Review Paper

A review on fabrication of nanofibers via electrospinning and their applications

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Abstract
In the history of modern science, nanotechnology accomplished the most attraction by the researchers as nanomaterials exhibit novel and significantly improved properties in term of physical, chemical, and biological properties and they can be modified accordingly. These are mainly because there is an increase in surface area as compared to volume as particles get smaller. Electrospinning is one of the most suitable method for producing continuous nanomaterials with varying physical, chemical and biological properties. In this review paper we discussed the theory and the experimental setup of electrospinning along with the history of this process. We also review on the effect of parameters (solution, processing and ambient) on the fiber morphology and the potential applications of electrospun nanofibers. This is followed by geometrical, chemical, physical and mechanical characterization procedure of electrospun nanofiber.

Keywords Electrospinning · Nanofibers · Polymers · Collector · Spinneret

Abbreviations

DMF	Dimethyl formamide
PVA	Poly (vinyl alcohol)
PEO	Poly (ethylene oxide)
SEM	Scanning electron microscopy
FESEM	Field emission scanning electron microscopy
TEM	Transmission electron microscopy
AFM	Atomic force microscopy
FTIR	Fourier transform infra-red
NMR	Nuclear magnetic resonance
WAXD	Wide angle X-ray diffraction
SAXC	Small angle X-ray scattering
DSC	Differential scanning calorimeter
TGA	Thermo gravimetric analyzer
XPS	X-ray photo electron spectroscopy
DMPC	Dynamic moisture vapor permeation cell
MF	Microfiltration
UF	Ultrafiltration
ENM	Electrospun nanofiber membrane
PGA	Poly glycolic acid (PGA),
P(LLA-CL)	Poly(lactic-*co*-glycolic acid)
PLLA	Poly(ʟ-lactide-*co*-ε-caprolactone)

1 Introduction

In recent years nanofibers are used in a wide range of applications due to their unique properties like extremely high surface area to weight ratio, low density, high pore volume, small pore size, superior stiffness and tensile strength as compared to conventional fibers [1, 2]. Drawing, template synthesis, phase separation, self-assembly and electrospinning are the available methods for producing polymer nanofibers. Drawing process is suitable for producing only discontinuous nanofibers [3], template synthesis process produced fibers of specific diameters [4], phase separation method is suitable only for some specific polymers [5] and by self-assembly method, fibers are produced at a very slow speed [6]. However, electrospinning process offers the opportunity to produce continuous

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nanofibers and vary the fiber dimensions as required [7]. This process also offers to form various fiber assemblies including nonwoven fiber mesh, aligned fiber mesh, patterned fiber mesh, random three-dimensional structures, sub-micron spring and convoluted fibers [8]. This method uses both natural and synthetic polymers, liquid crystals, suspensions of solid particles, ceramics and emulsions, to produce fibers ranging from 2 nm to several micrometers in diameters [9].

2 Electrospinning setup

A typical electrospinning setup consists of three components, a high voltage supplier, a capillary tube with a needle and a collecting screen [10]. Figure 1a, b shows a typical electrospinning setup. According to Taylor, for the initiation of the electrospinning process to occur, 6 kV applied voltage is required [11]. However, when a grounded target is introduced nearer to the spinneret, it is possible to run the electrospinning process at a lower applied voltage [12].

Clip spinneret, tube-less spinneret, co-axial spinneret and heating spinneret are the widely used spinneret. Figure 2 shows the different type of spinnerets. Clip spinnerets are easily cleanable and using this reduces changeover time [15], where tube-less spinneret reduces the waste of solutions [16]. Materials having low spinnability can be electrospun by using co-axial electrospinning [16]. By using multi jet spinneret, materials can be electrospun at low voltages [17]. Materials that needs high temperature to dissolve in the solution, can be electrospun by using heating spinneret [16].

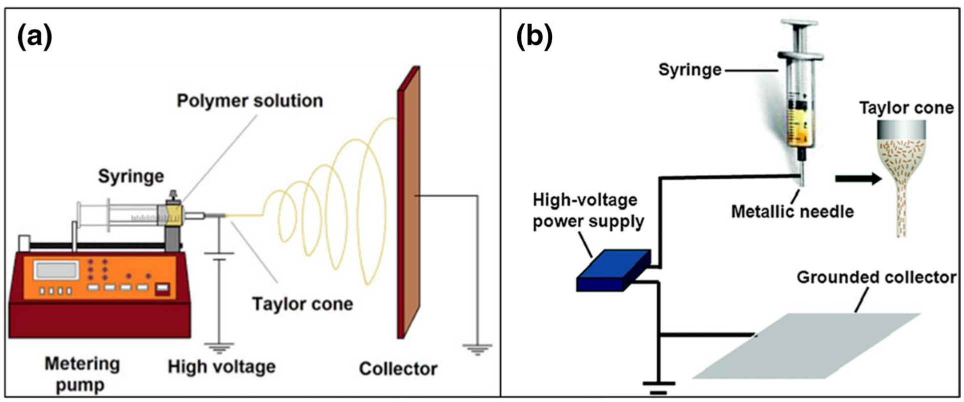

Fig. 1 Schematic diagram of set up of electrospinning apparatus **a** horizontal set up [13] and **b** vertical setup [14]

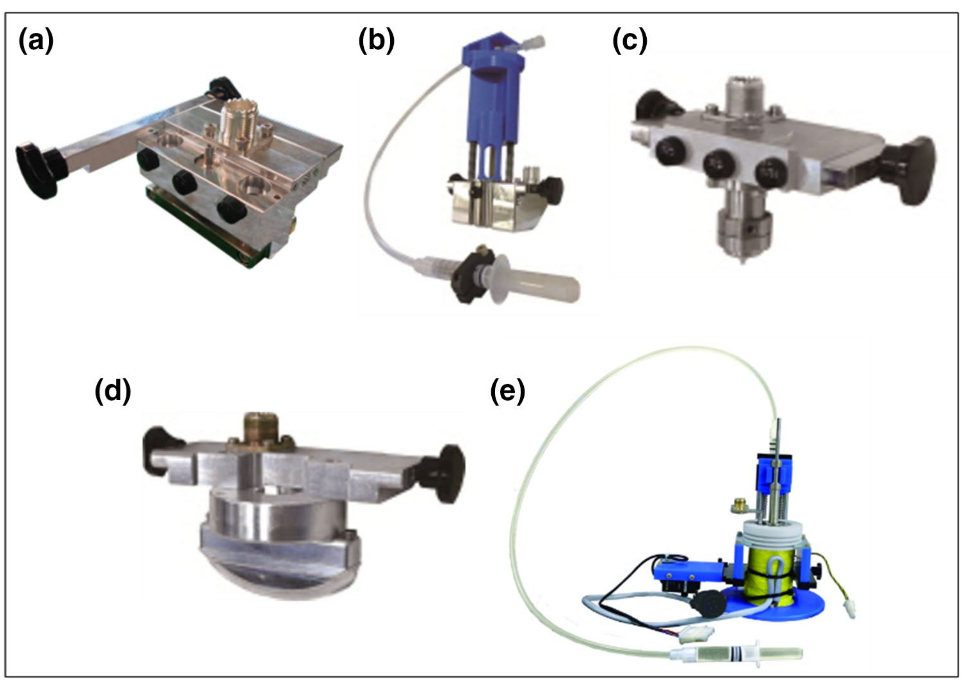

Fig. 2 Different types of spinneret **a** clip spinneret, **b** tube-less spinneret, **c** co-axial spinneret, **d** multi jet spinneret, and **e** heating spinneret

Plate collector [18], rotary drum collector, grid type collector [19], edge type collector [20], mandrel collector [8], steel sheet collector [21], dual rings collector [22] are used by the researchers, based on the applications and characteristics of fiber produced. Other than these, a syringe pump with feeding rate from 0.1 to 60 mL/h is required for electrospinning process [23].

3 Rudiment of electrospinning

Electrospinning procedure is based on the application of high voltage to produce charged jet by generating mutual repulsive forces to overcome surface tension in the charged polymer liquid and attenuation of the charged jet for thinning is done mainly by the bending instability associated with the electrospinning jet [24]. Voltage is applied between the spinneret and collector and a surface charge builds up on the surface of the solution. When the electric field surpasses a certain value, electrostatic repulsion force of surface charges overcome surface tension and a charge fluid jet is ejected from the tip of the Taylor cone and an unstable rapid whipping of the jet occurs in the space between the capillary tip and collector which leads to evaporation of the solvent thus fibers are produced [11].

4 Genesis and development of electrospinning

The first realistic attempt on electrospinning was detected on the early twentieth century. John Francis Cooley, the first to archive patent on electrospinning [25], filed three patents in 1900, 1902 and 1903. W.J. Morton described the method of preparing fibers which can be used in textile or other purpose and patented it in 1902 [26]. In 1934, Antonin Formhals invented the procedure for fabricating textile yarns from cellulose acetate by using 57 kV applied voltage, acetone and mono methyl ether as solvents [27]. In the next few years a series of patent had been filed by Formhals, made notable contributions in the field of electrospinning, which were described, the procedure of preparing fine fibers by drawing the spinning solutions through a nozzle using high electrical current [28], the process of influencing artificial fiber length, the process of preparing continuous fiber filament and the preparation procedure of composite fiber [29]. In 1936 Charles L. Norton invented the electric current and air stream assisted melt spinning process of fabricating fibers from viscous solution [30]. In 1952, Vonnegut and Newbauer invented the method of preparing diameter of 0.1 mm uniform droplets by electrical disintegration of liquids [31]. Taylor, in 1964 proposed the mathematical modelling for the shape of the cone of the fluid droplet that is formed during the electrospinning process for the impact of electric current [11] and in 1969 examined the shape of polymer droplet which is formed during electrospinning process at the tip of the spinneret [32]. Baumgarten, in 1971, invented the procedure of fabricating acrylic fibers by electrospinning of acrylic resin in dimethyl formamide (DMF) solvent [33]. In 1987, a research group led by Hayati, showed the effect of liquid conductivity on the electrospinning procedure and suggested that, relatively stable jets are produced by semi conducting and insulating liquids than highly conductive fluids [34]. Now-a-days, worldwide more than 200 universities and research institutes are studying the electrospinning process and every year the number of research paper on electrospinning process is increasing [35].

5 Electrospinnable polymers

By adjusting the molecular parameters, process parameters and ambient parameter, approximately all soluble or fusible polymers (natural polymers, synthetic polymers or a blend of both) can be used for electrospinning [36]. This wide range of polymers include proteins, nucleic acids, and polysaccharides [37].

The list of Electrospinnable polymers are listed in Table 1.

6 Factors affecting electrospinning

Solution parameters, process parameters and ambient parameters are responsible for the variations in morphology and diameters of the nanofibers produced by electrospinning [67]. Here we will discuss the effects of various parameters in electrospinning.

6.1 Effect of solution parameters

6.1.1 Effect of dielectric property of solvent

In general, during electrospinning the tendency of the formation of beads and produced fiber diameter are reduced with the solution having higher dielectric property [68]. To improve the dielectric property of the solution to be electrospun, some solvents like Acetonitrile, Acetic acid, m-Cresol, Tetrahydrofuran, Toluene, Acetone, Chloroform, Ethyl Acetate [69], Dichloromethane, Dimethylformamide, Ethanol [70], etc. can be used. According to Hsu et al., higher dielectric constant of the solvent leads to the higher bending instability of the electrospinning jets thus causes the increased of fibers deposition area. Furthermore, due to this increased jet path, resultant fiber

Table 1 Electrospinnable polymers

Polymer	Solvent	Application	References
Polycarbonate	Mixture of Tetrahydrofuran and Dimethyl formamide	To produce TiO_2 nanotubes	[38]
Poly acrylic acid	Deionized water	In filtration	[39]
		Two dimensional polymer nano webs	[40]
Collagen-I	1,1,1,3,3,3-hexafluoro-2-propanol	Matrix for tissue engineering	[41]
	2,2,2-trifluoroethanol	Matrix for tissue engineering	[42]
Collagen-II	hexafluoro-2-propanol	Scaffolds for tissue engineering and Cartilage engineering	[43]
Collagen-III	hexafluoro-2-propanol	Scaffolds for tissue engineering	[44]
Collagen/PEO	Hydrochloric acid	Wound healing and tissue engineering	[45]
Collagen/PCL	Methanol-Chloroform	Tissue engineering	[46]
Chitosan	Dilute hydrochloric acid, acetic acid, formic acid and tri fluoro acetic acid.	To prepare non-woven fabrics and Biomedical applications	[47]
Chitosan/PEO	Acetic acid	Biomedical Applications	[48]
	Dimethyl Sulfoxide	Non-woven mats	[49]
Chitosan/PVA	Acetic acid	Biomedical applications	[50]
		As a support for enzyme immobilization	[51]
PVA	Distilled water & Ethanol	Filters and Submicron fiber mats	[52]
Chitin	Hexafluoro isopropanol	Wound healing	[53]
Silk	Hexafluoro-2-propanol	Biomedical Applications	[54]
Polybenzimidazole	Dimethyl acetamide	Nano fiber reinforced composites	[55]
Polyurethane	Dimethyl formamide	Preparation of ultrafine elastic fibers	[56]
		Ultrafiltration, ultrasensitive sensors	[57]
Polyvinyl Chloride	Tetra hydro furan and *N*,*N*-dimethyl formamide	Non-woven mats	[58]
Nylon-6,6	Formic acid	Protective coating in textiles	[59]
Lecithin	Dimethyl formamide	Antibacterial applications	[60]
Dextran	Water	Wound dressing	[61]
Pullulan	Water	Food package materials	[62]
Silicone	Acetone and Xylene	Coating of stent wires	[63]
Zein	Dimethyl formamide	As drug release membrane	[64]
PMMA	Dimethyl formamide	In filtration application	[65]
Polyamide	Formic and Acetic acid	In filtration application	[66]

diameter is reduced [71]. According to Son et al., Solvent having much higher dielectric constant usually consists of higher net charge density and in that case during electrospinning higher elongation forces are enforced to the charged jet which leads in lesser beads and thinner fiber diameter [68].

6.1.2 Effect of surface charge density

Higher surface charge density influences electrospinning jet to carry more charges and addition of ions can influence the formation of jets [35]. Zong et al. examined the effect of NaCl, NaH_2PO_4 and KH_2PO_4 on poly (D,L-lactic acid) and found that fibers produced from dissolved NaCl solution had smallest diameter, whereas dissolved KH_2PO_4 had the largest. As sodium and chloride ion possess smaller atomic radius than potassium and phosphate ion, thus they have higher mobility under the applied voltage, as a result the jets containing sodium ion face higher elongation force which leads to the reduced fiber diameter [72]. Researchers also found that, beads formation can occur from solution with low surface charge density [34], and no fibers are formed with zero surface charge density [73]. The electrospinning jets from the solution having low surface charge density possess lower mobility thus experienced lower elongation force than required which leads to the formation of beads [34] and the solution having zero surface charge density do not have any dipole moment for jet formation thus no fibers are produced [74].

6.1.3 Effect of Surface tension

Surface tension of the solution to be electrospun needs to be overcome for the commencement of electrospinning process. It was reported that by reducing the surface tension of the solution beadless fibers can be achieved, in contrast, increasing the solution surface tension leads to the instability of the jets. At low surface tension there is a greater interaction between the polymers and the solvent molecules, as a result, the solvent molecules try to spread over the entangled polymer molecules which leads to the beadless fiber and at higher surface tension solvent molecules tend to assembled in a spherical shape thus beads formation are expected. However, lower surface tension of a solution is not always be favorable for electrospinning. Generally, with all the conditions remain same, surface tension of the solution helps to determine the upper and lower boundaries of the electrospinning window [75]. To reduce the surface tension, solvent with a low surface tension can be used, or surfactant can be added into the solution [76].

6.1.4 Effect of solution viscosity

For a successful electrospinning procedure, selection of appropriate solution viscosity is among the key parameter. That is because continuous fibers cannot be produced with a solution of low viscosity and at high solution viscosity, the electrical charges failed to generate required strength to attenuate the solution to form fibers [77]. With the increase of viscosity, the amount of polymer chains entanglement of the solution also increase and the shape of beads transformed from spherical to spindle like until smooth fiber produced [74]. It has been found that, the optimum spinning viscosities ranges from 1 to 200 poise approximately, but at 1 to 20 viscosity level uniform nanofibers can be produced [35].

6.1.5 Effect of molecular weight

Polymer solution to be electrospun must have adequate molecular weight [5]. Nonetheless if sufficient intermolecular interactions can be provided through chain entanglements, electrospinning can occur in some special cases, for instance oligomer sized phospholipids nonwoven from lecithin solution [78]. Moreover, molecular weight influences the other factors such as viscosity, surface tension, surface charge density and dielectric strength [75]. During electrospinning, if the concentration of the solution remain the same, decreasing molecular weight of polymer leads to more beads formation, and increasing molecular weight will lead to formation of smooth fiber and further increasing it, micro-ribbon will be formed [79].

6.1.6 Effect of concentration

The formation of fiber during electrospinning is emerged by the stretching of the charged jets on uniaxial directions [77]. At low concentration due to low viscosity and high surface tension, the charged jets lose their intermolecular attractions thus discrete into droplets from the Taylor cone [36]. When the concentration becomes higher, a mixture of beads and fibers will be produced. On the other hand, smooth fiber can be achieved when using not too high and suitable solution concentration, nonetheless after a certain limit helix shaped micro ribbons will be formed [70].

6.2 Effect of processing parameters

6.2.1 Effect of voltage

Generally more than 6 kV applied voltage is required for jet initiation [11]. At high voltage, there is a possibility of more ejection of polymer solution [56] and due to the greater electrostatic interaction in the charged solution, greater stretching and generation of greater repulsive force on the fluid jets happen that leads to generate fiber of small diameter [80]. The applied voltage also influences the arrangement of fiber molecules. At high voltage, due to the electrostatic attenuation of the polymer molecules, they become more ordered thus improve the crystallinity of the fiber, however after a certain induced voltage due to the shorter flight time of the jets crystallinity may be reduced [81].

6.2.2 Effect of flow rate

Diameter, porosity and geometry of electrospun nanofiber are greatly influenced by the flow rate of the solution to be electrospun. For producing beadless uniform fibers, the polymer solution have to be given enough time for polarization thus slow flow rate is suggested by the researchers [82], but a minimum flow rate is mandatory for electrospinning [83]. An increased flow rate associates the increase in diameter and pore size but too high flow rate increase the tendency to form beaded fibers [32].

6.2.3 Effect of different types of collector

In the common electrospinning setups, a conductive collector plate is used as collector to create potential difference between the source and the collector. Pin type, wire mesh, plate with protrusions array, series of parallel ridges, grids, parallel bars, rotating wheel, liquid non solvent, etc. are the collectors used by the researchers based on the fibers produced for various applications [84]. In case of no conducting or less conducting material collector, the charged jets are quickly assembled in the collector and the amount of fiber deposited will be reduced and beaded fibers will be generated [85]. According to Deitzel et al. in case of non-conducting collectors due to the repulsive forces of charges, 3D fiber structures are formed and as long as there is enough density of charges on the fiber mesh, repulsion occurs among the subsequent fibers which leads to the formation of honey comb structures [86]. Rotating collector helps to get dry fibers as the fibers get more time to evaporate. Rotating collectors also help to get aligned fibers [86]. Boland et al. [87] and Matthews et al. [88] became successful to obtain aligned fibers of poly (glycolic acid) and type I collagen by using rotating collectors. As the charged jets travel at a high speed during electrospinning, the collector should rotate at a certain speed which is known as alignment speed. If the speed of the collector is lower than that specific value then more fibers are collected in the collector where assembling of charges may repel the incoming fiber resulting less oriented fibers.

6.2.4 Effect of distance between needle tip and collector

In general, varying the distance between needle tip and collector can affect the size and morphology of the fibers. However the influence is not as severe as the other parameters [89, 90]. Short distance between the needle tip and collector leads to formation of defected fibers. Due to the shorter distance that have to travel by the charged jet, some inter and intra layer bonding among the fibers at their junctions are formed for having shorter time to solidify which lead to form beaded fiber [80]. On the other side, average fiber diameter may be decreased with the increase of distance between these two [91]. However there are exceptions, Lee et al. prepared PVA nano-fibers with larger diameter by applying lower electrostatic force and larger distance [92]. Thus, it is understandable that for producing beadles fibers by electrospinning, an optimum distance between the needle tip and collector is necessary [93].

6.3 Effect of electrospinning setup

Gravitational force has an impact on the shape of the polymer droplet and Taylor cone. For producing beadles continuous fibers, with a horizontal arrangement higher flow rate is required than the vertical arrangement. Rodoplu & Mutlu showed that, to get beadless fiber via electrospinning of 10 wt% PVA solution, for horizontal setup 1.6 mL/h feed rate is required whereas for vertical setup 4 mL/h feed rate is required [94].

6.4 Effect of ambient parameters

6.4.1 Effect of temperature

Higher ambient temperature will lead to the lower solvent evaporation rate, thus the charged jet will then take a longer time to solidify. Also, the viscosity of the polymer solution decreases, and due to lower viscosity there are higher stretching of fibers, cause thinner fiber formation [95]. Moreover, if biological substances like enzymes and proteins are used during electrospinning, for higher temperature they can lose their functionality as reported by Fujihara et al. [5].

6.4.2 Effect of humidity

Variation in humidity during electrospinning influences the morphology of the electrospun fibers. Casper et al. showed that, increasing humidity during electrospinning leads to the formation of small circular pores on the fiber surface. These are formed as a result of evaporative cooling of the solvent that occurs during the electrospinning jets are travelling from needle tip to the collector. Further increasing humidity may cause to produce fiber with non-uniformed structures [96]. According to Megelski et al. at high humidity, the fibers produced from polymers dissolved in volatile solvents may have condensed water on the surface [97]. Li and Xia suggested that, high humidity assist the discharge of fibers during electrospinning [98]. Also at low humidity the removal of the solvent from the tip of the needle is slower than the evaporation rate of solvent thus causing needle tip to be clogged and the electrospinning will be stopped as reported by Baumgarten [33].

7 Characterization of electrospun nanofibers

7.1 Geometrical characterization

Geometrical characterization is to characterize the geometric properties of nanofibers such as fiber diameter, diameter distribution, fiber orientation and fiber morphology. Scanning electron microscopy (SEM), field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM) and atomic force microscopy (AFM) [56] are used to characterize these geometric properties. Fiber morphology has been observed using SEM by many researchers [99]. For SEM, the sample must be made electrically conductive which requires the electrospun nanofiber be coated with gold or platinum that may alter the fiber diameter at higher magnification. Again, the sample must be in a dry state for SEM compared with another method, TEM, where dry state of sample is not required. TEM can be used to determine fiber diameter up to < 300 nm. AFM being an accurate measurement of nanofiber diameter requires a rather precise procedure that includes tip convulation. However AFM is the best measurement to observe surface morphology and exact description of the fiber surface. AFM can also be used to characterize the roughness of the fiber [56].

7.2 Chemical characterization

Chemical characterization of a material gives information about its composition. Chemical composition of electrospun fibres can be determined by Fourier transform infra-red (FTIR) and nuclear magnetic resonance (NMR) techniques [100]. These methods can determine both the structure and intermolecular interaction of two polymers when they are blended together for nanofiber fabrication. In case of a collagen and PEO blend, the NMR spectrum showed a new phase structure which was caused by the hydrogen bond formation between the ether oxygen of PEO and the protons of the amino and hydroxyl groups in collagen [101]. The configuration of the macromolecules in a nanofiber can be characterized by optical birefringence [80], wide angle X-ray diffraction (WAXD), small angle X-ray scattering (SAXC) and differential scanning calorimeter (DSC) [102]. Surface chemical properties of nanofibers can be evaluated by XPS, water contact angle analysis of the nanofiber membrane surface and ATR-FTIR analyses [103]. Researchers have used Raman Spectroscopy and Fourier Transform Infrared Spectroscopy for the changes that may be taking place at the molecular level [104].

7.3 Physical characterization

Generally Physical characterization means the determination of all the physical properties of a material such as stability, melting point, water uptake etc. It's possible to measure thermal properties such as the melting point, the crystallization point and the glass transition with a differential scanning calorimeter (DSC). The thermal stability of a compound is checked with a thermo gravimetric analyzer (TGA) which measures the mass loss during a heating ramp rate. Dynamic moisture vapor permeation cell (DMPC) is used to measure air and vapor transport properties of nanofibrous mats [105]. Both moisture vapor transport and the air permeability of continuous films, fabrics, coated textiles and open foams can be measured by this device.

7.4 Mechanical characterization

Mechanical characterization of nanofibrous nonwoven membranes can be done using conventional mechanical testing techniques [44, 45]. Mechanical characterization is achieved by applying loads to specimens prepared from the electrospun ultra-fine non-woven fiber mats [106]. Various approaches have been applied towards mechanical characterization of nanofiber and nanowires by employing nanoindentation, bending tests, resonance frequency measurements, and microscale tension tests [58]. Young's modulus, tensile strength, and the strain at break can be determined by performing tensile tests with single polymer fibers. According to Tan et al., a commercial nano tensile testing system (Nano Bionix System, MTS, TN, USA) is being used to conduct the tensile test for the evaluation of mechanical properties of single ultrafine polymeric fibers of polycaprolactone [107]. Inai et al. have also carried out tensile tests of single electrospun poly (L-lactic acid) nanofiber collected from a rotating disc at different collection speeds [108]. AFM, used to determine the elastic properties of electrospun membranes, consists of a cantilever and tip assembly. Atomic resolution can be obtained with very slight contact by measuring the deflection of the cantilever due to the repulsion of contacting atomic shells of the tip and the sample [109]. AFM Phase Imaging being an extension of tapping mode allows detection of variations in composition and hardness [110]. The bending moduli and shear moduli of the electrospun collagen fibers have been determined by AFM by performing micromechanical bending tests with native and glutaraldehyde cross-linked single electrospun fibers [111]. Researchers have used resonant contact AFM approaches for measuring the elastic modulus of the nanofiber [112]. In this testing method, nanofiber must be attached to a cantilever tip [113].

8 Application of electrospun nanofibers

Application of electrospun nanofibers become wider gradually due to some outstanding characteristics that can be conveniently engineered in various forms as well as their large specific surface area. The fields of application of nanofibers are immense and some are briefly discussed below to have an idea of it.

8.1 Electrospun nanofibers in filtration purposes

Filtration is a widely used process in both household and industries for removing solid substances from air or liquid. Due to the characteristics such as high surface area to volume ratio, high porosity and large interconnected pores, nanofibers provide advantageous filtration property.

Furthermore, they can be used to a wide variety of application ranging from water purification to air filtration media [114]. By using chemical and physical crosslinking treatments, the porous structure of the nanofibrous mat can be stabilized thus providing with long term filtration performance.

8.1.1 Air filtration

Nanofiber mats are being used in air filtration now-a-days. It is obvious that nanofiber mats provide better efficiency in air filtration because of their smaller dimension. The nanofibers used in filtration are up to 800 times smaller than the conventional filtration media [115]. By physical trapping and adsorption, the electrospun membranes can filtrate all airborne particle with diameters between 1 and 5 µm [116]. Large part of daily life time spent in an indoor or an enclosed environment makes indoor air filtration a significant matter of concern. Hospitals, being very sensitive indoor place, need intensive attention regarding the air filtration thus the germs and viruses may not spread through circulating air. For this purpose, nanofiber membrane is a potential solution for indoor air filtration. Due to their large surface area and high porosity, they can capture the dust as well as allow a good air circulation by allowing more air to pass through [117].

8.1.2 Vehicle cabin filtration

Vehicle cabin filters are important in mining work cabin and airplane cabin where personnel deals with machinery and equipment. It's a matter of great concern that these places must be kept contamination free. Investigation has been done by Arumuganathar et al. to determine the effectiveness of nanofiber media in reducing the cabin contaminant concentration [118]. They found that the nanofiber composite filter exhibited higher percentage (92%) of both sub-micron and respirable (> 1 µm) dust removal while the standard cellulose filter remove 68% and 86% respectively.

8.1.3 Liquid filtration

Nanofibrous membrane being highly permeable due to their high porosity and interconnected pores offer better water filtration at lower energy costs compared to conventional filtration materials. It is important to remove micron sized as well as other suspended solid particles from water. Membrane processes like microfiltration (MF) and ultrafiltration (UF) are very common to achieve higher removal of micron sized and other suspended solid particles from water. These MF and UF can be prepared by the phase inversion method [119], spun bonded, melt blown and electrospinning techniques [120]. Researches compared the filtration performance between a commercial MF membrane and an electrospun nanofiber membrane (ENM) of the same polymeric material [121]. At the same applied pressure, the ENM exhibited several times higher water flux. Therefore ENM can be used as energy saving membrane. Nanofiber membrane made from polysulfone can contribute to the removal of micron sized particles [122]. The pore size can be controlled by altering electrospinning parameters. A nanofibrous membrane with fixed pore size has been filtered for different sized polystyrene particles under the same operating conditions.

8.2 Electrospun nanofibers in biomedical engineering

8.2.1 Tissue engineering scaffolds

In recent years, natural polymer, biodegradable and non-degradable synthetic polymers, and hybrid blends of these two are electrospun by varying mechanical and biometric properties, as well as the fiber orientation and pore size. They are used in tissue engineering applications like blood vessels, skins, bones, neural tissues, muscles, for providing support for cells to regenerate new extra cellular matrix that are demolished by injury or diseases [123].

8.2.2 Blood vessels

Now-a-days, biomaterials with the noble properties like, biodegradability, great mechanical properties (tensile stiffness, compressibility, elasticity), improved cell adhesion, proliferation, differentiation, are produced by electrospinning process with a view to assist the replacement of small blood vessels [124]. The major components of the extracellular matrix are collagen (types I and III) which provides the tensile stiffness for the resistance against rupture, elastin influenced the elastic properties, proteoglycans control the compressibility and glycoproteins along with elastin prevent the formation during pulsatile blood flow [125]. The main reason for using electrospun nanofibers for the replacement of blood vessels is the size (ranging from 200 nm to 2 µm), shape and geometrical distribution and disordered arrangement in the space of the fibers, are highly similar to the collagen fibrils present in the natural extra cellular matrix [124]. First artificial blood vessel based on collagen scaffold is fabricated at 1986 [126]. Till then every year the interest on vascular tissue engineering is increased.

8.2.3 Bones

Natural bone is composed of inorganic (mainly hydroxyapatite crystals) and organic (mainly Type I collagen matrix) materials [127]. To provide proper bone grafts for successful replacement or repair of defected bone tissues electrospun scaffolds are extensively used because they offer some unique properties like biodegradability, osteoinductivity, high porosity with interconnected pores and mechanical stability which are mostly important requirements for a tissue engineering scaffold [128]. As bone tissue scaffolds synthetic degradable polyesters including polylactide and polyglycolide are commonly used individually or combination with inorganic minerals [129]. But recently poly(lactide-*co*-glycolide) and Hydroxyapatite are mostly used as scaffold materials for bone repair due to better biocompatibility, non-toxicity and non-inflammation property [130]. Beniceuicz and Hopper combine biodegradable polymers like Polyglutamic acid, Polylactic acid with bioceramics to prepare materials for bone repair [131]. Fujihara et al. investigated Polycaprolactone/$CaCO_3$ composite nanofibers as a bone substrate [132]. Researchers suggest the pore size of the nanofiber membrane must be in between 200 and 400 µm to allow cell infiltration and proliferation, or there should be growth of non-mineralized osteoid tissue and prevention of neovascularization [133].

8.2.4 Muscles

For culturing smooth muscle cell, collagen nanofibers were first used [44]. On these collagen nanofibers, the cell growth was increased and well integrated into the nanofiber network after seeding of 7 days. When other polymer nanofiber mats were blended with collagen, smooth muscle cells were also adhered and proliferated on them. Also collagen incorporation resulted in improved fiber elasticity, tensile strength and cell adhesion [134]. The fiber surface wettability and nanofiber alignment are important factors as these influence cell attachment significantly. Baker et al. reported that, an increased fiber wettability can be achieved when the polystyrene nanofibers were treated with argon plasma resulting in better cell attachment by two folds [135]. The nanofiber alignment can affect some phenomena like inducing cell orientation, promoting skeletal muscle cell morphologenesis and formation of aligned myotube. An alignment factor of 0.74 can be exhibited by the cells cultured on aligned nanofiber compared with 0.19 on randomly oriented scaffold. Dong et al. investigated that smooth muscle cell culture on polymer nanofibers like Poly glycolic acid (PGA), *poly(lactic-co-glycolic acid*) and Poly(l-lactide-*co*-ε-caprolactone) causes degradation of the nanofibers, specially for PGA. For P(LLA-CL), the degradation rate is the slowest, so this nanofiber facilitate long term cell growth of 1–3 months [136]. Wang et al. produced a biocompatible polymer tube from poly(l-lactide) and polydimethylsiloxane for regulating smooth muscle cell growth [137]. Ricotti et al. have done the electrospinning of poly (hydroxy butyrate) to produce fibers for differentiation of skeletal and cardiac muscle cells [138].

8.2.5 Neural tissues

Due to injury neural tissues are often damaged. It is known that, it takes a longer period of time to regenerate the damage tissues and sometimes larger nerves never heal. It has been reported that only 50% of the patients are able to regain useful functions of damaged neural tissues [139]. So for nerve regeneration, tubular scaffolds are produced by electrospinning that provides an artificial extra cellular matrix and influence the regrowth of the peripheral nerve [140]. Electrospun mats of poly l-lactic acid, polyesters, poly glycolic acid, and poly ε-caprolactone with aligned and/or random fiber arrangements are commonly used in neural tissue engineering [141]. Poly ε-caprolactone fibers help to culture the mouse embryonic stem cell differentiation to get neurons, astrocytes, and oligodendrocytes [142]. Poly l-lactic acid nanofiber scaffolds support the neural stem cells differentiation and enhance adhesion [143]. They also support the growth of dorsal root ganglion and primary motor neurons [144].

8.3 Electrospun nanofibers in wound dressing

Scaffolds generated by electrospinning are more homogenous than conventional skin substitutes, structurally heterogeneous, which are generated by freeze drying. When freeze-dried (FD) and Electrospun (ES) were compared by Powell et al. [145] based on collagen for cell distribution, a proliferation, organization and healing of full thickness wounds in thymic mice, no significance difference found for the mentioned parameters but the wound contraction was reduced with ES. This resulted in a reduced morbidity with ES collagen skin substitution. Like the extracellular matrix, these scaffolds provide with support for the new healthy tissue growth in an injured area reducing scar formation [146]. They also provides with protection from infection and dehydration due to nano pore size and large surface area allowing fluid absorption and oxygen permeation. Some polymers both natural and synthetic like carboxyethyl chitosan/PVA [147], collagen/chitosan [148], Silk fibroin [149], ABA type poly(dioxanoneco-l-lactide)-block-poly(ethylene glycol) (PPDO/PLLA-b-PEG) block copolymer [150] are suggested for wound dressing.

8.4 Electrospun nanofibers as drug delivery carrier

Due to the high specific surface area and short diffusion passage length, electrospun nanofibers are extensively used in the delivery of a number of drugs including antibiotics [151], anticancer drugs [152], proteins [153], and DNA [154]. During drug delivery, electrospun nanofibers, enclose the medicinal agent to maintain integrity and bioactivity of the drug molecules and at wound treatment they can significantly reduce the systemic absorption of the drug and reduce any side effects from the drugs by localized inoculation of medicines [155]. The medicinal agents can be enclosed by either mixing with polymers and electrospun together to form the encapsulated fibers or by creating core shell structure by using coaxial spinneret [156]. Also by varying the electrospinning parameters like the mesh size and fiber diameter drug release can be controlled to be used in diseases like AIDS and some forms of cancer [157].

8.5 Electrospun nanofibers in cosmetics

Electrospun nanofiber membranes have various cosmetic applications such as facial masks, perfumes, deodorants, and anti-perspirants. For the treatment of skin healing, skin cleansing, or other therapeutical or medical properties they have been utilized as a cosmetic skin care mask with or without various additives [158]. These skin mask possess high surface area which offers rapid transfer rate of the additives to the skin [146]. For healing or care treatment, electrospun cosmetic skin mask can be introduced gently and painlessly and also directly to the three-dimensional topography of the skin [35]. By emulsion electrospinning (R)-(+)-limonene, a highly volatile fragrance is encapsulated in PVA fibrous matrix which can be used in cosmetics due to its high fragrance loading capacity [159]. Blend of extracts of mangosteen and PVA can be electrospun together to form nanofiber membrane that is suitable for many cosmetic applications, such as medicated soaps and anti-aging products [160].

8.6 Electrospun nanofibers as protective clothing

Due to the large surface area and easy incorporation property polymer nanofibers becomes a key element for protective clothing [59]. The large internal surface allows an enhanced contact between the protective medium and the dangerous environment consisting lethal gas, aerosols of contagious disease spores [161]. Moreover, the nanofibers has high porosity with very small pore size that offers resistance to the penetration of chemical agents in aerosol form [162]. chemical agents which could deactivate dangerous compounds can easily be incorporated into polymer solutions and polymer nanofibers without impedance of the air and water vapor permeability to the clothing and thus protect the personnel [146]. Gas masks can be an example of using such nanofibers containing deactivating agents.

8.7 Electrospun nanofibers in electrical application

Now-a-days, electrospun nanofibers are very attractive to use as porous electrodes for producing high performance battery due to their shorter diffusion path relative to the powder materials, faster intercalation kinetics for high mass to volume ratio, large number of pores for less charge-transfer resistance at the interface between the electrolyte and active electrode materials [163]. Nanofiber membranes of conductive materials also used in applications like electrostatic dissipation, corrosion protection, electromagnetic interference shielding, photovoltaic device etc. [164]. The most common electrospun nanofibers that are used in battery are, carbon nanofiber as anode in sodium ion battery [165], silicon/carbon hybrid nanofiber [166], carbon/tin oxide composite nanofiber [167], lithium iron phosphate/carbon nanofiber as cathodes, lithium lanthanum titanate oxide/polyacrylonitrile nanofiber as separators [163] in Lithium-ion batteries, carbon nanofiber with active material like polypyrrole and silicone [168], etc.

8.8 Electrospun nanofibers in metal ion adsorption

In this century due to the industrialization, extracted heavy metals has become a serious pollutants in water resources that is a serious threat to human health. For the removal of these contaminants most commonly used methods are adsorption and filtration. Electrospun nanofibers can be used in a successful manner for removing heavy metals by adsorption. These electrospun membranes possess a high surface-to-volume ratio and large surface area, high gas permeability, and small interfibrous-pore size [169] which are very important for metal ion adsorption and these electrospun membranes can offer both adsorption and filtration [117]. Addition of functional groups like amino, carboxyl, phosphoric, imidazoline and amidoxime improve the adsorption capacity of electrospun nanofiber membrane [170], like introduction of carboxyl group into chitosan/PEO nanofibers by incorporating activated carbon (AC), greatly improved the adsorption of chromium, iron, copper, zinc and lead ion by the chitosan/PEO/AC nanofiber [171].

8.9 Electrospun nanofibers in renewable energy

In the era of modern civilization, requirement of energy has been reached beyond the limit. So, in recent years advanced research has been done for inventing new procedures for renewable energy not only to reduce the pressure on fossil fuels but also to maintain regional stability. Nanotechnology can provide new opportunities on this phenomena as electrospun nanofibrous materials offers higher energy conversion and storage efficiency than their bulk counterparts. Fuel cells and solar cells are two most common area where the electrospun nanofibers offers better performances.

8.9.1 Fuel cells

Fuel cells are considered as an efficient renewable power source in this century. They convert the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent [172]. In a fuel cell system, the proton exchange membrane is one of the key components [173] and as a proton exchange membrane nafion has been widely used [174]. Though the high cost, low thermal stability, and high gas permeability of nafion makes it unpopular. Electrospun polymer electrolyte membranes of sulfonated aromatic hydrocarbon polymers can be an alternative to nafion due to the excellent chemical and thermal stabilities, and good mechanical strength [175], or polymer blend of Nafion/PEO nanofibers can have a high proton conductivity [176].

8.9.2 Solar cells

Solar cells converts the energy of light directly into electricity by the photovoltaic effect. It is a form of photoelectric cell whose electrical characteristics vary when exposed to light [177]. In Dye-sensitized solar cells, previously dye-anchored mesoporous nanoparticle thin layer in the presence of an electrolyte had been used. But this layer required higher specific surface area and larger number of pores to convert light into electric current [178]. By using one dimensional electrospun nanofibers having these specific characteristics can increase penetration of viscous polymer gel electrolyte in dye-sensitized solar cells and thus the photocurrent generation can be increased significantly [179]. In an organic solar cell there is a charge generating substance, a charge transporting substance and a protective layer for blocking low-wavelength light of below 450 nm. This protective layer helps to maintain high photo-electric conversion efficiency [180]. Electrospun nanofiber membrane of polypyrrole and PEO offers a higher electrical conductivity which will help to increase the conversion efficiency [180].

9 Challenges for the different applications of nanofiber

Electrospun nanofibers showed great potential in air and liquid filtration application. However, in air filtration successful utilization of electrospun fibers were only reported for particles ranges from (100 to 1000) nm. Therefore, further modification of the electrospun fiber surface may have been needed to capture particles less than 100 nm. Besides, engineered approaches are needed to prepare dimensionally stable electrospun fibrous scaffolds so that they can be employed in capturing volatile organic solvents [181]. Moreover, having poor mechanical properties restrict their application in large scale industrial applications especially in liquid filtration. Low mechanical stiffness of the membranes can lead to filter split. Therefore extensive research is still needed for sorting ways to improve mechanical stiffness of the nanofibre membranes which will also lead to the longer service life of the membranes [182].

Biomedical application is another exciting use of electrospun nanofibre membranes. However, electrospinning method tend to produce very dense fibers on a solid collector having smaller inter fiber pores which is much smaller than the cell size. Therefore, very little to no cell infiltration was observed by the researchers in the electrospun nanofiber scaffolds, as the cells tend to stay in the surface of the electrospun fiber and grow two dimensionally which needs to be overcome for true mimicking of the natural extra cellular matrix. Having larger pore structure can help to overcome the poor infiltration of the electrospun fiber. Therefore synthesizing nanofiber scaffolds with controllable pore size is a very promising area to be explored further [183]. Furthermore, two-dimensional nature of the electrospun scaffolds also need to be modified as three-dimensional structure of scaffolds are necessary for cell-permeability. Therefore more research needs to be done to synthesize 3-D scaffolds to have beneficiary effect in tissue engineering and drug delivery applications [184].

Use of electrospun fibers in wearable e-textiles as well as in solar energy conversion and electronic circuits are relatively new approaches. However, the primary challenge that still need to be overcome is the controlled alignment of fibers [185]. Besides, non-conductive polymers need to be added to the conductive polymers to increase their electrospinability which eventually reduce the electrical conductivity of the resultant electrospun fibers. Therefore smarter engineered ways need to be developed to increase the electrical conductivity of the polymer matrix to apply in real life [186].

Finally, in renewable energy applications, though electrospun nanofibers show great efficiency, getting uniform nanofibres with less than 50 nm diameter is an existing challenge. Besides the low rate of production of electrospun fibers with low diameter also an important challenge to overcome. Furthermore, well established way needs to be developed to produce electrospun fibers with controlled morphology so that maximum electron transport is possible [117]. Therefore it can be understandable that with future research these limitations will overcome and electrospun fibers will be used in solving unlimited problems of humankind.

10 Conclusion

Electrospinning procedure is used as a promising continuous fiber fabrication method for as many as 80 years. By varying the parameters like concentration, molecular weight, viscosity, surface tension, voltage, flow rate, syringe to collector distance etc. electrospun nanofibers can be used in wide range of applications like filtration, biomedical engineering, textiles, electrical engineering and renewable energy.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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