

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Electrospinning Technology in Non-Woven Fabric Manufacturing

Haoyi Li and Weimin Yang

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/62200>

Abstract

In the past two decades, research on electrospinning has boomed due to its simple process, small fiber diameter, and special physical and chemical properties. The electrospun fiber is spontaneously collected in a non-woven status in most cases. Therefore, the electrospinning method is becoming an ideal candidate for non-woven fabric manufacturing on a nano scale. More than 50,000 research papers have been published linked to the concept of "electrospinning", and the number is still increasing rapidly. At the early stage of electrospinning research, most of the published papers mainly focused on the research of spinning theories, material systems, and spinning processing. Since then research has turned to functional electrospun fiber preparation and characterization. In recent years, more and more researchers have started to develop a scaling-up method related to the applied products of electrospinning. Interestingly, most electrospinning products are in a non-woven state; that is why we dedicate one chapter to exhibit ongoing, on-woven fabric manufacturing and the basic research progress made using the electrospinning method.

Keywords: Electrospinning, non-woven fabrics, process, applications

1. Introduction

1.1. Electrospinning principle for manufacturing non-woven fabrics

The electrospinning method, as a versatile nanofiber preparation process, has drawn great attention in the past decades, due to its simple setup, easy process, extensive material options, and capability to form non-woven fabrics without any post processes.

The origin of electrospinning as a viable fiber-spinning technique can be traced back hundreds of years [1]. The process of electrospinning, also termed electrostatic spinning, was first

conceived by Lord Rayleigh [2] in the late 19th century. In 1902, Morton [3] and Cooley [4] disclosed a patent using the electrospinning process via a composite solution. This patent was issued for the production of fibers from a solution jet using an electric field. From 1934 to 1944, Formhals published a series of patents [5-9], describing an experimental setup for the production of polymer filaments using an electrostatic force. Since then, electrospinning truly emerged as a feasible technique for spinning fibers with small diameters.

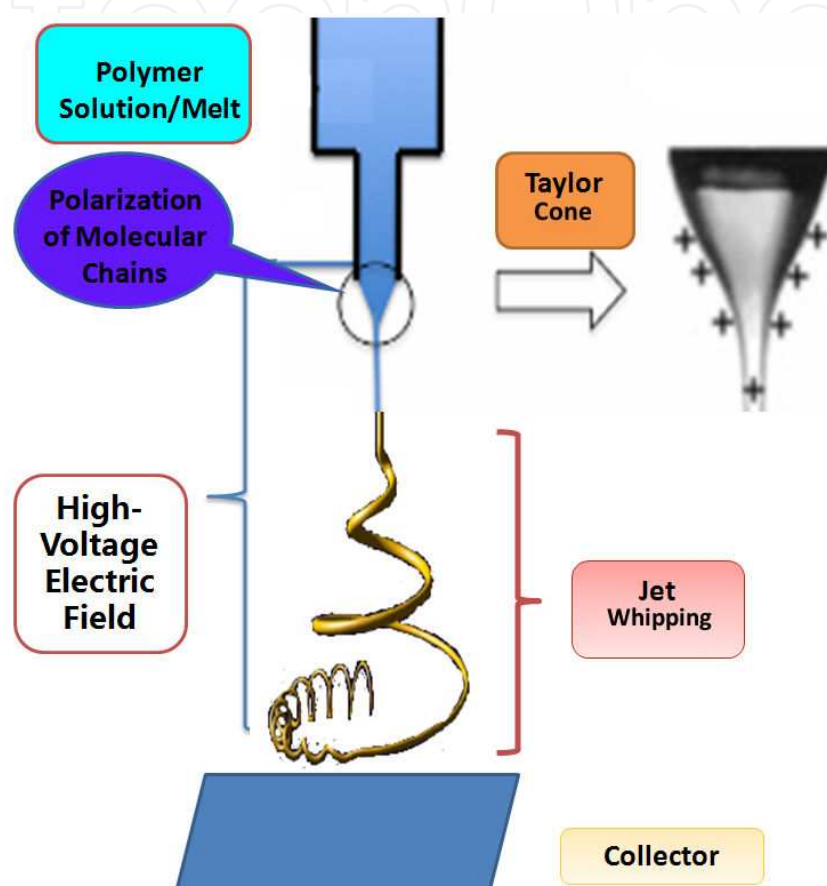


Figure 1. Diagram showing the principle of the electrospinning process.

A formal electrospinning process can be defined as below [10]: a polymer solution or melt is held at the end of a capillary tube and is subjected to a high static electric field (commonly $1\text{--}6 \times 10^6$ V/m); the charges are then induced on the liquid surface; the mutual charge repulsion causes a force directly opposite to the surface tension; as the intensity of the electric field increases, the hemispherical surface of the solution or melt elongates to form a conical shape known as a Taylor cone; when the static electric field surpasses a critical value, the repulsive electrical forces overcome surface tension forces, resulting in a charged jet ejected from the tip of the Taylor cone. The route and thinning of this jet can be controlled by the electric field. At the same time, the solvent either evaporates or the polymer melt solidifies, leaving behind a charged polymer fiber. Continuous fibers are finally collected in the form of a non-woven fabric.

Electrospinning technology uses a totally different method for non-woven fabrics than the manufacturing in any other methods used in industry. The excellent characteristics of electrospinning technology include the following.

1.1. Low power consumption

In the electrospinning process, the driving force during jet thinning is the electrostatic force. Usually, in electrospinning the current carried by a typical jet is around 0.1-1 μ A [11]. This means that one jet in the electrospinning process consumes less than 0.1 W/h (power per hour). In other words, a mobile phone battery can drive more than 5-10 electrospinning jets for more than ten hours. Consequently, it is easy to develop handheld electrospinning equipment [12].

1.2. Nanoscale fibers

Although only a few fibers smaller than 1 μ m can be detected in traditional non-woven processes as for so-called "sea-island melt spinning" [13] and the recently developed flash-spinning process [14], small continuous fibers with nanoscale diameters can be easily attained via the electrospinning process. Before the 1990s, researches had produced ultrafine fiber around 1 μ m and found this method had the potential for nanometer fiber preparation. Until 1996, works by Darrell H Reneker and Iksoo Chun [11] demonstrated that many polymer solutions and melts can be produced into nanofiber in the range 40-2000nm. After that, great attention was given to this technique for nanofiber production. Nowadays more than 3,000 papers and patents per year (Figure 2) are published on electrospun nanofiber preparation and its applications based on more than 200 kinds of polymers.

Non-woven fabrics using nanoscale fibers always exhibit a high specific surface area and smaller pores and channels though the fabric, which means more functional molecules become exposed on the surface of the fiber or channels. This advantage can be applied into several high-end fields like high sensitive flexible sensor, efficient filter element, immobilized catalyst, and high energy storage element.

1.3. Long and continuous fiber [15]

The electrospinning process usually produced long nanofibers as any other traditional non-woven processes did; so scholars claimed electrospinning as a continuous nanofiber manufacturing method. In Beachley V's results [15], an electrospun polycaprolactone (PCL) fiber had a length ranging from 30 to 50cm, which is close to that of melt-blown nanofiber lengths obtained by Christopher J. Ellison [16]. This high draft ratio is attributed to the principle of electrospinning: electromicro stretch. Traditional industrial spinning fiber is stretched from one end. All the molecular chains between the spinning pool and the jet end are stretched by the force transferring from its end, as shown in Figure 3a. However, the driving force of polymer chains in electrospinning is different; not from the end, but between the adjacent charges which endure a repulsion or attracting force in the electric field, shown in Figure 3b. In this way, an electrospinning jet represents an equilibrium state in a tug of war between

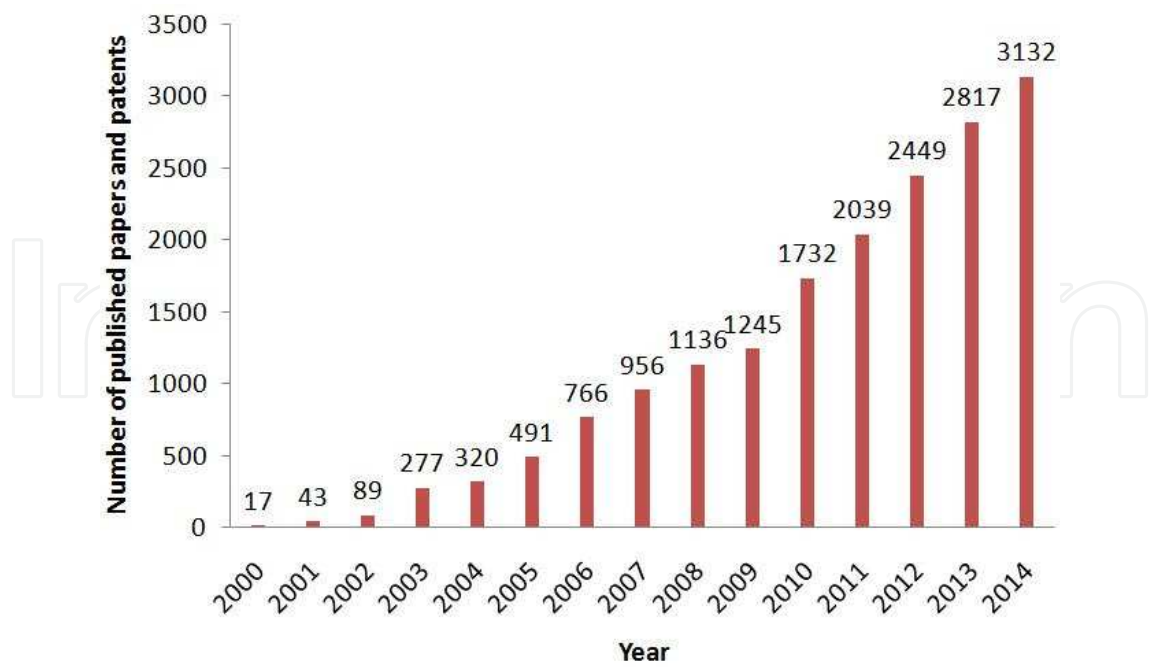


Figure 2. Number of published papers and patents containing the concept of the "electrospinning" process searched for on web "SciFinder".

electrostatic force and surface tension force. Liu et al. [17] demonstrated this tug of war process by a simulation method of dissipative particle dynamics.

Non-woven fabrics produced by nanofibers may have eliminated the falling out of short fibers and hence avoid some potential pollution of nanomaterials.

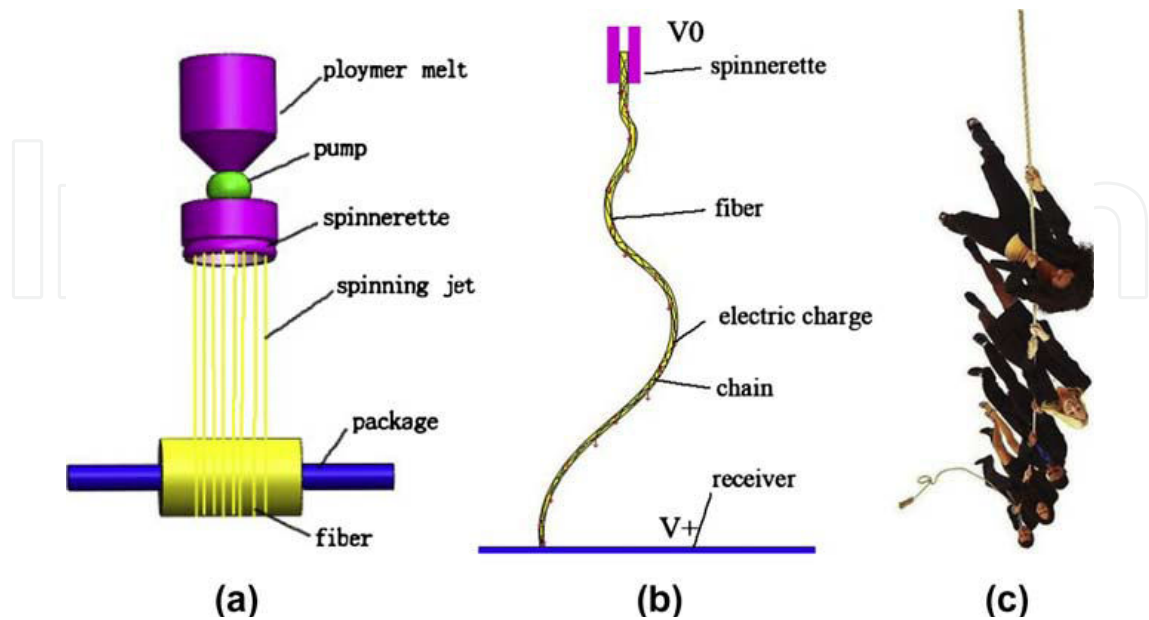


Figure 3. Schematic process of (a) industrial melt spinning, (b) melt electrospinning, and (c) tug of war [17].

2. Electrospinning parameters and fiber properties

Electrospinning can be divided into two methods based on material properties: melt electrospinning and solution electrospinning. The former is less investigated because of its thick resultant fiber and high applied voltage [18], while the latter is widely researched and applied in several areas such as non-woven fabrics. However, melt electrospinning is attracting more and more attention since it can process Polypropylene(PP), polyethylene(PE), and other thermoplastic polymers without using any toxic solvents. Processing parameters always play important roles in judging spinnability and controlling fiber properties in both electrospinning processes.

2.1. Viscosity

Viscosity of the polymer melt or solution has a great effect on spinnability. Over a certain range, decreasing viscosity contributes to better spinnability, and smaller fiber diameter. The viscosity of the electrospun materials must be within a certain range (for solution electrospinning, it is commonly 5–20 Pa.s, while for melt electrospinning, it is commonly 20–200 Pa.s [18]). If the solution viscosity is lower than a certain value, some microspheres may be electrically ejected onto the fabrics because of insufficient chain entanglement [19]. They would then melt with a low viscosity due to a very low molecular weight and would also be unable to produce fiber. Commonly, polymer melt or solutions with high viscosity produce thick fiber, while a modified material with a viscosity reducer [20] or surfactant [21] can produce a relatively small fiber. For example, in order to prepare fiber smaller than 1 μm by melt electrospinning, researchers have tried a variety of methods to reduce the melt viscosity – including using plasticizer and conductive additives [22–23].

2.2. Applied voltage

The electrospinning process generates fiber when the applied voltage surpassed a given value required to balance the surface tension of the solution or melt. The electrical field intensity is estimated as the applied voltage divided by the distance between the tip and collector in most research. A higher electric field intensity value is obtained either through decreasing the distance between the tip and collector or by applying higher voltages. In 1969, Taylor deduced the threshold voltage of electrospinning [24], which defined the relationship between threshold voltage and the processed material. That is to say when the applied voltage exceeds this value, it breaks the balance between the electric force and the surface tension of the droplet, so a jet is ejected.

For solution electrospinning, it is commonly found that fiber diameter decreases with an increase in the applied voltage. However, for some polymer solutions like polyvinyl alcohol (PVA) and polyethylene oxide (PEO), they do not follow this rule [25]. The applied voltage has an important effect on non-woven morphology as well. Too weak or too strong an electrical field intensity, may cause beads of fiber in solution electrospun, non-woven fabrics and result in a rough surface [25]. For different materials, there is a suitable applied voltage range when other parameters are fixed.

For melt electrospinning, because of the dielectric properties and high viscosity of the polymer melt, the applied voltage is more than 2 times that used in solution electrospinning. Therefore, 20–100 kV is needed to polarize the polymer melt, and induce the generation of polymer jets [26], while usually 5–20 kV is loaded on the end of the syringe needle in solution electrospinning. Increasing the voltage is a common measure used to obtain finer fiber in melt electrospinning, but it can cause corona or breakdown if the voltage is too high. Ratthapol [27] proposed a vacuum melt electrospinning method, improving the threshold voltage, in which the loading voltage can reach 1–30 kV/cm without breakdown, however, this method may prove costly if used in large-scale production.

2.3. Conductivity

High conductivity of processed material means a greater number of net charges on the jet when high voltage is loaded, therefore, a smaller fiber diameter can be attained by elevating the conductivity. Higher conductivity also may cause a drastic whipping of the electrospun jet, especially for polymer solutions, however, this may lead to a wide diameter distribution of the electrospun, non-woven fabrics. A widely used method to improve conductivity is by adding salts [28–29], pyridine [30], or carbon nano tube(CNT) [31] in polymer solution or polymer melts. However, this may change the original fiber properties. Some researchers have investigated additives that evaporate when jetting [32].

2.4. Spinning distance

Spinning distance was defined as the distance between the spinning tip and the collector. This distance is exactly the route that the electrospun jet experiences. Changing the spinning distance may cause a change in solvent evaporating velocity, the electrical field intensity, and the solidifying state, and thus affect the fiber properties indirectly. When the spinning distance is too short, the fiber will not be thinned enough because of a lack of the whipping process and inadequate solvent evaporation, as a result, the beads may accrue and even prepared fabrics may dissolve back into concentrated solution at this stage [33]. On the contrary, if there is an increase in the spinning distance, and a fixed electric field intensity, smaller fiber can be produced, and naturally, a larger area of deposited non-woven fabrics is prepared [34]. The spinning distance in most cases was set at 7–15 cm.

It should be noticed that near-field electrospinning has been developed for a patterned deposition of nanofiber, in which the spinning distance was set smaller than 1 mm and jet whipping was almost eliminated [35].

2.5. Solvent properties

Solvent properties including the surface tension [36] and conductivity [37], determine the final solution properties, and effect fiber properties indirectly. Solvent with low surface tension is a good candidate for better electrospinning solution preparation, thus the electrospinning process can be easily carried out by loading a relatively low voltage [36]. Volatility should be another concern when choosing the right solvent. If the volatility is too high, a blockage at the

spinneret may occur from time to time [38]; if the solvent evaporates as slowly as water, then an adhesive and thick fiber may be obtained [39]. In addition, inadequate evaporation of the solvent in the spinning solution may cause a toxic solvent residual in fabrics, which is not wanted in medicinal and sensor applications [40]. Solution conductivity in electrospinning has been discussed. In a solution system, the selected solvent's conductivity is the first factor defining solution conductivity, and using additives to improve conductivity is the second factor considered to adjust the solution's conductivity [37].

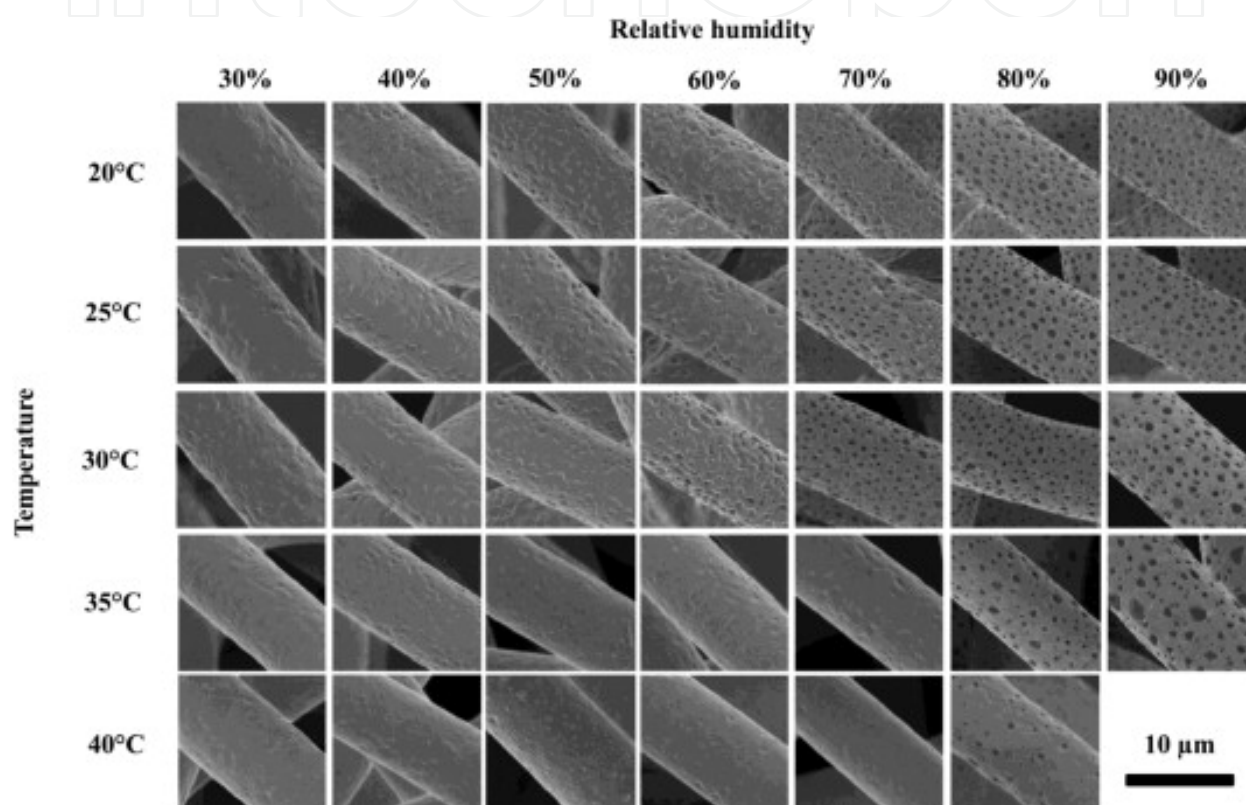


Figure 4. SEM pictures of solution electrospun fibers at different temperatures and relative humidities [45].

2.6. Collector

Non-woven fabrics are usually defined as random deposited fibers. However, sometimes controlled deposition of fibers, at least partially oriented fibers or patterned fabrics are needed in areas like cell scaffolds, sensors, and tailored filters. Therefore, different collectors or collectors with certain movement were utilized to realize specially controlled fabrics in electrospinning. Li, Wang, and Xia [41] have demonstrated that the nanofibers can be uniaxially aligned by introducing an insulating gap into the conductive collector. Other interesting methods including the use of collector-like knife-edged blades [42], rotating wire drums [43], rings placed in parallel [44], etc., have also been proposed and tested.

2.7. Ambient temperature and humidity

High temperature and low humidity in the spinning area benefit the evaporation of solvent, and this is helpful to obtain smaller fiber diameters [45]. When the temperature is too high in solution electrospinning, the spinneret may easily be blocked because of fast evaporation. In melt electrospinning, the high ambient temperature can keep the spinning jet in melt state for a long time, which increases the thinning time of the jet and is beneficial to smaller fiber production [46]. The electrospinning process can rarely be carried out when the humidity surpasses some value since a corona or breakdown may happen [47]. Obvious changes on the surface of the solution electrospun fiber have been observed when spinning temperatures and humidities change [45].

3. Scaling-up the technology of electrospinning

A basic electrospinning setup includes a chamber of polymer melt or solution, a spinning head, a high-voltage supplier, and a collector. Most electrospinning setups have their spinning heads connected to a positive high-voltage output end while the collectors are earthed or connected to a relatively low negative voltage. The electrospinning process requires a very small flow rate supply, so a microfluidic pump or fluid distributor is usually used to control the flow.

However, output of most solution-based, single-jet electrospinning setups is only 0.01-0.1g per hour, which is much smaller than that of traditional melt-blowing processes [48]. A lot of researchers have made great effort to improve the efficiency of the electrospinning process in different ways. The methods used can be grouped into two types. One method works by multiplying the output by establishing matrices of commonly used orifices (Figure 5a) [49]. The other uses a fluid-free surface or creates some protuberances on a fluid-free surface to motivate multiple jets by loading extremely high voltages (Figure 5b) [50].

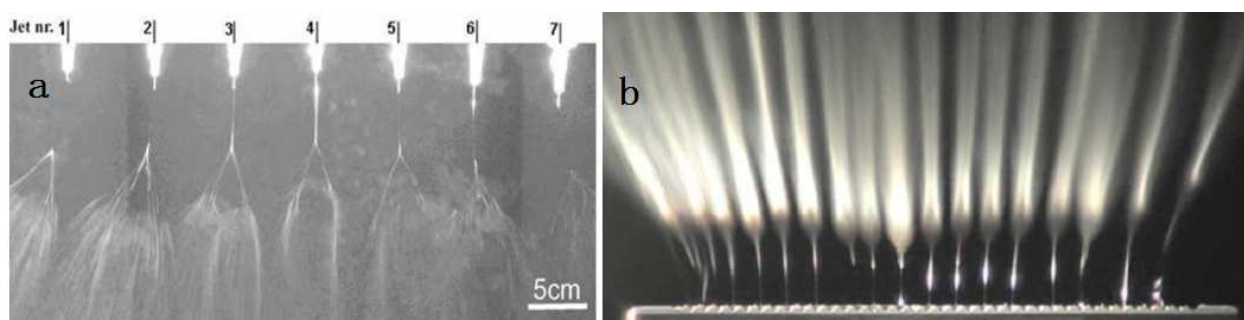


Figure 5. Pictures of (a) multineedle electrospinning and (b) needleless electrospinning setups [49, 50].

The spinneret matrices for scaling-up electrospinning as figure 5(a) shows is an on-brain method by simply copying single spinnerets. Its most impressive advantage is that there is no risk in carrying out any scaling-up processes of materials that are realized in a single needle setup. However, if the neighboring spinning heads are too close, the jets' distribution on the

deposited fabrics will not be even because of the electrical field interference between the needles [49]. In order to deal with this problem, it has been suggested that the array parameters, of the spinning heads, be improved [49]. It has also been demonstrated that the interference of the electrical field can be minimized by adding a hat to the spinning head [51].

The latter method, needleless electrospinning [50] or so-called free-surface electrospinning [52] or the nozzleless electrospinning method [53], is much simpler than the method mentioned above. This was first published by A.L. Yarin and E. Zussman [54] in 2003. They used magnetic fl003 prepared by mixing magnetic powder in kerosene with oleic acid as a stabilizer to initiate multiple jetting from the free surface under the action of the normal magnetic and electric field, which yields about 26 jets/cm², while the former method with nine orifices yields only 2.25 jets/cm² [49]. Subsequently, many kinds of varieties of method emerged by improving the spinning heads (as shown in Table 1). Outputs have been listed below, from which we can find that most of them have yield close to 10g/h.

Character of spinning head	Fiber diameter (nm)	Spinning voltage (kV)	Output (g/h)
Single orifice	3–500	<30	0.01–0.1
Laser heated linear sheet	<1000	16–41	0.36–1.28
Circling linear head	282–552	25–55	4.2
Edge of a disc	595–1235	20–50	6.85
Magnetic fluid surface	200–800	>32	0.12–1.2
Cylinder surface	100–800	40–70	1.25–12.5
Spraying from cylinder surface	150–400	40–50	0.44–6
Bubbles	50–200	10–35	0.06–0.6
Layered pyramid	87–289	55–70	2.3–5.7
Conical coil	100–700	45–70	0.86–2.75
Spiral coil	164–424	40–70	2.94–9.42

Table 1. Comparison of different nozzles [55].

It is hard to evaluate and compare which method is the best when considering jet number per unit area. However, the most popularly used systems in industry may reflect such an evaluation. Table 2 lists some pioneering companies which have used electrospinning machines for scaling-up production, among which, Elmarco is the most popular company supplying complete equipment [56]. Their technology has evolved from drum type to wire type, which can produce 80,000,000m²/year using an NS 8S1600U machine. For melt electrospinning, thick fiber and high voltage security have always represented an obstacle until Yang's team developed a new method called melt differential electrospinning [57]. In this method more than 60 simultaneous electrified jets are attained using umbellate systems with a flow rate of about 12 g/h [57–58]. The authors also indicated that a scaling-up machine has been established for non-woven fabric production with a 1-m width [58].

Company name	Country	Product/Service	Website
Elmarco	Czech Republic	Supplier of industrial level and lab-scale electrospinning machines	http://www.elmarco.cz/
MECC Co. Ltd	Japan	Supplier of lab-scale and semi-industrial level electrospinning machines	http://www.mecc.co.jp/en/html/nanon/list.html
Fuence	Japan	Lab-scale electrospinning setup and semi-industrial level electrospinning machines Contract manufacturing of nanofibers	http://www.fuence.co.jp/en
ANSTCO (Asian Nanostructures Technology Company)	Iran	Supplier of industrial level and lab-scale electrospinning machines	http://anstco.com/english/indexen.html
Fnm Co. (Fanavaran Nano-Meghyas)	Iran	Supplier of industrial level and lab-scale electrospinning machines and accessories	http://en.fnm.ir/
Inovenso	Turkey	Supplier of industrial level and lab-scale electrospinning machines	http://www.inovenso.com
Yflow	Spain	Supplier of lab-scale and industrial level electrospinning machines	http://www.yflow.com/
SPUR	Czech Republic	Supplier of industrial level setups	http://www.spur-nanotechnologies.cz/
Bioinicia	Spain	Custom manufacturer of electrospinning machines and accessories, both basic and industry setups	http://bioinicia.com/Fuidnatek® http://fluidnatek.com/
Yinglan Lab	China	Scaling-up melt electrospinning machines	http://www.p-processing.com/

Table 2. Companies supplying mass production machines

4. Prospects of electrospinning technology for non-woven fabric production

4.1. Productivity improvement

Different measures have been adopted to improve the productivity of electrospinning for non-woven fabric production [56], however, limited output still exists compared with traditional processes. Needleless electrospinning has shown great potential having advantages over needle-based lines, but a lot of problems remain to be solved. The electrospinning conditions

required restrict control of temperature, humidity, and dust around the spinning pool; the processed polymer should be well dissolved into the solvent and kept for hours or days; and the evaporated solvent should be completely collected and recycled during electrospinning. These requirements change when the material changes. Presently, only a few polymers like PAN, PA6, and PVA can be processed well on a needleless electrospinning line. More polymers and their composites need to be tested to find suitable processing parameters. It should be noticed that it would be difficult to carry out electrospinning without needle-based setups for some materials and morphologies, especially for two component nanofiber and core-shell nanofiber [59]. Therefore, fundamental research should be carried out to optimize on-going production lines to cater for different requirements.

4.2. Eco-friendly material and processes

The use of toxic solvents in solution electrospinning has brought about 3 main problems. First, most of the solvents used in solution electrospinning are toxic [23], such as dimethyl formamide (DMF), isopropyl alcohol, acetone, hexafluoroisopropanol (HFIP), and trifluoroacetic acid (TFA)[60], which means the whole manufacturing process from mix processing of solvents to post-processing of fibers needs a closed environment to ensure worker safety or to measure up to the required standards [61]. Extra processes increase costs and more importantly, fibers with residual toxicity for applications in biomedicine can bring about significant damage to cells [62]. Second, during the mass production process, solvent evaporation may cause a change in ambient temperature and humidity, which means an extra temperature–humidity control system is needed. More specifically, the solvent ratio in most solution systems exceeds 90% in solution electrospinning, and air humidity needs to remain below 30% [63], this means there will be an increase in the cost of mass production [62]. Third, solvent evaporation will cause tiny holes on the fiber surface – ranging from a few to dozens of nanometers in size, which weakens the strength of single fibers. In addition, it is difficult to find solvents for some special polymers at ambient temperature [64].

On the contrary, solvent-free melt electrospinning has some advantages in nature. Melt electrospinning has no complicated process route like solution mixing and recycling. The surface of the resultant fiber is smooth and the fiber has high intensity. Polymer melt is completely transformed into the target product [62]. This method can process almost all thermoplastic polymers such as polypropylene (PP)[65], polyethylene (PE)[66], polyamide (PA), polylactic acid (PLA), polycaprolactone (PCL)[67], polyethylene glycol terephthalate (PET)[68], polyphenylene sulfide (PPS), and thermoplastic polyurethane (TPU)[69]. So a stable melt electrospinning route for nanofiber mass production would be an important choice in pursuing eco-friendly manufacturing methods [63]. More attention should also be given to some water soluble polymers or modified water soluble polymers that can be solution electrospun.

4.3. Fundamental research of as-spun, non-woven fabrics

Although mountains of research work has been done on the process and fiber morphology of electrospinning non-woven fabrics, little information about the as-spun, non-woven fabrics

has been revealed. Specifically, we know little about its mechanical properties including tensile strength, tearing strength, and bursting strength. The combination of electrospun non-woven fabrics with traditional non-woven fabrics or textiles should also be tested since the bonding of nanofiber to thick fiber-based substrate seems difficult.

5. Applications of electrospun non-woven fabrics

Electrospun non-woven fabrics have been used in several fields including high-efficiency filtration, battery separation, biological medicine, sensors, and functional nanofiber textiles, because of their high specific surface area, small pores, and special physical and chemical properties like high conductivity, heat insulating ability, electromagnetic shielding, and biocompatibility [70].

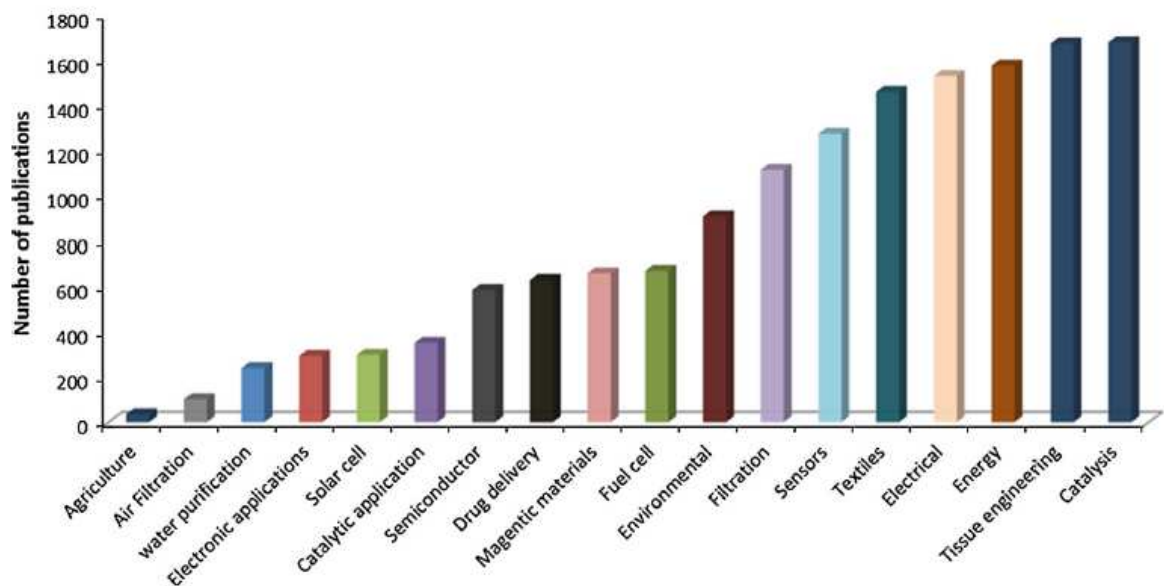


Figure 6. Overview of the number of publications featuring nanofibers used in various applications [70].

5.1. Filtration

In the air filtration field, electrospun non-woven fabrics are taking the place of traditional filter media like activated carbon and fiberglass, because of their excellent performance in filter efficiency and pressure loss. It has been demonstrated by various authors [71] that electrospun nanofibers can remove the volatile organic compounds (VOC) in the air, with some samples filtering faster than conventional activated carbon. Scientists have found that the slip flow mechanism becomes dominant due to the ability of the smaller fiber to disturb the air flow instead of non-slip flow in traditional filters [72]. Surface loading of dust particles takes place on non-woven fabrics coating conventional filters. In one work, Heikkila et al. [73] optimized the coating thickness of polyamide nanofibers required to improve filtration efficiency and

obtain an efficiency of over 95% (0.16 μm Particles) for a 0.5 g/m^2 coating; in another work, Hung et al. [74] studied the effect of fiber diameter on capture efficiency and pressure drop and they observed that when fiber diameter was reduced from 185 to 94 nm, the filtration of 50–500 nm nanoaerosol can be achieved only with a significant increase in the pressure drop.

In the water filtration field, typically used membranes for ultra-filtration (UF) or nano-filtration (NF) filters are made using the phase immersion method. The torturous porosity in these membranes usually has a low flux rate. Therefore, some researchers turned to electrospun non-woven fabrics to make use of their high flux rates. The electrospun non-woven fabrics usually appear as a functional layer in a composite membrane. Yoon et al. [75] studied a composite membrane containing an electrospun PAN scaffold with an average diameter from 124 to 720 nm and a porosity of about 70%, together with a chitosan top layer, and found this membrane exhibited a flux rate that was an order magnitude higher than commercial NF membranes over 24 hours of operation, while maintaining the same rejection efficiency (>99.9%) for oily wastewater filtration. Many other materials having composite membranes with electrospun non-woven layers also have proved this characteristic [76-78]. Some other research has also demonstrated electrospun non-woven fabrics' notable performance in selective filtration of cells or bacteria and adsorption for viruses from fluid [79-80].

5.2. Medical applications

Biopolymers including polysaccharides (cellulose, chitin, chitosan, and dextrose), proteins (collagen, gelatin, silk, etc.), and DNA [81], as well as some biopolymer derivatives and composites, have been successfully electrospun into non-woven fabrics [82]. Applications of these as-spun fabrics have been carried out in many medical fields like tissue engineering, drug delivery, and wound dressing.

Using electrospun non-woven fabrics or partially aligned fabrics as cell scaffold in tissue engineering is one promising application. Scientists found that alignment of fiber in scaffold would be beneficial. Cell elongation and proliferation have been demonstrated to occur along the direction of these nanofibers, which could improve tissue engineering applications [83]. In some other examples, it was found that the number of anchoring points for cells, wetting-properties, and degradation rates can all be varied by adjusting the porosity of as-spun fabrics [84]. However, in most cases, the pores in solution electrospun fabrics were too small for cells to pass through and influenced both cellular and enzymatic behavior [85]. Thus, a lot of measures were adopted to enlarge the diameter of the pores between as-spun fibers including multilayering and mixing electrospinning techniques [86] and combination of electrospun fiber and traditional microscale fiber [81, 87]. A more effective solution was to use the melt electrospinning method and its meshed fabrics as scaffolds, which, had large spaces for cell penetration and tailored aliment for effective cell proliferation [88].

Drug delivery alleviating medical conditions is another application of electrospun fabrics because nanofiber can be controlled to deliver drugs efficiently to a specific area at a controlled release rate via a dissoluble starting material [89]. Most cases focused on drug delivery materials specially applied in tissue engineering scaffold such as bioactive growth factors or

factors to prevent infection while repair and regeneration occur [90], other samples used these non-woven fabrics as a targeted drug carrier for oral medicine [91].

However, electrospinning is still an emerging technology, which requires further theoretical and experimental study. Consideration should be given to the design of a patient-compliant dosage form, material choice, and process controlling. Scaling-up and commercial production are other challenges which need to be overcome for biopolymer composites.

5.3. Functional nanofiber textiles

A lot of functions have been realized or enhanced by the use of nanotechnology in traditional textile materials. Electrospun non-woven fabrics, are widely investigated as a functional layer on some traditional substrates because of its high specific surface area, high gas permeability, and softness. The most promising application is that of protective cloth [92]. In some cases, TiO_2 [93], ZnO [94], or MOF [95] was added in the electrospun fiber or spun into core-shell nanofiber as a photocatalyst [93] or adsorbent to prevent the penetration of organic toxic gas or fluid and UV light. Some research used PP [96], PA66 [97], or PAN [98] to directly produce a non-woven layer on a substrate layer as a protective textile. Yan, Jian, and Zachariah [99] prepared non-woven, fabric-based thermite textiles and tested their reactive properties. He found that this material can yield up to a 1000 times increase in propagation rate compared to its micro-sized counterparts. Other applications of electrospun non-woven materials as a functional layer in textiles include full-color, light-emitting electrospun nanofiber [100] and energy harvesting and self-powered textiles [101].

These applications illustrate the bright future of electrospun non-woven fabrics in functional textiles, however, few industrial products have been pushed to market. More fundamental research work is still required to find out how to adhere non-woven fabrics to traditional textiles without influencing their properties [97]. Although mass production has been carried out by some companies, fewer examples have been revealed using functional materials.

5.4. Sensors

Many kinds of materials such as polymers [102], semiconductors [103], and organic/inorganic composites [104] have been used as sensing materials to detect targeted toxic gases, toxic solid, or toxic fluid materials based on various sensing techniques and principles. Electrospun non-woven fabrics have a specific surface approximately 1–2 orders of magnitude larger than flat films, making them excellent candidates for applications in ultrasensitive sensors. Different electrospun non-woven materials have been applied as ultrasensitive sensors to detect the signal changes of acoustic waves [105], resistivity [106], photoelectricity [107], optical waves [108], and amperometric parameters [109]. It was found that parameters including specific surface area, fiber diameter, and membrane thickness have great influence on the detecting properties of sensors. Higher surface-to-volume ratios of electrospun non-woven fabrics represents the key to guarantee fast and sensitive mass transport, electric charge transport, and signal-to-noise current ratios. Therefore, regulating the parameters of the electrospinning process or solution properties has been adopted to produce more porous fiber and even hollow

fiber structures [110]. A thick membrane was found to own a larger sensing area and vacant volume into which more analytes could be absorbed and diffused [111]. However, more experimental studies and theoretical work is required in order to achieve a better control over the size and secondary structure of electrospun non-woven fabrics.

Author details

Haoyi Li^{1,2} and Weimin Yang^{1,2*}

*Address all correspondence to: lihaoyi-hoy@163.com

1 College of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, Beijing, China

2 State Key Laboratory of Organic-Inorganic Composites, Beijing University of Chemical Technology, Beijing, China

References

- [1] Gilbert W, Thompson S P. On the Magnet, Magnetic Bodies Also, and on the Great Magnet the Earth: A New Physiology, Demonstrated by Many Arguments & Experiments [M]. Chiswick Press, 1900.
- [2] Ayres C E, Jha B S, Sell S A, et al. Nanotechnology in the design of soft tissue scaffolds: innovations in structure and function[J]. Wiley Interdisciplinary Reviews: *Nanomedicine and Nanobiotechnology*, 2010, 2(1): 20–34.
- [3] Morton W J. Method of dispersing fluids: U.S. Patent 705,691[P]. 1902-7-29.
- [4] Cooley J F. Apparatus for electrically dispersing fluids: U.S. Patent 692,631[P]. 1902-2-4.
- [5] Anton F. Process and apparatus for preparing artificial threads: U.S. Patent 1,975,504[P]. 1934-10-2.
- [6] Anton F. Method and apparatus for spinning: U.S. Patent 2,160,962[P]. 1939-6-6.
- [7] Anton F. Artificial thread and method of producing same: U.S. Patent 2,187,306[P]. 1940-1-16..
- [8] Anton F. Production of artificial fibers from fiber forming liquids: U.S. Patent 2,323,025[P]. 1943-6-29.
- [9] Anton F. Method and apparatus for spinning: U.S. Patent 2,349,950[P]. 1944-5-30.

- [10] Doshi J, Reneker D H. Electrospinning process and applications of electrospun fibers. Industry Applications Society Annual Meeting, 1993., Conference Record of the 1993 IEEE. IEEE, 1993: 1698–1703.
- [11] Reneker D H, Chun I. Nanometre diameter fibres of polymer, produced by electrospinning. *Nanotechnology*, 1996, 7(3): 216.
- [12] Xu S C, Qin C C, Yu M, et al. A battery-operated portable handheld electrospinning apparatus. *Nanoscale*, 2015, 7(29): 12351–12355.
- [13] Pourdeyehimi B, Fedorova N V, Sharp S R. High strength, durable micro and nano-fiber fabrics produced by fibrillating bicomponent islands in the sea fibers: U.S. Patent 8,420,556[P]. 2013-4-16.
- [14] Weinberg M, Dee G, Harding T. Flash spun web containing sub-micron filaments and process for forming same: U.S. Patent Application 11/015,527[P]. 2004-12-17.
- [15] Beachley V, Wen X. Effect of electrospinning parameters on the nanofiber diameter and length. *Materials Science and Engineering: C*, 2009, 29(3): 663–668.
- [16] Ellison C J, Phatak A, Giles D W, et al. Melt blown nanofibers: Fiber diameter distributions and onset of fiber breakup. *Polymer*, 2007, 48(11): 3306–3316.
- [17] Liu Z, Liu Y, Ding Y, et al. Tug of war effect in melt electrospinning. *Journal of Non-Newtonian Fluid Mechanics*, 2013, 202: 131–136.
- [18] Hutmacher D W, Dalton P D. Melt electrospinning. *Chemistry, an Asian journal*, 2011, 6(1): 44–56.
- [19] Fong H, Chun I, Reneker D H. Beaded nanofibers formed during electrospinning. *Polymer*, 1999, 40(16): 4585–4592.
- [20] Wang X. Melt-electrospinning of PMMA. *Chinese Journal of Polymer Science*, 2010, 28(1): 45–53.
- [21] Jia L, Qin X. The effect of different surfactants on the electrospinning poly (vinyl alcohol)(PVA) nanofibers. *Journal of thermal analysis and calorimetry*, 2013, 112(2): 595–605.
- [22] Ogata N, Yamaguchi S, Shimada N, et al. Poly (lactide) nanofibers produced by a melt-electrospinning system with a laser melting device. *Journal of applied polymer science*, 2007, 104(3): 1640–1645.
- [23] Dalton P D, Grafahrend D, Klinkhammer K, et al. Electrospinning of polymer melts: Phenomenological observations. *Polymer*, 2007, 48(23): 6823–6833.
- [24] Taylor G I. Electrically Driven Jets. *London Ser A*, 1969, 313(1515): 453–457.
- [25] Demir M M, Yilgor I, Yilgor E E A, et al. Electrospinning of polyurethane fibers. *Polymer*, 2002, 43(11): 3303–3309.

- [26] Hao Mingfeng, Liu Yong, Deng Rongjian, et al. Research on typical materials by melt electrospinning. *Engineering Plastics Application*, 2010, 38(3): 24–27 (in Chinese).
- [27] Ratthapol R, Darrell H R. Electrospinning Process of Molten Polypropylene in Vacuum. *Journal of Metals, Materials and Minerals*, 2003, 12(2): 81–87.
- [28] Lee C K, Kim S I, Kim S J. The influence of added ionic salt on nanofiber uniformity for electrospinning of electrolyte polymer. *Synthetic metals*, 2005, 154(1–3): 209–212.
- [29] Nayak R, Kyratzis I L, Truong Y B, et al. Melt-electrospinning of polypropylene with conductive additives. *Journal of Materials Science*, 2012, 47(17): 6387–6396.
- [30] Tan S H, Inai R, Kotaki M, et al. Systematic parameter study for ultra-fine fiber fabrication via electrospinning process. *Polymer*, 2005, 46(16): 6128–6134.
- [31] Mazinani S, Ajji A, Dubois C. Morphology, structure and properties of conductive PS/CNT nanocomposite electrospun mat. *Polymer*, 2009, 50(14): 3329–3342.
- [32] Moghe A K, Hufenus R, Hudson S M, et al. Effect of the addition of a fugitive salt on electrospinnability of poly (ϵ -caprolactone). *Polymer*, 2009, 50(14): 3311–3318.
- [33] Ki C S, Baek D H, Gang K D, et al. Characterization of gelatin nanofiber prepared from gelatin–formic acid solution. *Polymer*, 2005, 46(14): 5094–5102.
- [34] Zhang Y, He X, Li J, et al. Fabrication and ethanol-sensing properties of micro gas sensor based on electrospun SnO₂ nanofibers. *Sensors and Actuators B: Chemical*, 2008, 132(1): 67–73.
- [35] Chang C, Limkrailassiri K, Lin L. Continuous near-field electrospinning for large area deposition of orderly nanofiber patterns. *Applied Physics Letters*, 2008, 93(12): 123111(1-3).
- [36] Lee K H, Kim H Y, Bang H J, et al. The change of bead morphology formed on electrospun polystyrene fibers. *Polymer*, 2003, 44(14): 4029–4034.
- [37] Uyar T, Besenbacher F. Electrospinning of uniform polystyrene fibers: The effect of solvent conductivity. *Polymer*, 2008, 49(24): 5336–5343.
- [38] Sun G E, Teng H, Zhang C L, et al. Preparation of Ultrafine Water-soluble Polymers Nanofiber Mats via Electrospinning. *Chemical Research in Chinese Universities*, 2010, 26(2): 318–322.
- [39] Subbiah T, Bhat G S, Tock R W, et al. Electrospinning of nanofibers. *Journal of Applied Polymer Science*, 2005, 96(2): 557–569.
- [40] Wei A, Wang J, Wang X, et al. Preparation and characterization of the electrospun nanofibers loaded with clarithromycin. *Journal of Applied Polymer Science*, 2010, 118(1): 346–352.
- [41] Li D, Wang Y, Xia Y. Electrospinning nanofibers as uniaxially aligned arrays and layer-by-layer stacked films. *Advanced Materials*, 2004, 16(4): 361–366.

- [42] Teo W E, Ramakrishna S. Electrospun fibre bundle made of aligned nanofibres over two fixed points. *Nanotechnology*, 2005, 16(9): 1878-1884
- [43] Katta P, Alessandro M, Ramsier R D, et al. Continuous electrospinning of aligned polymer nanofibers onto a wire drum collector. *Nano Letters*, 2004, 4(11): 2215-2218.
- [44] Dalton P D, Klee D, Möller M. Electrospinning with dual collection rings. *Polymer*, 2005, 46(3): 611-614.
- [45] Putti M, Simonet M, Solberg R, et al. Electrospinning poly (ϵ -caprolactone) under controlled environmental conditions: Influence on fiber morphology and orientation. *Polymer*, 2015, 63: 189-195.
- [46] Zhou H, Green T B, Joo Y L. The thermal effects on electrospinning of polylactic acid melts. *Polymer*, 2006, 47(21): 7497-7505.
- [47] Kalayci V E, Patra P K, Kim Y K, et al. Charge consequences in electrospun polyacrylonitrile (PAN) nanofibers. *Polymer*, 2005, 46(18): 7191-7200.
- [48] Pinchuk L S, Goldade V A, Makarevich A V, et al. Melt blowing: Equipment, Technology, and Polymer Fibrous Materials. Springer Science & Business Media, 2012.
- [49] Theron S A, Yarin A L, Zussman E, et al. Multiple jets in electrospinning: experiment and modeling. *Polymer*, 2005, 46(9): 2889-2899.
- [50] Niu H, Lin T. Fiber generators in needleless electrospinning. *Journal of Nanomaterials*, 2012, 2012: 1-12.
- [51] Kim G H, Cho Y S, Kim W D. Stability analysis for multi-jets electrospinning process modified with a cylindrical electrode. *European Polymer Journal*, 2006, 42(9): 2031-2038.
- [52] Lukas D, Sarkar A, Pokorny P. Self-organization of jets in electrospinning from free liquid surface: a generalized approach. *Journal of Applied Physics*, 2008, 103(8): 084309(1-7).
- [53] Petrik S, Maly M. Production nozzle-less electrospinning nanofiber technology. MRS Proceedings. Cambridge University Press, 2009, 1240: 1240-WW03-07.
- [54] Yarin A L, Zussman E. Upward needleless electrospinning of multiple nanofibers. *Polymer*, 2004, 45(9): 2977-2980.
- [55] Xiao G, Li H, Li X, et al. Research progress of fluid differential electrostatic spinning nozzle design. *Journal of Textile Research*, 2014, 35(12): 153-158 (in Chinese).
- [56] Persano L, Camposeo A, Tekmen C, et al. Industrial upscaling of electrospinning and applications of polymer nanofibers: a review. *Macromolecular Materials and Engineering*, 2013, 298(5): 504-520.

- [57] Li H, Chen H, Zhong X, et al. Interjet distance in needleless melt differential electrospinning with umbellate nozzles. *Journal of Applied Polymer Science*, 2014, 131(15): 40515(1-8)
- [58] Li H Y, Bubakir M M, Xia T, et al. Mass production of ultra-fine fibre by melt electrospinning method using umbellate spinneret. *Materials Research Innovations*, 2014, 18(S4): 921-925.
- [59] Forward K M, Flores A, Rutledge G C. Production of core/shell fibers by electrospinning from a free surface. *Chemical Engineering Science*, 2013, 104: 250–259.
- [60] Jiang Q, Reddy N, Yang Y. Cytocompatible cross-linking of electrospun zein fibers for the development of water-stable tissue engineering scaffolds. *Acta Biomaterialia*, 2010, 6(10): 4042–4051.
- [61] Wei A, Wang J, Wang X, et al. Preparation and characterization of the electrospun nanofibers loaded with clarithromycin. *Journal of Applied Polymer Science*, 2010, 118(1): 346–352.
- [62] Nagy Z K, Balogh A, Drávavölgyi G, et al. Solvent-free melt electrospinning for preparation of fast dissolving drug delivery system and comparison with solvent-based electrospun and melt extruded systems. *Journal of Pharmaceutical Sciences*, 2013, 102(2): 508–517.
- [63] Wang C, Lu X F. High Voltage Electrospinning and Nanofibers. Science Press, 2011: 21. 31–48 (in Chinese)
- [64] Sarkar K, Gomez C, Zambrano S, et al. Electrospinning to forcespinning™. *Materials Today*, 2010, 13(11): 12–14.
- [65] Fang J, Zhang L, Sutton D, et al. Needleless melt-electrospinning of polypropylene nanofibres. *Journal of Nanomaterials*, 2012, 2012: 1-9.
- [66] Deng R, Liu Y, Ding Y, et al. Melt electrospinning of low-density polyethylene having a low-melt flow index. *Journal of Applied Polymer Science*, 2009, 114(1): 166–175.
- [67] Hao. M. F, Liu. Y, Deng. J. R, et, al. Researches on melt electrospinning of typical materials. *Engineering Plastics Application*, 2010, 38(3): 24–27 (in Chinese).
- [68] Ogata N, Shimada N, Yamaguchi S, et al. Melt-electrospinning of poly (ethylene terephthalate) and polyalirate. *Journal of Applied Polymer Science*, 2007, 105(3): 1127–1132.
- [69] Dasdemir M, Topalbekiroglu M, Demir A. Electrospinning of thermoplastic polyurethane microfibers and nanofibers from polymer solution and melt. *Journal of Applied Polymer Science*, 2013, 127(3): 1901–1908.
- [70] Kaur S, Sundarrajan S, Rana D, et al. Review: the characterization of electrospun nanofibrous liquid filtration membranes. *Journal of Materials Science*, 2014, 49(18): 6143–6159.

- [71] Scholten E, Bromberg L, Rutledge G C, et al. Electrospun polyurethane fibers for absorption of volatile organic compounds from air. *ACS Applied Materials & Interfaces*, 2011, 3(10): 3902–3909.
- [72] Graham K, Ouyang M, Raether T, et al. Polymeric nanofibers in air filtration applications. Fifteenth Annual Technical Conference & Expo of the American Filtration & Separations Society, Galveston, Texas. 2002: 9–12.
- [73] Heikkilä P, Taipale A, Lehtimäki M, et al. Electrospinning of polyamides with different chain compositions for filtration application. *Polymer Engineering & Science*, 2008, 48(6): 1168–1176.
- [74] Hung C H, Leung W W F. Filtration of nano-aerosol using nanofiber filter under low Peclet number and transitional flow regime. *Separation and Purification Technology*, 2011, 79(1): 34–42.
- [75] Yoon K, Kim K, Wang X, et al. High flux ultrafiltration membranes based on electrospun nanofibrous PAN scaffolds and chitosan coating. *Polymer*, 2006, 47(7): 2434–2441.
- [76] Aussawasathien D, Teerawattananon C, Vongachariya A. Separation of micron to sub-micron particles from water: electrospun nylon-6 nanofibrous membranes as pre-filters. *Journal of Membrane Science*, 2008, 315(1): 11–19.
- [77] Yoon K, Hsiao B S, Chu B. Formation of functional polyethersulfone electrospun membrane for water purification by mixed solvent and oxidation processes. *Polymer*, 2009, 50(13): 2893–2899.
- [78] Gopal R, Kaur S, Feng C Y, et al. Electrospun nanofibrous polysulfone membranes as pre-filters: Particulate removal. *Journal of Membrane Science*, 2007, 289(1): 210–219.
- [79] Lemma S M, Esposito A, Mason M, et al. Removal of bacteria and yeast in water and beer by nylon nanofibrous membranes. *Journal of Food Engineering*, 2015, 157: 1–6.
- [80] Sato A, Wang R, Ma H, et al. Novel nanofibrous scaffolds for water filtration with bacteria and virus removal capability. *Journal of Electron Microscopy*, 2011, 60(3): 201–209.
- [81] Luu Y K, Kim K, Hsiao B S, et al. Development of a nanostructured DNA delivery scaffold via electrospinning of PLGA and PLA–PEG block copolymers. *Journal of Controlled Release*, 2003, 89(2): 341–353.
- [82] Schiffman J D, Schauer C L. A review: electrospinning of biopolymer nanofibers and their applications. *Polymer Reviews*, 2008, 48(2): 317–352.
- [83] Teo W E, Ramakrishna S. A review on electrospinning design and nanofibre assemblies. *Nanotechnology*, 2006, 17(14): R89.

- [84] Casper C L, Stephens J S, Tassi N G, et al. Controlling surface morphology of electrospun polystyrene fibers: effect of humidity and molecular weight in the electrospinning process. *Macromolecules*, 2004, 37(2): 573–578.
- [85] Shin S H, Purevdorj O, Castano O, et al. A short review: recent advances in electrospinning for bone tissue regeneration. *Journal of Tissue Engineering*, 2012, 3(1): 2041731412443530(1-11).
- [86] Kidoaki S, Kwon I K, Matsuda T. Mesoscopic spatial designs of nano-and microfiber meshes for tissue-engineering matrix and scaffold based on newly devised multi-layering and mixing electrospinning techniques. *Biomaterials*, 2005, 26(1): 37–46.
- [87] Thorvaldsson A, Stenhamre H, Gatenholm P, et al. Electrospinning of highly porous scaffolds for cartilage regeneration. *Biomacromolecules*, 2008, 9(3): 1044–1049.
- [88] Lourdes M C M, Hutmacher Dietmar W, Dalton Paul D. Melt electrospinning and its technologization in tissue engineering. *Tissue Engineering Part B: Reviews*, 2015, 21(2): 187-202
- [89] Kenawy E R, Abdel-Hay F I, El-Newehy M H, et al. Processing of polymer nanofibers through electrospinning as drug delivery systems. *Materials Chemistry and Physics*, 2009, 113(1): 296–302.
- [90] Pham Q P, Sharma U, Mikos A G. Electrospinning of polymeric nanofibers for tissue engineering applications: a review. *Tissue Engineering*, 2006, 12(5): 1197–1211.
- [91] Ignatious F, Sun L, Lee C P, et al. Electrospun nanofibers in oral drug delivery. *Pharmaceutical Research*, 2010, 27(4): 576–588.
- [92] Schreuder-Gibson H, Gibson P, Senecal K, et al. Protective textile materials based on electrospun nanofibers. *Journal of Advanced Materials*, 2002, 34(3): 44–55.
- [93] Pant H R, Bajgai M P, Nam K T, et al. Electrospun nylon-6 spider-net like nanofiber mat containing TiO₂ nanoparticles: a multifunctional nanocomposite textile material. *Journal of Hazardous Materials*, 2011, 185(1): 124–130.
- [94] Lee S. Developing UV-protective textiles based on electrospun zinc oxide nanocomposite fibers. *Fibers and Polymers*, 2009, 10(3): 295–301.
- [95] Rose M, Boehringer B, Jolly M, et al. MOF processing by electrospinning for functional textiles. *Advanced Engineering Materials*, 2011, 13(4): 356–360.
- [96] Lee S, Kay Obendorf S. Developing protective textile materials as barriers to liquid penetration using melt-electrospinning. *Journal of Applied Polymer Science*, 2006, 102(4): 3430–3437.
- [97] Heikkilä P, Sipilä A, Peltola M, et al. Electrospun PA-66 coating on textile surfaces. *Textile Research Journal*, 2007, 77(11): 864–870.

- [98] Bagherzadeh R, Latifi M, Najar S S, et al. Transport properties of multi-layer fabric based on electrospun nanofiber mats as a breathable barrier textile material. *Textile Research Journal*, 2012, 82(1): 70–76.
- [99] Yan S, Jian G, Zachariah M R. Electrospun nanofiber-based thermite textiles and their reactive properties. *ACS Applied Materials & Interfaces*, 2012, 4(12): 6432–6435.
- [100] Moran-Mirabal J M, Slinker J D, DeFranco J A, et al. Electrospun light-emitting nanofibers. *Nano Letters*, 2007, 7(2): 458–463.
- [101] Gheibi A, Latifi M, Merati A A, et al. Piezoelectric electrospun nanofibrous materials for self-powering wearable electronic textiles applications. *Journal of Polymer Research*, 2014, 21(7): 1–7.
- [102] Slater J M, Paynter J, Watt E J. Multi-layer conducting polymer gas sensor arrays for olfactory sensing. *Analyst*, 1993, 118(4): 379–384.
- [103] Savage N, Chwieroth B, Ginwalla A, et al. Composite n–p semiconducting titanium oxides as gas sensors. *Sensors and Actuators B: Chemical*, 2001, 79(1): 17–27.
- [104] Unde S, Ganu J, Radhakrishnan S. Conducting polymer-based chemical sensor: Characteristics and evaluation of polyaniline composite films. *Advanced Materials for Optics and Electronics*, 1996, 6(3): 151–157.
- [105] Sheng L, Dajing C, Yuquan C. A surface acoustic wave humidity sensor with high sensitivity based on electrospun MWCNT/Nafion nanofiber films. *Nanotechnology*, 2011, 22(26) : 265504–265504.
- [106] Modafferi V, Panzera G, Donato A, et al. Highly sensitive ammonia resistive sensor based on electrospun V_2O_5 fibers. *Sensors and Actuators B: Chemical*, 2012, 163(1): 61–68.
- [107] Yang M, Xie T, Peng L, et al. Fabrication and photoelectric oxygen sensing characteristics of electrospun Co doped ZnO nanofibres. *Applied Physics A*, 2007, 89(2): 427–430.
- [108] Wang X, Drew C, Lee S H, et al. Electrospun nanofibrous membranes for highly sensitive optical sensors. *Nano Letters*, 2002, 2(11): 1273–1275.
- [109] Hu G, Zhou Z, Guo Y, et al. Electrospun rhodium nanoparticle-loaded carbon nanofibers for highly selective amperometric sensing of hydrazine. *Electrochemistry Communications*, 2010, 12(3): 422–426.
- [110] Li D, McCann J T, Xia Y. Use of electrospinning to directly fabricate hollow nanofibers with functionalized inner and outer surfaces. *Small*, 2005, 1(1): 83–86.
- [111] Ding B, Wang M, Wang X, et al. Electrospun nanomaterials for ultrasensitive sensors. *Materials Today*, 2010, 13(11): 16–27.