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Polymer Nanofibers Electrospinning: A review

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ELECTROSPUN nanofibers have found many applications as useful material with reasonable properties and morphology. The electrospinning technique is better than other conventional nanofiber fabrication techniques owing to the ease of formation and controlling fiber orientation. Electrospun nanofiber has unique properties such as a high surface area to volume ratio, easily in surface functionality, interfibrous pore sizes, and the ability to change the nanofiber composition to get specific functions and properties. The current review highlights the electrospinning principles, types of electrospinning, and the parameters that affect the nanofibers fabrication. Finally, we provided some nanofiber applications area such as biomedical, protective clothing, sensors, electrical, and filtration.

Keywords: Electrospinning; Nanofibers; Polymer

Abbreviations

WAXD: wide-angle X-ray ; SEM: Scanning electron microscopy; TEM: Transmission electron microscopy; DSC:Differential scanning calorimetry; PCL: Poly (έ-caprolactone); PLA: Polylactide; PEO: Poly(ethylene oxide); PVA: Polyvinyl alcohol; PU: Polyurethane; PVP: Polyvinylpyrrolidone; PLGA: Poly(lactic-co-glycolic acid); PLCL: Poly(L-lactide-co-caprolactone); PBI: Polybenzimida- zole; PS: Polystyrene; SF: Silk fibroin; PAN: Polyacrylonitrile; HA: Hyaluronic acid; PLLA: Poly(l-lactide); PVDF: Poly(vinylidene fluoride); CNF: carbon nanofiber; PESU: Polyethersulfone.

Introduction

Electrospinning is a process used for produce polymer fibers in the submicron range using polymer melts or solution of both natural and synthetic polymers [1-3]. The properties of these fibers are difficult to achieve by using other technology techniques (like greater surface area and smaller pores size than regular fibers) [3-5]. These fibers have enormous applications in different fields like tissue scaffolds, filtration, biodiesel production, healthcare, protective clothing, defense and security, biomedical, biotechnology, optical electronics, nanocatalysis and pharmaceutical [6-8]. The electrospinning procedure depends on an electric field with high voltage to produce jets from polymer (i.e. electrically charged). The charged fibers are moved towards the positively charged collector to gather the fibers (has different shapes relying on the target of prepared fiber). Nanofibers were produced by solvent evaporation from polymer jets when it traveled from spinneret to collector. We aim from this review to introduce the history of electrospinning and different variables that affect the structural morphology and properties of the fibers. Also, we will discuss some applications of the nanofibers.

History and concept of the electrospinning process

The beginning of electrospinning as a fiber making process can be back to the beginning of the 1930s (as the electrospinning is an old method). Formhals had the first patented for the electrospinning technique using an electric field

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for artificial filaments preparation [9]. Many patents were published (from1934 to 1944) focusing on the experimental setup for polymer filaments production using an electric field [10-12]. Taylor studied the polymer droplet shape formed at the end of the needle after applied an electric field [13]. The results indicated that it is a cone and the jets are emitted from the tops of this cone. This jet conical shape was later referred to the "Taylor Cone" in literature. Researchers focused on studying relations between the process parameters, structures and applications using many techniques like wide-angle X-ray diffraction (WAXD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and differential scanning calorimetry (DSC). Now, due to fast progress in the nanotechnology area, the electrospinning process has acquired extra attention. Because various polymers can be simply fabricated in the form fibrous structures or ultrafine fibers [10].

The electrospinning technique is a simple technique to create fibers from polymer melts or solutions using an electric field. The produced fibers have a great surface area and a small diameter (till nanometre) than those got from traditional spinning techniques. The electrospinning technique depends on the principle that the strong reciprocal electrical repulsive forces overcome surface tension weaker forces (in the charged polymer liquid) [14]. There are two standard electrospinning setups, horizontal and vertical Fig. 1 (a, b). Also there are a lot of sophisticated systems that produce more complicated nanofibrous structures in an efficient manner and more controlled [15, 16]. The device used for electrospinning is simple in structure, which contains three main parts: a high voltage source, a spinneret (a syringe pump with tubes or capillaries to carry polymer solution from the syringe to the spinneret), and a grounded conducting collector. The role of the high voltage source to produce a charge of a certain polarity into a polymer melt or solution, which is then moved towards collector (positively charged) [17, 18]. The collection way of the produced fibers on the collector can influence the fiber orientation. Collection schemes currently used for collectors include a single ground, dual ring, dual-bar, rotating single ground, single horizontal ring (Fig. 2) [19]. Spun polymer melt or solution is forced by a syringe pump to produce a pendant drop of the polymer at the spinneret tip which is subjected to the electric field. Once the used electric field reaches a high value, the repulsive electrical forces surpass the surface tension forces for the polymer solution. Finally, the solution charged jet is ejected from the Taylor cone tip towards the opposite polarity collector. Evaporation of the solvent occurs in the area between the spinneret tip and collector, as the jet travels through the atmosphere, leaving the dry fibers behind [13, 20, 21]. Therefore, the electrospinning method offers a simple process for fiber formation.

Polymers used in electrospinning

There is a wide range of polymers (synthetic or natural) used in the electrospinning technique. Those polymers are capable of forming submicron range fibers and used for different applications. Table 1 illustrates some polymers which have been used in the electrospinning technique. Electrospun nanofibers can be formed from natural, synthetic polymers, or a blend of both and sometimes it may be containing proteins, polysaccharide and nucleic acids [1, 22, 23]. Natural polymers have the ability for binding cells and so it used in the electrospinning process particularly in the biomedical applications [24, 25]. Natural polymers include, for example, chitosan [26, 27], hyaluronic acid [28], gelatin [29], collagen [30, 31] and silk protein [32, 33]. Synthetic polymers usually offer several merits than natural polymers. Those merits include the desired degradation rate and the required mechanical properties [34]. There are many synthetic polymers applied in the electrospinning like poly (έ-caprolactone) (PCL) [30, 35], polylactide (PLA) [36, 37], poly(ethylene oxide) (PEO) [38] and polyvinyl alcohol (PVA) [39, 40].

Effect of different parameters on electrospinning

Many parameters effect on the electrospinning process (Fig. 3 shows the summary). These parameters classified into: (a) solution factors such as molecular weight, viscosity, surface tension and conductivity; (b) process parameters include applied voltage, gap (distance between the needle tip and the collector), and flow rate; (c) ambient parameters such as humidity, temperature and air speed in the electrospinning cabinet [69, 70].

Solution parameters

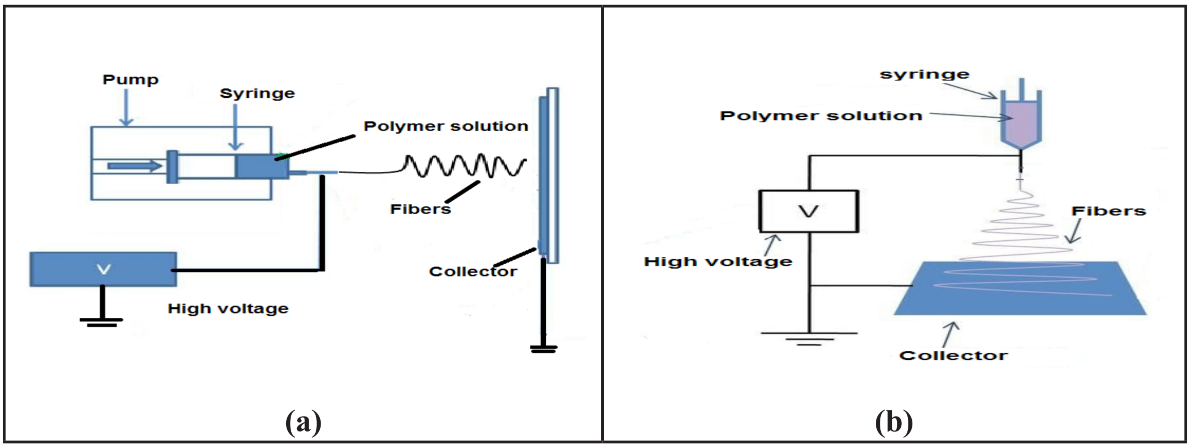
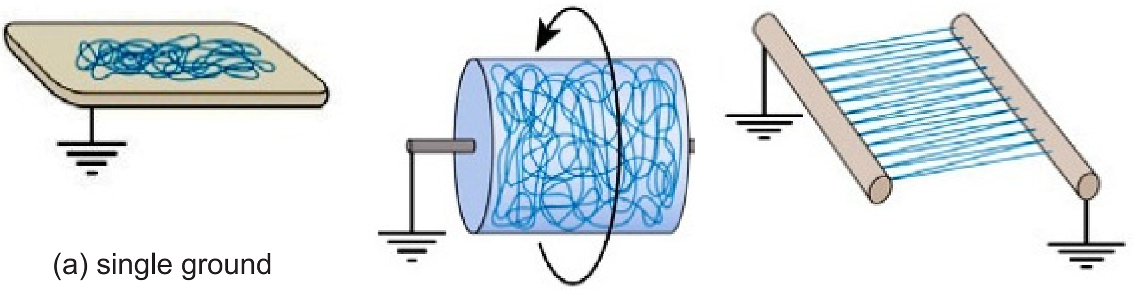


Fig. 1. Electrospinning setup (a) typical vertical setup and (b) horizontal set up

TABLE 1. Some polymers have been used in electrospinning process.

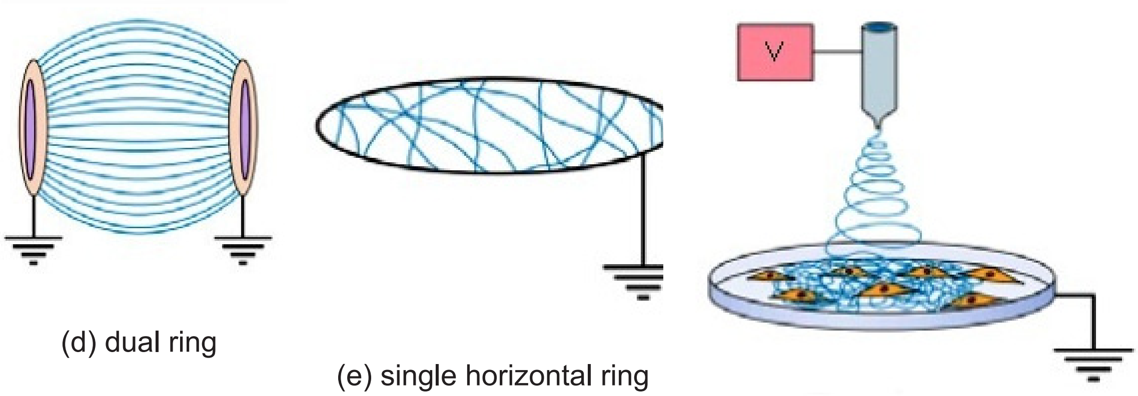
polymer	Application	references
Nylon 6,6	Protective clothing, Transparent composite	[41, 42]
Polyacrylonitrile (PAN)	Carbon nanofiber	[43]
Polyvinyl alcohol (PVA)	Wound dressings, Antimicrobial agent	[44, 45]
polyamide-6,6/chitosan	Tissue engineering	[46]
Collagen	Tissue engineering	[31, 47]
Collagen-PEO	Wound healing, tissue engineering, hemostatic agents	[48, 49]
Collagen/chitosan	Biomaterials	[50]
Cellulose	Affinity membrane	[51]
Cellulose acetate	Adsorptive membranes	[52]
Poly (vinyl alcohol)/cellulose acetate (PVA/CA)	Biomaterials	[53]
Polyvinyl carbazole	Sensor, filter	[54 ,53]
Silk/PEO blend	Biomaterial scaffolds	[55]
polyvinylpyrrolidone (PVP)	Wound dressing	[56]
Silk fibroin (SF)	Nanofibrous scaffolds for wound healing	[57, 58]
Polystyrene (PS)	Air filtration / Electrical application	[59, 60]
Hyaluronic acid (HA)	Wound dressing	[28]
Polyurethanes (PU)	Biomedical applications	[61]
Polybenzimidazole (PBI)	Protective clothing	[62]
Chitosan	Wound dressing	[63]
Poly(l-lactide) (PLLA)	3D cell substrate	[36]
Polyurethane (PU)	Biomedical applications	[64]
Polycaprolactone (PCL)	Bone tissue engineering	[35]
poly(vinyl pyrrolidone) (PVP)	Drug release	[65]
poly(ethylene oxide) (PEO)	Biomedical applications	[38]
poly(acrylonitrile-co-glycidyl methacrylate)	Affinity separation	[66]
Polyethersulfone (PESU)	Filtration	[67]
Polyvinylidene fluoride (PVDF)	Filtration	[68]



(a) single ground

(b) Rotating single ground

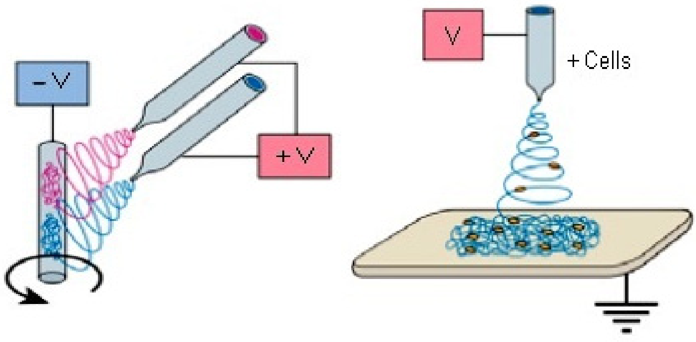
(c) dual bar



(d) dual ring

(e) single horizontal ring

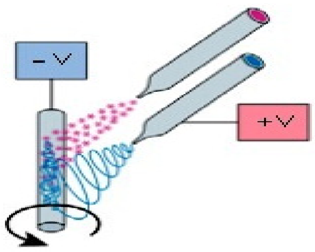
(f) electrospinning in vitro onto cells



(g) dual spinneret electrospinning (with second pink fibers)

(h) electrospinning cells with polymer

(i) perpendicular spinnerets



(j) electrospinning/ electrospraying with parallel

Fig. 2. Different electrospinning collecting schemes. (a) single ground, (b) Rotating single ground, (c) dual bar, (d) dual ring, (e) single horizontal ring, (f) electrospinning in vitro onto cells, (g) dual spinneret electrospinning (with second pink fibers), (h) electrospinning cells with polymer, (i) perpendicular spinnerets and (j) electrospinning/ electrospraying with parallel [Reprinted from reference 19].

Concentration: Solution concentration determines the limiting borders for the formation of electrospun fibers due to differences in the viscosity and surface tension [71]. At low solution concentration, a mixture of beads and fibers or completely beads is formed instead of fibers. Furthermore, when the solution concentration increases, the fibers are formed due to the higher viscosity resistance (Fig. 4) [71,72]. So the suitable solution concentration for the electrospinning process should be adjusted for each experiment.

Viscosity: The solution viscosity is one of the almost considerable parameters that impact the fiber diameter and morphology during the electrospinning process (Fig. 5) [73, 74]. When a solid polymer dissolves in a solvent, the solution viscosity is relative to the polymer concentration [75]. Viscosity, polymer concentration and molecular weight of the polymer are correlated to each other [76]. There were several works show low and high viscosity effects on nanofibers formation [77, 78]. With very low viscosity there are beads or beaded fibers formation as the surface tension is the main factor and with high viscosity, there is the hardness in the ejection of jets from polymer solution [69, 78]. Moreover, a controlled increase in solution viscosity or concentration led to a larger and more uniform fiber diameter [71, 79]. The relation between the polymer viscosity and/or concentration and fibers obtained from electrospinning has been considered in many systems [76, 80].

Molecular weight: Polymer molecular weight has a worth effect on electrospun fiber morphology and electrical properties like conductivity, viscosity, surface tension and dielectric strength [81]. In principle, polymer molecular weight shows the number of entanglements of polymer chains in a solution, called solution viscosity [82]. Chain entanglement shows an important role in electrospinning processing. It has been observed that too low molecular weight solution tends to form beads instead of fibers (electrospray occurs) and high molecular weight solution gives fibers with larger average diameters [83]. Generally, solutions of high molecular weight polymers have been used in the electrospinning process as they supply the wanted viscosity for the fiber generation [84].

Surface tension: Surface tension, as a function of solvent behavior for the solution, a very important factor in the electrospinning process. If all other factors are kept constant, surface tension can determine the upper and lower boundaries of the electrospinning process border [85, 86]. The formation of fibers, beads, and droplets depends on the solution surface tension: (a) with lower surface tension for spinning solution this helps electrospinning to occur at a lower electric field, (b) with high solution surface tension the electrospinning process was inhibited because of instability of the jets and in this case droplets sprayed generated instead of nanofiber formation [87]. Generally, with fixed concentration, nanofibers can be obtained without beads by reducing the surface tension of the nanofiber solution. Also, the solvents used in the electrospinning process have an important effect on the surface tensions of the solution [88-90].

Conductivity/surface charge density: The conductivity of the solution is depending on the polymer nature, the solvent used, and the availability of salts [89, 91, 92]. Most polymers are conductive and the charged ions in the polymer solution are extremely effective in jet formation. Increasing electrical conductivity of the solution led to a considerable decrease in the diameter of the electrospun nanofibers. While it is not easy to produce uniform fiber and observation for beads occur with low solution conductivity [93]. Fiber formation from natural polymers is difficult in contrast to synthetic polymers. Because natural polymers are polyelectrolytes, in which the ions increase the ability of the polymer jet to carry a charge, which leads to higher tension under the electric field [94]. Usually, the solution electrical conductivity can be controlled by using ionic salts like NaCl, KH_2PO_4, NaH_2PO_4 and so on [95]. Nanofibers with a very small diameter can be formed with the aid of these ionic salts and there is a decrease in beads formation [85, 96].

Processing parameters

Applied voltage: The applied voltage is a critical factor in the electrospinning process. Charged jets ejected (from Taylor Cone) occur if applied voltage higher than the threshold voltage. The spinning conditions (viscosity, voltage, and feed rate) have a strong effect on the drop initiating shape for the electrospinning solution [97]. The effect of the applied voltages on the electrospun fibers diameter is a little debatable.

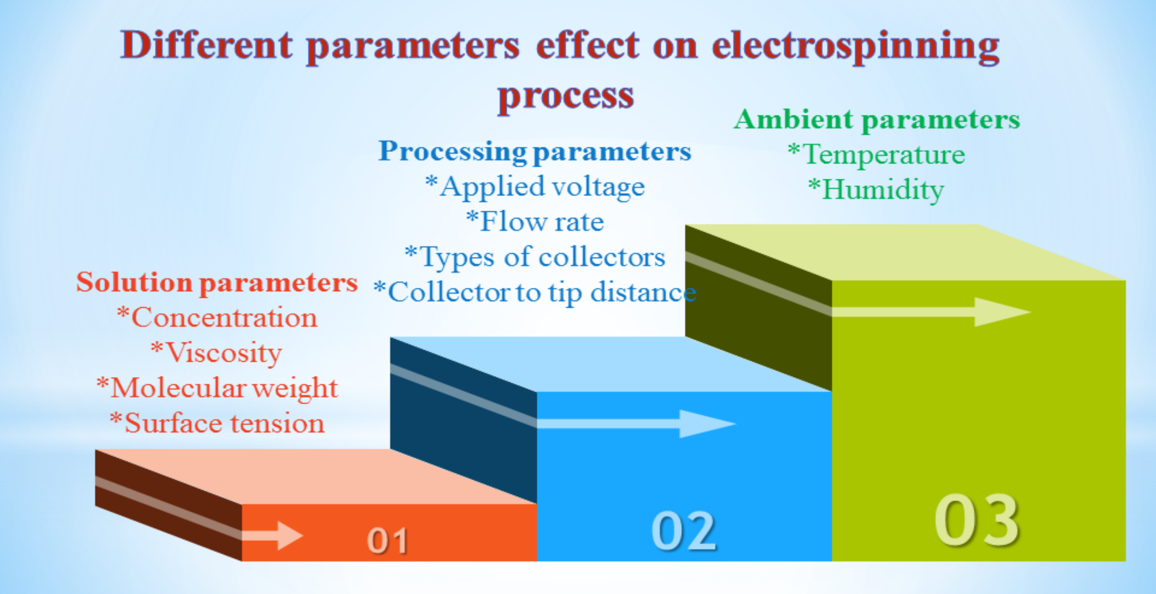


Fig. 3. The different parameters effect on electrospinning process

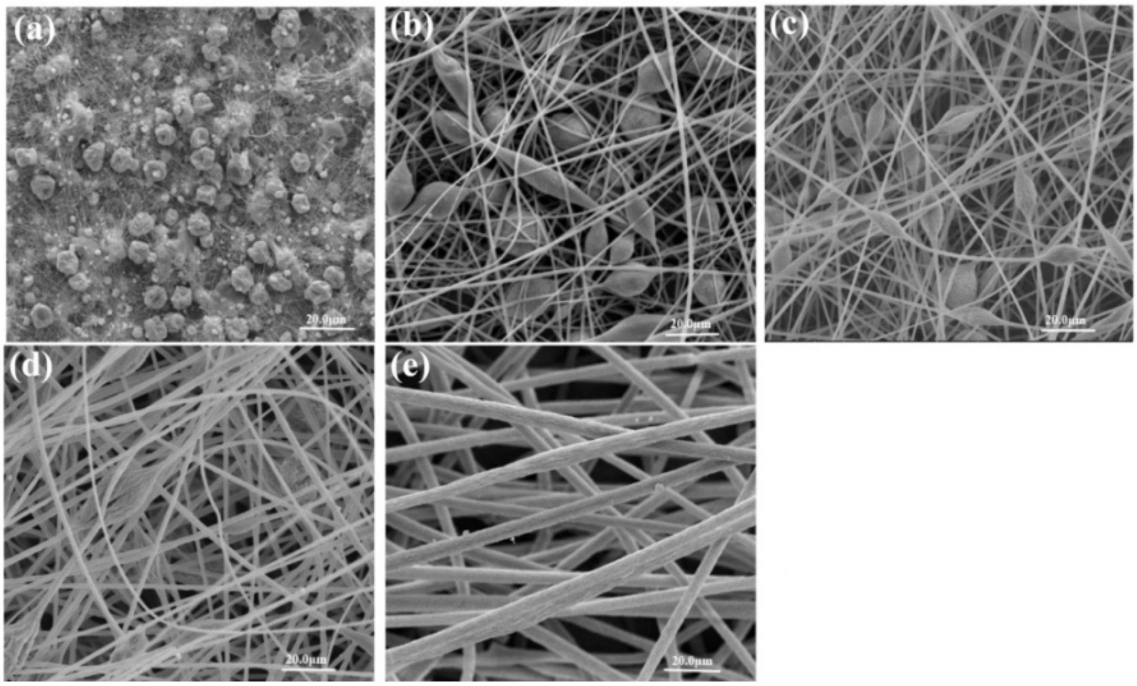


Fig 4. Scanning electron micrographs of electrospun polystyrene (PS) fibers with different concentrations of PS/ DMF solutions (a) 10% (b) 23% (c) 27% (d) 32% (e) 40% (w/v) [Reprinted from reference 72].

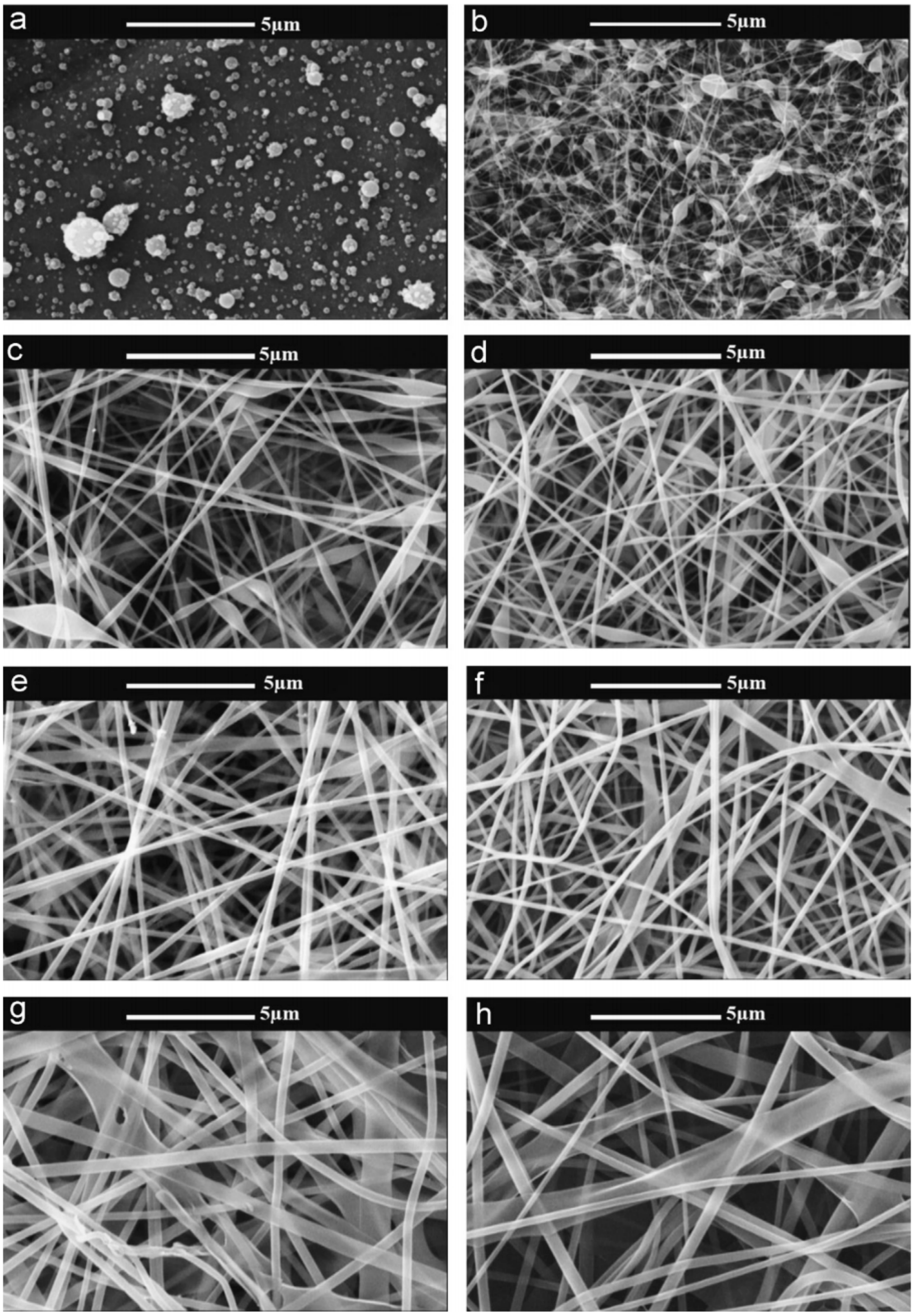


Fig. 5. Morphologies of electrospun fibres with (a) 0 wt%, (b) 2 wt%, (c) 4 wt%, (d) 5 wt%, (e) 6 wt%, (f) 7 wt%, (g) 8 wt% and (h) 1 wt% of Polyvinyl alcohol (PVA) [Reprinted from reference 73].

Some authors suggested that the applied voltage has not much effect on the fiber diameter [98]. While some authors suggested that more polymer ejection occurs when applied high voltage as this facilitates the formation of a large fiber diameter [75]. Using high voltage, sometimes, causes better stretching of the solution due to the higher columbic forces in the jet. Besides, these effects lead to decrease in the fiber diameter and fast solvent evaporation from the resulted fibers [93]. But, there is a probability of beads formation by using high voltage [99, 100]. Thus, applied voltage effect on fiber diameter, but the level of the effect depends on the polymer solution concentration and the distance between the collector and the tip [101].

Flow rate: The polymer solution flow rate from the metallic needle tip determines the morphology of the electrospun nanofibers. Because it controls in the material transfer rate and the jet velocity from spinneret to the collector [72, 89]. Usually, the lower flow rate is preferred as the polymer solution (in metallic needle) will get enough time for polarization and the solvent (from fiber) will get enough time for evaporation leaving dry fiber on the collector [89, 94, 102]. Beaded fibers formed by using high flow rates due to low stretching forces and short drying time for the fiber before reaching the collector [89, 103].

Types of collectors: Generally, collectors acted as the conductive substrate to collect the charged nanofibers during the electrospinning process [89]. Usually, aluminum foil is used as a collector but it is tricky to move the collected nanofibers to other substrates for different applications. Different collectors have been developed as a result of needing fibers transferring like pin [104], wire mesh [105], rotating rod, wheel [106], parallel or gridded bar [107] and others types of collectors are common nowadays (Fig. 2). Depending on the type of collector and its rotation speed the fiber alignment is determined [108]. Due to the bending instability of the charged jet of polymer solution the formed nanofibers are collected on the collector as a random lump [109]. To get aligned electrospun fibers, a collector in the form of the metal frame or rotating drum or a rotating wheel-like bobbin are used [69, 71, 110].

Collector to tip distance:
The distance between the collector and the tip of the syringe affects the nanofiber morphologies and diameter because of their dependence on the evaporation rate, deposition time, and instability interval or whipping [111]. Generally, the nanofiber will not have enough time to solidify before reaching the collector if the distance is too short (i.e. wet fiber); whereas bead fiber can be obtained if the distance is too long [111, 112]. Thus, there should be an optimum distance between the collector and tip which gives the nanofibers enough time to dry before reaching the collector.

Ambient parameters

Ambient parameters that include temperature, humidity, vacuum conditions, surrounding gas, etc. can also affect the nanofiber diameters and morphologies [77]. The effect of temperature on the electrospinning process was examined and the results showed that the fiber diameter was decreased when temperature increased [96]. While low humidity may increase the velocity of the solvent evaporation and so the fibers completely dry [74, 89, 113]. On the contrary, high humidity will form thicker fiber diameter because the charges on the jet can be neutralized and the stretching forces will become small [113].

Applications of nanofibers

Electrospun fibers and mats have been attracting the attention as it provides several merits such as very high porosity, high surface to volume ratio, and enhanced physico-mechanical properties of the materials. Besides, the electrospinning process itself is versatile as electrospun fibers can be formed into any shape using different types of polymers [69, 114]. Electrospun nanofibers are wieldy applied in health care (targeted drug delivery, artificial joints and tissue replacement); chemical industry (nanotubes, nanocomposites and cosmetic creams); textile industry (novel apparels, hydrophobic and non-soiling fabrics); environment (filtration, biodegradation and removal of impurities) and electronics (storage devices, spintronics, bioelectronics and quantum electronics). A graphical diagram for different fields using electrospun fibers is shown in Fig. 6. A brief discussion on some nanofiber applications will be discussed in this section.

Biomedical applications

Nanofibers are interesting material for biomedical applications for many reasons like their unique properties such as high surface-area-to-volume ratio, their morphology (dimensions), and inter/intra fibrous porosity. In addition, nanofibrous scaffolds have shown enhanced cell adhesion, protein adsorption and stimulated cell growth [115]. In the next paragraphs, some biomedical application of nanofibers will be discussed

Tissue Engineering: Tissue engineering concept is meaning the replacement of damaged tissues including the skin, bones, cartilage, lymph nodes, blood vessels, muscles, and other tissues. The electrospinning process is a very effective method and provides a simpler means for manufacturing tissue scaffold mesh of micron- to submicron-sized fibers (Fig. 7). Various types of scaffolds have been generated for human tissue and organ regeneration, including bones [116], cartilage [117], arterial blood vessels [118], nerves [119], heart [120], etc. The use of electrospinning techniques to create nanofibrous scaffolds for tissue engineering has been increased because these scaffolds positively enhance cell-cell and cell-matrix interactions with the cells having a normal phenotypic shape [115, 121]. The electrospun nanofibers, which are used in the scaffold preparation, need to be well prepared and must have dimension uniformity. In addition, other requirements such as large surface area, high porosity (better pore size distribution), perfect mechanical properties, biocompatibility, biodegradability, and non-toxicity to the cell are also remarkable factors when using electrospinning process in tissue engineering [122]. Both natural and synthetic polymers electrospun nanofibers have been used in making these scaffolds like collagen [47], Poly (lactic acid) [123], gelatin [29], polyurethane [61,120], poly(ε-caprolactone)/Zein [124] and polyamide-6,6/chitosan [46]. Natural polymers are often used for preparing nanofibrous scaffolds more than synthetic polymer, because of their enhanced biocompatibility and bio-functional concepts, such as silk protein, collagen, fibrinogen, alginate, hyaluronic acid, starch and chitosan [26-28]. Generally, the aligned scaffold produced by electrospinning with a rotational collector exhibits a characteristic fiber alignment when compared to the random fibrous mats generated with normal static collector [10].

Wound dressings:

A novel dressing materials are prepared using the electrospinning technique valuable for wound healing made of spun biopolymers contain various active components (Fig 8). An ideal wound dressing should have specific properties such as (a) providing an effectively prolonged close contact between dressing and skin area around the wound, (b) ensuring protection from heat, (c) allowing the air goes across, (d) maintaining moist environment around the wound, and (e) absorbing extra secretions exuded from the wound [125]. Using polymer nanofibrous as a wound dressing is very useful because it meets most of the requirements for ideal dressing scaffold. Furthermore, the nanofibrous materials have microfibrous and nanofibrous structures which provide the nonwoven textile with desirable properties [100]. Different polymers have been used to produce fibers to act as a wound dressing in different forms like membranes, scaffolds, or implants. Those polymer include synthetic polymers like polyurethane (PU) [120], Poly(vinyl alcohol) (PVA) [40] and polyvinylpyrrolidone (PVP) [56] or natural polymers like cyclodextrin [126], chitosan [64], and chitin [64].

Drug delivery:

The electrospinning process shows great flexibility in materials selected for drug delivery applications. Either non-degradable or biodegradable materials can be used to control drug release (occurs via diffusion and scaffold degradation or diffusion only) [127]. The large surface area associated with nanospun mates allows for effective and quick solvent evaporation, which prevents incorporated drug to recrystallize which prefer the formation of solid solutions or amorphous dispersions [128]. When selecting a specific material to use as drug delivery materials, it should have specific requirements like biodegradation [127]. Various materials including synthetic polymers, natural polymers, and hybrid blends of the two have been used to obtain electrospun fibers. Synthetic polymers have great ability in modification and synthesis, but these polymers lack cell affinity because of their lack of surface cell recognition sites and low hydrophilicity [129]. On the other hand, natural polymers exhibit low immunogenicity and better biocompatibility, and some show effective antibacterial properties and good clinical functionality but tend to display poor mechanical properties and processing ability [129]. Hence, it is favorable to fabricate composite fibrous membranes including both natural polymers for cellular attachment and synthetic polymers for the backbone (which may

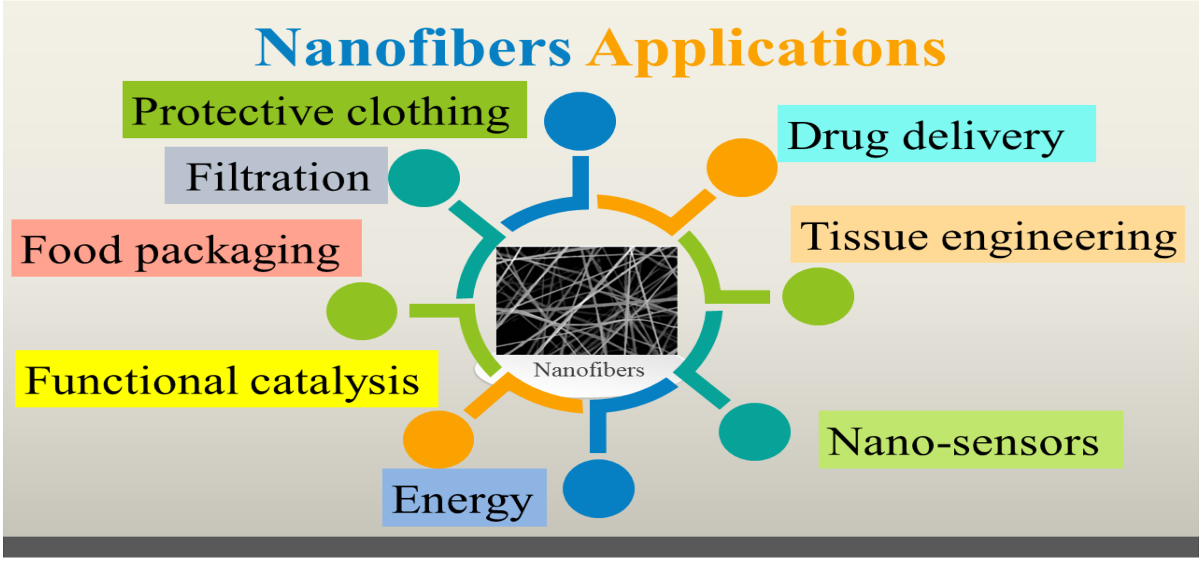


Fig. 6. Some application of electrospun fibers in different fields

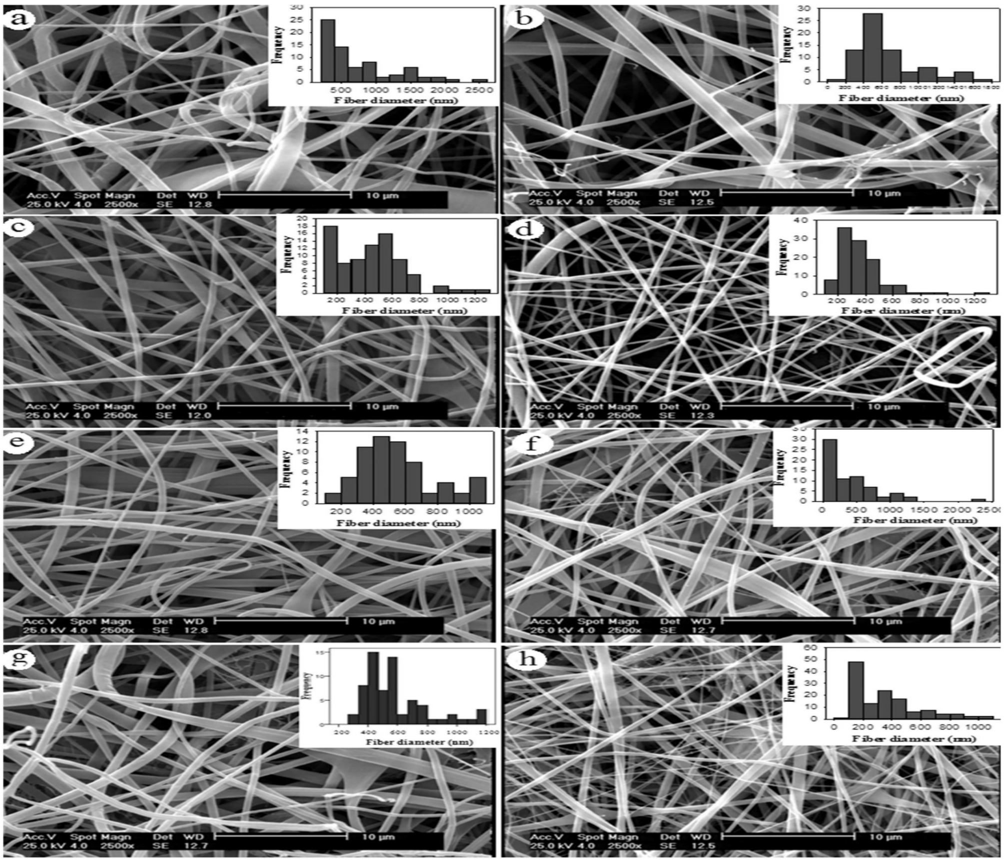


Fig. 7. Surface morphology of Calendula officinalis extract/ Poly (ε-caprolactone) (PCL)/Zein/Gum arabic nanofibrous [Reprinted from reference 124].

have appropriate mechanical properties) [130]. Ideal natural polymers include proteins (collagen, gelatin, silk, etc.), polysaccharides (cellulose, chitin, chitosan, dextrose), DNA, as well as some biopolymer derivatives and composites [131]. Synthetic polymers gain special attention in electrospinning due to the elimination of a second surgery to remove the implanted carrier [132]. Polymers such as poly(ε-caprolactone) (PCL), poly(lactic acid) (PLA), and copolymers, such as poly(lactic-co-glycolic acid) (PLGA) and poly(L-lactide-co-caprolactone) (PLCL) , have been extensively investigated to fabricate fibers with desired properties for drug delivery and tissue engineering applications [133]. Many drugs can be used for drug delivery like proteins [134], anticancer drugs [52, 135], and antibiotics [136]. There are many ways can be used for drug loading like encapsulated, embedded drug and coatings [137].

Protective clothing application

The protective clothing is particularly expected to help maximize the survivability, sustainability, and form an effective system against extreme weather conditions and enhanced toxic chemical resistance [138]. Electrospun nanofiber materials have been recognized as the best choice for protective clothing applications, because of their large surface area, light weight, great filtration efficiency, high porosity, resistant to harmful chemical agents penetration in the aerosol form [139]. Electrospun nanofiber materials are capable of neutralization of chemical agents because of their great surface area (Fig. 9). Also, its resistance the air and water vapor permeability to the clothing [138,139]. Many polymers used in this application like nylon 6, 6, [140], polyurethanes (PU) [141], and polybenzimidazole (PBI) [142].

Electrical application

Conductive nanofibers have potential applications like corrosion protection, electromagnetic interference shielding, photovoltaic device, electrostatic dissipation and fabrication of tiny electronic devices or machines such as Schottky junctions, sensors and actuators [2, 143,144]. Conductive nanofibrous materials are suitable for use as a porous electrode in improving high-performance battery and polymer electrolyte membrane fuel cells because it had high porosity and inherent large total surface area (Fig 10). Because the rate of electrochemical reactions is proportional to the surface area of the electrode [143, 144]. Many polymers are used in this application like poly(vinylidene fluoride) (PVDF) [145], polyvinylpyrrolidone (PVP) [65, 66], and poly(e-caprolactone) (PCL) [146].

As biosensors

Nanofibers are used in sensors to improve their performance. The sensitivity of a film is proportional to the surface area of the film per unit mass. Thin films made of nanofibers have a surface area approximately one to two orders of magnitude larger than continuous films and therefore their sensitivities are potentially as large [147]. Polymer nanofibers have an advantage over the existing sensor substrates because it has large available surface. Nanofibrous supports with designed hierarchical pore structure architecture can provide a unique environment for biosensing. Due to controlled fluid delivery, retention, and ability to facilitate direct electron transfer [147].

It was found that electrospun fibers had better strength, uniformity during fabrication, and gave reproducible results (Fig. 11) [148-150]. To improve the conductivity and resolution of the fibers, metal ions such as Ag [150], and Si [151, 152] are electrodeposited or coated onto the surface of the fiber. The literature shows that polymers such as polyvinylpyrrolidone (PVP) [153], polyaniline [154] have been electrospun and successfully used as sensing interfaces. The application scope of biosensors can be generally classified into two categories: environmental (as there is a strong need for detection of biological substances and gases at very low concentration) and biomedical [155,156]. Recent progress in biomedical technology has resulted in the development of novel sensor products which are becoming more and more accurate and inexpensive [154]. Recently, efforts were undertaken in the production of nanofibers for more advanced biosensor applications.

As affinity membrane

Affinity membrane was developed to improve the purification process for molecules based on biological functions rather than molecular size/

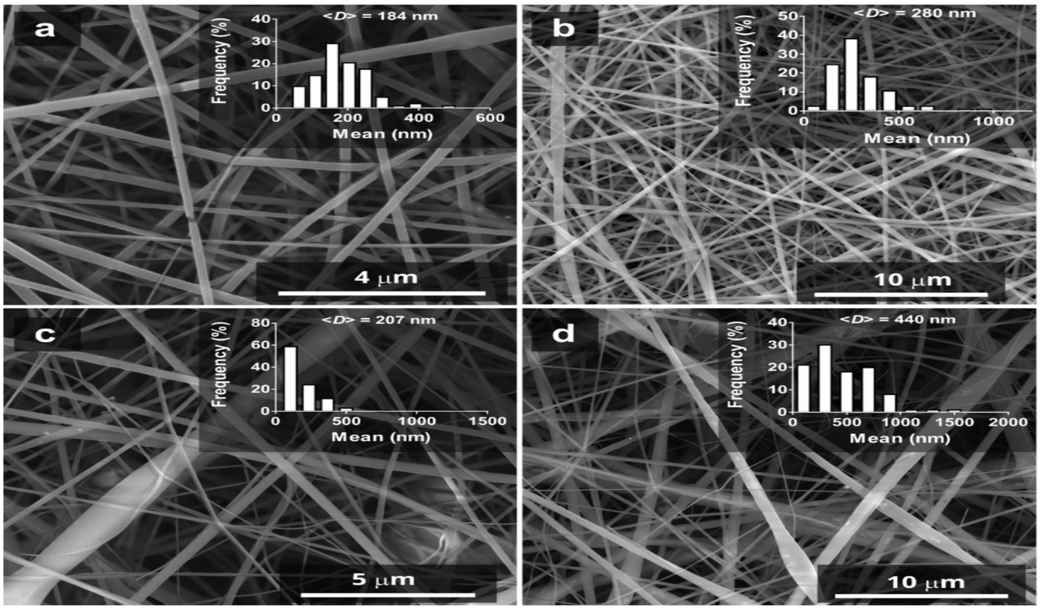


Fig. 8. Scanning electron micrographs of the Hydroxypropyl-β-cyclodextrin/Ag-NPs nanofibers [Reprinted from reference 126].

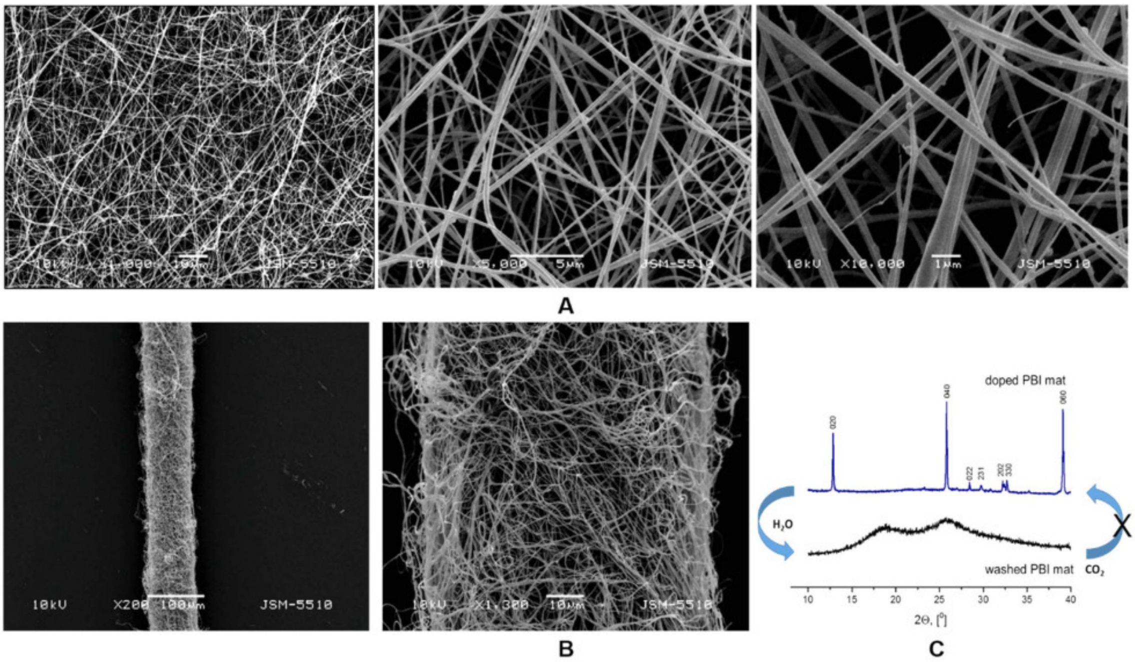


Fig. 9. SEM micrographs electrospun from 14 wt% polybenzimidazole (PBI) solution deposited on rotating collector [Reprinted from reference 142].

weight or chemical/physical properties. The separation process using an affinity membrane depends on the selectivity of the membrane to 'capture' specific molecules, by immobilizing specific ligands onto the membrane surface [51]. Recently, membranes made up of nanofibers have amazing characteristics such as the large surface area to volume ratio and excellent mechanical properties compared with traditional membranes (Fig. 12) [157,158]. Technology advances in both membrane filtration and fixed-bed liquid chromatography was reflected by affinity membrane application [157]. Many polymers were used as electrospun membranes for affinity separation like polyvinylidene fluoride (PVDF) [157], polyurethane [159], Polyacrylonitrile [160], polycaprolactone (PCL) [161], and poly(acrylonitrile-co-glycidyl methacryl- ate) [66].

filtration

The electrospun nanofiber has several notable properties such as high porosity, high surface area to volume ratio and pore size in nano range which makes them beneficial in filtration applications [162]. Filter media can be classified as surface filters, depth filters and adsorptive filters [163]. Nanofibers materials as the membranes can improve low fouling, separation efficiency, accompanied by higher permeability (i.e. lower energy consumption) [164, 165]. Nanofibers filtrations display optimum filtration efficiency because it is pronounced by higher inertial interception and impaction than with conventional filtration microfibers. Many industries such as respiratory protection, air cleaning of smelter effluents and processing of hazardous and nuclear materials used nanofiber materials [166-168]. Nanofibers filters have been widely used to separate aerosol solid/particles from air flow because of their lower energy consumption, longer life and easy maintenance, low material cost, high filtration efficiency (Fig. 13) [168,169]. Also, the electrospun nanofiber membranes have been used for effecti- ve water microfiltration membranes and for antibacterial filter application [72, 73, 170, 171].

Current challenges and future prospects

The electrospinning process become important technique in science and technology for fiber formation. Every day there is development for novel multifunctional, hierarchically organized, nanostructured materials involving electrospun fibers that exhibit many superior properties. New approaches that overcome some of the technical problems for normal electrospinning include multicomponent spinning, co-axial fiber production, bubble spinning, electro-blow spinning, near-field spinning and parallel-target spinning [15, 195, 196]. Methods like suspension electrospinning and emulsion electrospinning are being developed to minimize toxicity and environmental safety concerns [197]. Current research for polymer electrospinning is focused on materials processing and fiber production to enhance control over fiber orientation, morphology, functionality, and applicability. On the other hand, there are many research aspects related to biodegradability, health, renewability, safety, and sustainability for using polymer in the electrospinning process. By using copolymerization for polymer mixtures, the attainment of the desired biological and physical properties of nanofibrous mesh has become easy now. There is continuous research for the scale-up of this process and the improvement of nanofiber properties. Soon electrospun nanofibers will prove it is a promising candidate method for a broad range of new applications.

Conclusion

Polymer electrospinning is a simple, cost-effective and scalable technology that produces fibers in the range of tens of nanometers to several microns with high surface area to volume ratio and tunable porosity. Because of these properties this process appears to be a promising method for various applications such as drug delivery, tissue engineering scaffolds, wound healing, protective clothing, biosensors, affinity membranes, filtration applications, etc. There are many factors affect the morphology and style of the formed fiber like solution parameters (molecular weight, viscosity, conductivity and concentration of the polymer), processing parameters (tip to collector distance, an applied voltage) and ambient parameters (temperature, humidity, vacuum conditions, surrounding gas). By optimizing these parameters one can get desired properties of the fiber for definite application. In general, the electrospinning process shows an excellent way for more and more applications.

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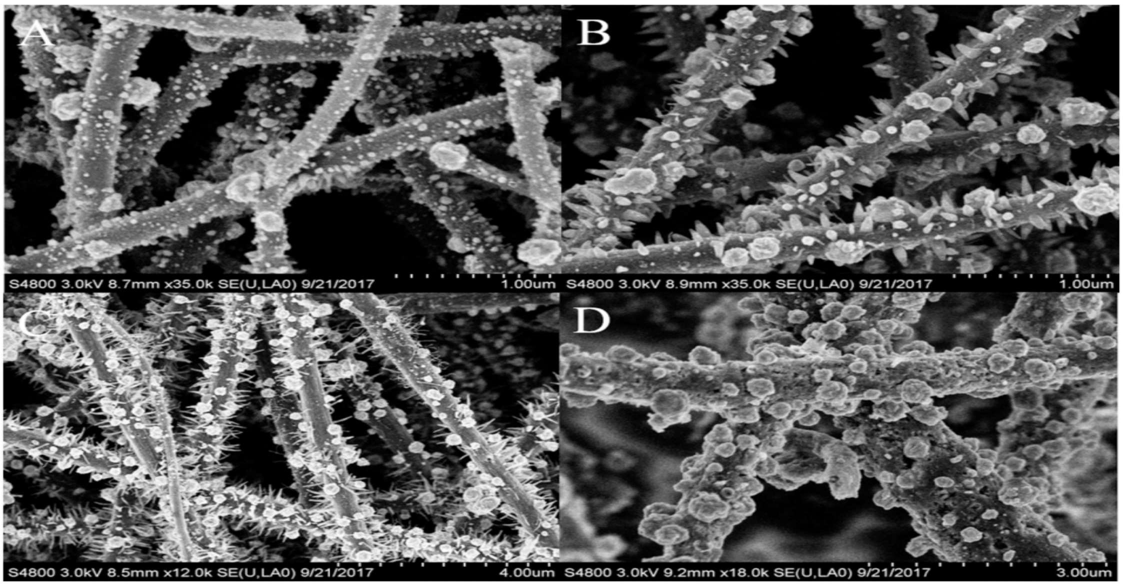
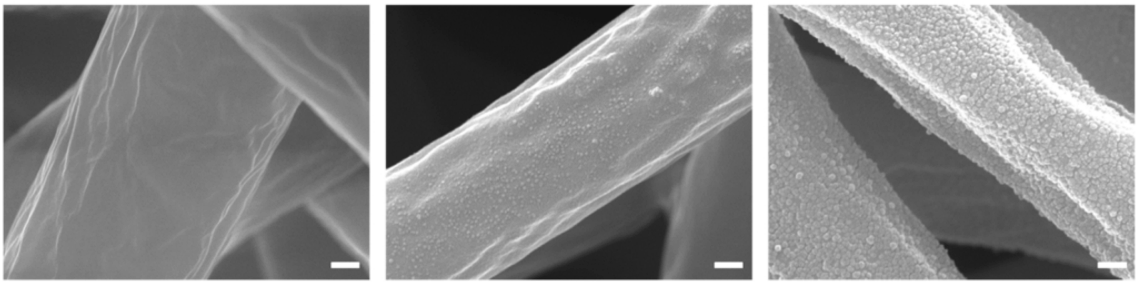


Fig. 10. SEM images of Ni-CoO/ carbon nanofiber (CNF) with different mass ratio of SDS [Reprinted from reference 144].



PCL fibers **Ag-PCL** **Ag@SiO$_2$-PCL**

Fig. 11. Surface morphology characterization of different fibrous substrates of Ag@SiO$_2$- Poly (έ-caprolactone) (PCL) [Reprinted from reference 150].

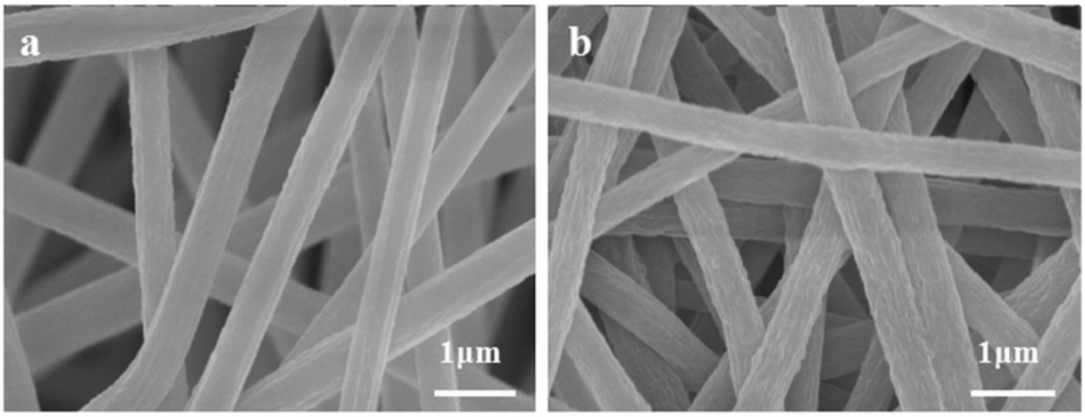


Fig. 12. SEM images of Poly(vinylidene fluoride)(PVDF) membrane [Reprinted from reference 157].

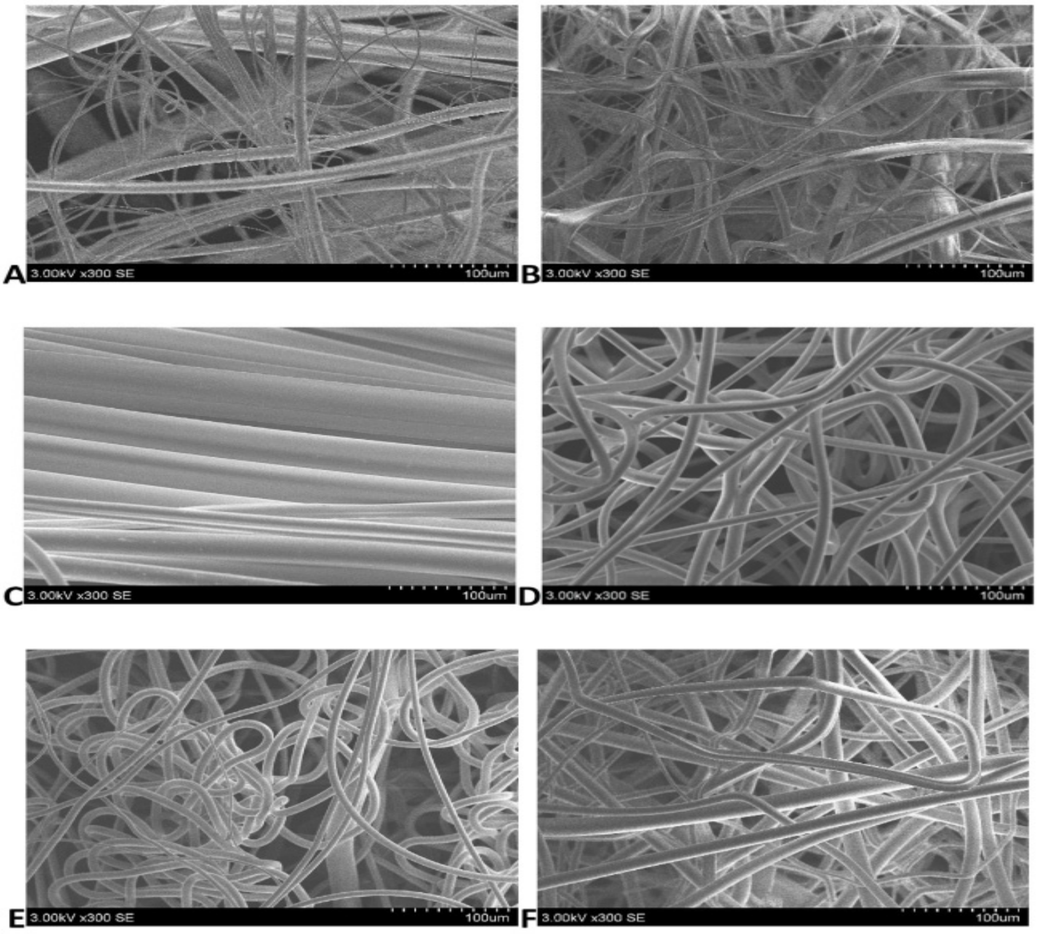


Fig. 13. SEM images of typical morphologies of polyamide and polyolefin-based polymers [Reprinted from reference 169].

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تقنيه الغزل الكهربى لانتاج الياف نانومتريه من البوليمر: بحث مرجعى

***جمعه فاروق الفوال**

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وجدت الألياف النانومتريه العديد من التطبيقات كمادة ذات خصائص و صفات مميزة. تعتبر تقنية الغزل الكهربائي أفضل من غيرها من تقنيات تصنيع الألياف النانومتريه التقليدية بسبب سهولة تكوين الألياف و التحكم فى شكلها. تمتلك الألياف النانومتريه خصائص فريدة مثل كبر نسبة المساحة إلى الحجم ، سهولة في اضافه وظائف لسطح الألياف، و اختلاف أحجام المسام ، والقدرة على تغيير تكوين الألياف النانومتريه للحصول على وظائف وخصائص محددة. يسلط البحث المرجعى الحالي الضوء على مبادئ الغزل الكهربائي، وأنواع الغزل الكهربائي، و العوامل التى تؤثر على عمليه تصنيع الألياف. وأخيرا، قدمنا بعض تطبيقات الألياف النانومتريه فى المجال الطبي، الملابس الواقية، أجهزة الاستشعار، الأجهزه الكهربائية، والترشيح.