generally, the parameters are the same for molten polymer electrospinning as it is for the polymer solution

electrospinning. Just like the latter, a large diameter is taken using a polymer with higher molecular wt and in the maximum cases, the melted one also has both nano and micrometer-scale fibers but there are some differences as well. The method for fabrication of nanofibers by electrospinning setup is illustrated in

In melt electrospinning, before initiating an uninterrupted heat supply to the reservoir, it had to be made sure that the solution of polymer is in the molten state. The gap between the tip and collector is roughly around 2 cm in melt electrospinning whereas it's around 10 cm in the conventional polymer solution electrospinning. A greater charge is required to start the jets in melt electrospinning because the viscosity of polymer melt is higher in the molten electrospinning when compared to the conventional polymer solution electrospinning.⁵⁴

B. UV-curing electrospinning

UV-curing electrospinning method is used to develop fibers that are ultrathin nanofibres, modifications have to be done for creating an oxygen-free environment. Then only the precursors can be electrospun with the ultra-violet radiation and within the nitrogen then problems like solvent evaporation are not faced and fibers can be made ultrathin. The method utilizes an ultra-violet mendable material. An oxygen-free environment is created so that the precursors can be electro-spun under UV light and nitrogen into ultrathin fibers.^{53,55}

C. Anion-curing electrospinning

Only two components are there in the solution, the cyanoacrylate (*ca.*) monomer and polymethyl methacrylate (PMMA). The latter is added to the former to increase the viscosity. Room temperature is enough for more than 90% of the precursor to be electrospun into ultrathin fibers. The acrylic resin (*ca.* monomer) may polymerize quickly and create strong chains in the presence of an anion. Just as the room temperature has a compelling impact on the diameter of the electrospun fibers created by the traditional method, it also affects the morphology of the anion-cured electro-spun fibers.⁴⁷

D. Supercritical CO₂-assisted electrospinning

In this method, electrostatic forces and supercritical CO₂ solvents were used to make the polymer fibers. Carbon dioxide is the most commonly found supercritical solvent used in many processes and is known as a material that possesses both the temperature and pressure above the critical point because the supercritical stage is performed in a vessel with high pressure (14 mPa). So, it's difficult to employ a moving collector. The apparatus for this approach is far more sophisticated than any other method.⁵³

Magnetic-field-assisted electrospinning

Fibers made using this technique don't split much like the ones without a magnetic field and are much more uniform. The advantage of the fibers which are made from this method is that they are more uniform and are with much less splitting than others. In this method, either 2 parallel permanent magnets should be used or Helmholtz coils, plus a syringe that contains the solutions that are compatible and can respond to magnets that are used. With this method, fibers with smaller diameters were attained because of high speed.⁵⁶ Below the setup of two parallel magnets with magnetic field-assisted electrospinning.

Bicomponent spinning

This technique can be used to make mono and multi-component nanofibers. It's a 2-step process that involves producing nanofibers by splitting or removing one of the components when 2 polymers are spun through a spinning die. For us to produce a nanofiber there should be at least one component that has a cross-section in the nanoscale. Some of the common shapes for the bi-component fibers are segmented pie (hollow, ribbon, plain), sheath-core, side by side, *etc.* If shapes are to be explained, for instance, islands in the sea in which the sea is of one polymer need to be enclosed by other polymers known as islands (multiple individual fibrils) as shown in the.⁵⁷

Force spinning (centrifugal spinning)

This particular method is known to be well refined and is also called rotational/rotary spinning. The only dissemblance between the said method and the original one is the use of *c*-force in place of the electric field. In this method when the speed of rotation reaches a certain point then the *c*-force will be significant enough to subdue the surface tension then only the liquid jet will be excluded from the tip. Ultimately, the *c*-force will make the jet stretched and nanofibers will be deposited on the collector. The most significant drawback of centrifugal spinning is that material characteristics and spinneret design have a significant impact on fiber quality and production.

Charge injection method

This technique was refined for electro-spraying still it can be used for electrospinning. This method is dissimilar from the ones used by other devices. This method doesn't involve the formation of Taylor cones and the splitting of the jet is done by an electrical charge. Out of many configurations for this technique, one of them involves three electrodes (power supply-high voltage, collector, and non-conducting pressurized fluid) and two out of those are submerged into the solution

The "emitter electrode's" sharpened tip is situated above a grounded orifice *i.e.* blunt electrode. A strong *e*-field is created in the solution due to the narrow proximity between electrodes. As the fluid travels between the electrodes, it is continually pushed through the aperture at increased pressure and becomes highly charged, the extruded filaments from the orifice might be drawn towards the collector. Because of the proximity of the emitter electrode and aperture, this method has some certain disadvantages, like the lack of control over the size distribution of the fibers and that only fluids which have low conductivity/insulating can be used. As a matter of fact, the electro-spun mats are normally made of microfibers which are interconnected branches of nanoscale fibers.⁶⁰

NFES (near-field electrospinning)

Apart from the distance between the needle and the collector the system setup is the same as standard. The reduction in the distance (500 μm to 3 mm) is to avert the curving unsteadiness of the jet. The distance in the question employs a sturdy area of the electro-spun jet near the needle, which makes this system good for direct writing. But this closeness between the collector and the spinneret may create electric breakdown or splattering of the fibers because of insufficient evaporation of the solvent. As a result, an adjustment must be done with the polymer solution accurately. To initiate the process, a lower applied voltage (usually 100–600 V) is utilized. In contrast to traditional electrospinning, higher voltage has been observed to result in bigger diameter fibers in this method. With the volume of the collected fibers being limited, the alone droplet of the polymer is more than enough for the direct writing, negating the necessity for a consistent flow of polymer. To get an accurate control over orientation and deposition of the fibers the collector is normally put up on the XY-piezo stage.⁶¹ The setup of near-field electrospinning setup was well illustrated in

CONCLUSION

Over the past two decades or so, remarkable progress has been made with regard to the development of electrospinning methods and engineering of electrospun nanofibers to suit or enable various applications. Most of the advances were made possible through the achievement of a better understanding of the electrospinning mechanism and a better control of the materials. A wide variety of materials, including polymers, small molecules, and colloidal particles, as well as composites, have been successfully electrospun into nanofibers. In terms of methods, electrospinning has been performed in both far-and near-field configurations. The spinneret has been designed with a hollow, solid, or coaxial

structure and utilized as a single unit or in an array. In addition to conductive solid collectors with different surface patterns, liquid bath has been explored as a collector to enable the fabrication of nanofibers with novel structures and morphologies, in addition to the extension of dimensionality. During or post-electrospinning, it is also feasible to expand the diversity, scope, and functionality of electrospun nanofibers by engineering their composition, structure, morphology, and assembly. Notable examples include the fabrication of nanofibers made of carbon, ceramics, or metals; incorporation of enzymes, biological effectors, or nanoparticles into nanofibers; creation of pores and/or hollow interiors in the nanofibers; conjugation of specific functional groups or biological effectors to the surface of nanofibers; alignment of nanofibers into uniaxial or radial arrays; stacking of nanofibers into patterned architectures; and fabrication of 3D scaffolds by expanding a thin mat of nanofibers along the vertical direction.

As a result of their remarkable properties, electrospun nanofibers have found widespread use in a variety of applications ranging from catalysis to environmental protection, energy harvesting/conversion/storage, and biomedicine. Specifically, owing to their high porosity and large specific surface areas, nonwoven mats of electrospun nanofibers have been applied as advanced filters for the removal of pollutants from both polluted air and wastewater. Upon optimization in terms of diameter, porosity, alignment, stacking, surface functional groups, mechanical properties, and biodegradability, nanofiber-based scaffolds have been explored to enhance the repair or regeneration of various types of tissues, including nerve, skin, heart, blood vessel, musculoskeletal system, and tissue interfaces. Recent clinical trials on electrospun nanofibers have begun to pave the way for their ultimate implementation in regenerative medicine, especially for use as barrier membranes to prevent the adhesion between tissues after surgery.

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CONFLICT OF INTEREST:

All authors declared no conflict of interest for the work.

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